Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P541-cd

An Integrated Reliability, Availability, and Maintainability Approach for Metro Systems

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This paper presents the integrated Reliability, Availability, and Maintainability (RAM) approach applied to the design of Metro systems aiming to achieve the overall system-level RAM requirements. It presents the processes, plans, guidelines and techniques applied during the various design stages with the objective to assess RAM performance and at the same time influence design and procurement decisions. It explores the recording and management of RAM-derived requirements identified during various RAM studies that are transferred to the design, supply chain and operation and maintenance, preparing the grounds to allow the systems to perform as expected. Furthermore, it shows methodologies and procedures deployed during construction, testing and commissioning, trial running, and system acceptance periods to monitor, mitigate performance risks, and demonstrate RAM performance from the asset level to the system level, aiming to ensure the overall expected system performance is achieved.

Further details are provided about an integrated tool for RAM data management producing consistent and integrated outputs for Failure Modes, Effects and Criticality Analysis (FMECA), Spare Part Analysis, Special Tools and Equipment List, Preventative Maintenance Analysis, Corrective Maintenance Analysis and Life Cycle Cost (LCC). It also discusses how the various pieces of work are interlinked and integrated throughout the various stages of the projects.

Keywords: Reliability, Availability, Maintainability, FMECA, Analysis, LCC, Requirements, Demonstration, FRACAS.

1. Introduction

In today's global railway business, the requirement for a railway system capable of achieving high safety, availability and cost effectiveness is the primary focus. The technical performance of railway systems (e.g. high-speed, high capacity), has greatly improved over the recent years. Most railway organisations have implementing well defined Safety processes while availability and cost effectiveness are still at an early stage. However, low operational performance has an adverse influence on the quality of railway traffic service (e.g. frequent delay, increased cost of ownership, etc.). Thus, Reliability, Availability, and Maintainability (RAM) attributes and management becomes a significant decision-making factor in today's global and domestic railway business. Therefore, this paper focuses on the development of the systematic approach for an effective integrated RAM approach for Railway Systems. An Integrated Systems approach to RAM is necessary to achieve the following objectives:

- To integrate RAM management effectively into the railway systems engineering process,
- To perform RAM management consistently as an integrated part of the overall railway systems management,
- To achieve RAM requirements and operational objectives successfully,
- To improve the system product and organisation's performance continuously.

Reliability, Availability, and Maintainability (RAM) are design attributes of a system or an asset. Collectively, these parameters are leveraged to improve the productivity of the system or asset over its life cycle by reducing downtime, maximising profit, and ultimately, optimising the overall Life Cycle Cost (LCC). A quick definition of each parameter is provided below:

- **Reliability:** is defined as the probability of a system or asset performing its intended function under stated conditions without failure for a given period of time.
- **Maintainability:** describes the probability that a given maintenance action for an item under given usage conditions can be performed within a stated time interval when the maintenance is performed under stated conditions using stated procedures and resources. Maintainability has two categories: serviceability (the ease of conducting scheduled inspections and servicing) and repairability (the ease of restoring service after a failure).
- **Availability:** provides the probability that a repairable system or asset is operational at a given point in time under a given set of environmental conditions. Availability depends on reliability and maintainability.

Hence, the purpose of an integrated RAM analysis is to identify major causes of loss of Operational Availability (downtime) or other issues that may limit the performance of the system or asset (production throughput, on-time arrival, etc.). The end goal of a RAM analysis is to improve the system or asset design and maintenance programmes by optimising the overall LCC.

Having an Integrated Approach to RAM can provide an organization with a clear competitive advantage since the correct application of systems principles and RAM practices will realise substantial benefits that include: reduced design changes, reduced through-life cost, ability to manage change in a controlled way and management of risks amongst others.

2. When Should I Conduct a RAM Analysis?

RAM analysis can be applied at various stages of the life cycle of a system (Figure 1). However, conducting a RAM analysis at the early stages, whilst the design is still immature, is known to reduce the cost and schedule impact on the project. Delaying RAM activities until the later stages may lead to costly design changes or retrofit to resolve performance issues which could have been identified and resolved during the early planning, design or construction stages.

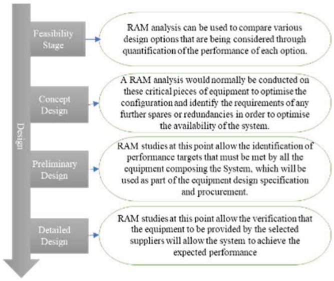

Fig. 1. RAM analysis in various design stages.

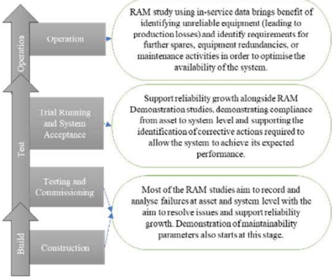

Fig. 2. RAM analysis during construction, testing and commissioning, and operation stages.

3. The Integrated RAM Approach

RAM high-level requirements are defined at the feasibility stage for the projects. Frequency of failures, time to repair, and availability targets are allocated for each one of the subsystems (i.e. Track, Control and Supervision, Power Supply, Signalling, Platform Screen Doors, Telecommunications, Radiocommunications, Rolling Stock, and Access Control and Fare Collection) as well as for MEP equipment at stations (e.g. lifts and escalators) and Depot Equipment, as well as for the overall system. Usually, these targets are further broken down for each one of the three failure categories

(Minor, Major, and Significant) as defined in EN 50126-1 (2017).

The RAM work for Metro and Rail projects follows the standard EN 50126-1 (2017) and its workstream evolves as the maturity of the design improves, and the RAM studies delivered in each design stage shall reflect this change. To support this work, the RAM team have developed in-house tools to manage component RAM information across the overall design life cycle, increasing efficiency in the data collection and RAM parameters update during the design (reducing cost on the project) linking it with in-house RAM database to ensure consistency across the analysis of various subsystems. The below sections describe the framework and deliverables required at each stage to ensure an integrated RAM approach.

3.1. *Concept Design Stage*

This stage sets out the scene for all the RAM works during the project life cycle. It also provides a clear framework with templates and guidelines that will be cascaded down to each subsystem to ensure consistency in the method and approaches, in such a way that system integration is facilitated in the various stages. In the Concept Design Stage, the main RAM deliverables are:

System Assurance RAM Plan: It defines the RAM management activities, responsibilities and RAM deliverables to be provided for the overall system and for each of its subsystems per stage of the system life-cycle, as well as details of the expected content of each one of the RAM documents to be produced. The RAM Plan is a live document that is reviewed as required throughout the project life cycle. It is the main guidance for all RAM activities to be developed during the design, construction, testing and commissioning, system acceptance and operation stages. The RAM Plan follows the high-level RAM requirements defined in the feasibility stage.

Spare Parts Guidelines: It defines the methodology for the calculation of the number of spare parts to be kept in stock based on RAM parameters and item criticality. The approach uses the Poisson Law and considers the item demand rate, turnaround time, and a variable target for the Probability of Not Stocking-Disruption depending on the item's criticality.

RAM Traceability Matrix: It presents a list of all RAM requirements and where (i.e. which document) and when (i.e. which stage) evidence of compliance will be available. The Traceability matrix is a live document that is reviewed in each one of the further design stages, mainly to incorporate RAM-Derived requirements that are identified as part of the detailed RAM works.

RAM Allocation (for the overall system and for each subsystem): At the system level, the RAM allocation focuses on verifying and amending, if necessary, the subsystem level targets in a way to ensure that the overall system performance is achieved once all the subsystems have achieved the expected performance. The system-level analysis also presents benchmarking data to support the decision around subsystem targets, making sure achievable expectations are set for each subsystem. At the subsystem level, the RAM Allocation considers the early design information available (i.e. system architecture and major components), breaking down each subsystem into the main pieces to be deployed (i.e. equipment/sub-subsystems), analyzing the consequences of failure of those pieces (FMEA), and building high-level Reliability Block Diagrams (RBD) considering data from previous experience (past projects), generic data sources (i.e. NPRD), or expert judgment to ensure the concept design being developed is able to comply with the requirements set. This process is carried throughout the Concept Design stage, with involvement from the designers and, in several instances, influences the design itself (removal of single points of failure, improvement of subsystem architecture). The main technical references for the RAM Allocations are IEC 60812 (2006) and IEC 61078 (2006).

3.2. *Preliminary Design Stage*

During the Preliminary Design Stage, more engineering details about the system architecture and components become available. As consequence, the level of details of the RAM studies delivered also increases. Setting out a full life cycle framework and clear methodology for subsystem owners allowing them to have a clear scope of delivery (reducing overall cost), a consistent in the approach for RAM calculations (reduce risk of discrepancies in calculation methods) and an understanding of the content level required to meet the expectations of the Client provides benefits for the overall RAM approach. In the Preliminary Design Stage, the main RAM deliverables are:

LCC Methodology: It defines the methodology for calculation of the overall system and subsystems' LCC, considering Spare Parts, Special Tools and Corrective and Preventative Maintenance Costs. The methodology follows IEC 60300-3-3 (2014).

FRACAS Procedure: It defines activities and responsibilities for deploying a Failure Reporting, Analysis and Corrective Action System (FRACAS), supporting the system and subsystem reliability growth and the RAM demonstration activities to be carried out at later stages.

Obsolescence Management Guidelines: it defines the methodology applied for analyzing the risks associated with the obsolescence of items (hardware and software) deployed in the projects. The guidelines follow IEC 62402 (2019).

Reliability Critical Items List (RCIL) & FMECA: it is developed for each subsystem at the component level (Line Replaceable Unit (LRU)), and it is fully aligned with the RAM Analysis and Prediction Report. The FMECA analysis contains the breakdown of Function Analysis (FA) and Functional Failure Analysis (FFA) from the subsystem level, down to the LRU level. Subsystem interface failures are analyzed as part of the Interface Failure Analysis (IFA). Functional Block Diagrams (FBD) are as well developed. During the preliminary design stage, data from previous experience (past projects), generic data sources (i.e. NPRD), or expert judgment is used alongside the proposed system architecture to deliver the results. The FMECA identifies single-point of failures, reliability and safety-critical items and consolidates the RAM-Derived requirements to be set for the procurement of components. Interaction with the designers is a crucial part of the analysis where the RAM Team can influence changes and improvements in design from the RAM performance perspective. The main technical references for the study are presented in references IEC 60812 (2006), MIL-STD-1629A (1980), and MIL-HDBK-472 (1984).

RAM Analysis and Prediction: it is developed for each subsystem at the component level (LRU), and it is fully aligned with the RCIL & FMECA. It summarizes the Common Cause Failure Analysis (CCFA), presents the RAM prediction outputs (compared with high-level requirements and calculated using RBD or Fault Tree Analysis (FTA)), and the list of Corrective Maintenance (CM) and Preventative Maintenance (PM) tasks expected for each component of the subsystem. It also provides a preliminary list of spare parts, special tools and quantities to be allocated for the projects. The main technical references for the study are presented in references IEC 60812 (2006), MIL-STD-1629A (1980), and MIL-HDBK-472 (1984).

Update of the RAM Traceability Matrix: It is updated to incorporate RAM-Derived requirements that have been identified in the various analysis performed during this stage. Most of the new requirements are applicable for procurement and define expected failure rates, time to repair and failure modes for each component type deployed in each subsystem. Non-procurement RAM-Derived requirements can also be identified to be addressed in the next design stage or to be transferred to Operation and Maintenance.

3.3. *Detailed Design Stage*

During the Detailed Design Stage, a mature system design architecture is available, and the suppliers have been selected. At this stage, the RAM works shall integrate the design architecture with the RAM information from suppliers. During the Detailed Design Stage, the main RAM deliverables are:

RAM Demonstration Plan: It defines the methodology to be applied during construction, testing and commissioning, trial running and system acceptance stage for the demonstration of compliance for the overall system, subsystem and component performance against the requirements set in the high-level RAM requirements and the RAM-Derived requirements identified as part of the RAM works. It covers tests, criteria and periods for the demonstration of reliability, availability, and maintainability parameters. The main technical references for the RAM Demonstration are MIL-HDBK-470A (1997), MIL-HDBK-781A (1996), and BS 5760-10.3 (1993).

Update of the RCIL & FMECA and RAM Analysis and Prediction: Having the suppliers on board the project allows the RAM data on those studies to be updated considering the specific RAM performance of each component as per supplier experience and available information. The suppliers' RAM data (failure modes, failure rates, time to repair, required resources [tools and labour], and recommended preventative maintenance plan) replaces the data used in the preliminary design stage and the studies are reviewed to assure that each subsystem RAM performance will meet the high-level RAM targets.

RAM Report: It integrates the subsystems RCIL and FMECA and RAM Analysis and Prediction outputs for the overall system to demonstrate design compliance against the overall system RAM targets at system level.

LCC Study: An LCC study is developed for each subsystem considering the predicted cost for the initial provision of Spare Parts, Tools, and Corrective and Preventative Maintenance [labour, consumables, and spares]. The studies follow the LCC Methodology and IEC 60300-3-3 (2014).

Obsolescence Study: An obsolescence risk assessment is carried out per subsystem to identify components presenting high obsolescence risk. For the critical components identified, proactive actions are proposed, prioritized, and monitored to control and mitigate the obsolescence risk identified. The studies follow the Obsolescence Management Guidelines and IEC 62402 (2019).

Update of the RAM Traceability Matrix: It is updated considering the latest requirement list per subsystem. This list is crucial for the next stages (construction, testing and commissioning, trial running and system acceptance), as throughout them each one of the RAM requirements will have to be demonstrated.

3.4. *Construction and Testing and Commissioning Stages*

During the Construction and Testing and Commissioning stages testing failures are identified and divergences are addressed by the subsystem designers and equipment suppliers. If applicable, the RAM studies, typically RCIL and FMECA and RAM Analysis and Prediction will have to be updated to reflect any applicable change. Additionally, to the required updates, the following RAM deliverables are expected:

Testing and Commissioning RAM Demonstration Protocols: It analyzes the on-field data and certification certificates coming from the Testing and Commissioning phases. The on-field data (recorded in the FRACAS database) is analyzed in order to demonstrate compliance with the RAM targets. Failures and errors are recorded, analyzed and resolved. The protocol defines the assets that are going to be sample tested to demonstrate compliance to the Maintainability parameters, the applicable test to be deployed to demonstrate compliance to the RAM parameters and its schedule.

FRACAS Monthly Reports: Pre-defined fields are incorporated into the Maintenance Management System for the collection of data on defects and failures, sufficient to estimate equipment RAM performance. A record of the time taken to complete repairs is collected in order to estimate Mean Time To Repair (MTTR) and Mean Down Time (MDT). Root causes are identified, and recommended corrective actions are agreed upon to prevent recurrence.

3.5. *Trial Running and System Acceptance Stages*

During the Trial Running and System Acceptance, the overall system is brought into operation, increasing the number of train services, and achieving a minimum level of performance before starting the commercial operation. At this stage, the FRACAS Monthly reports are still being produced. The main additional RAM deliverables are:

Monthly RAM Demonstration Reports: These reports present the RAM performance for each subsystem at the subsystem level as well as the component level performance throughout the Trial Running and Commercial Operation. Failures recorded on the FRACAS process are the main source of data for the Monthly RAM Demonstration reports.

Final RAM Demonstration Report: Final System and Subsystem RAM Demonstration Reports are produced to demonstrate that the RAM targets have been satisfied at the system, subsystem, and component levels, and so it provides evidence for closure of RAM requirements previously defined and recorded in the RAM Traceability Matrix. Final RAM Demonstration Reports present trends of failure events recorded on the FRACAS process, trends of the overall system and subsystem reliability, availability and maintainability, results of the tests applied at the component level for reliability, availability and maintainability with a special focus on reliability and safety-critical components, and a summary of the corrective actions implemented during the current and previous stages. At the end of this stage, the expectation is to have all high-level RAM requirements set in the feasibility stage successfully demonstrated.

4. The RAM Data Management Tool

A tailored tool was developed to manage RAM data throughout the project life cycle. It consists of a relational database that links various pieces of information as presented in the framework shown in Figure 3. The upper part of Figure 3 presents the input parameters, whilst the bottom part presents the outputs. The tool allows the management of the expansion of the level of granularity of the system model that happens as the design progresses throughout the various stages. It also allows easy consistency checks and provide standardized outputs.

The main advantages of the use of the tool are:

- Consistent RAM and Costs data linked to a single source database, providing full traceability and consistent with the outputs.
- Ability to progress the level of granularity of the RAM analysis alongside design.
- Easy updates to consider design developments or changes, avoiding manual checks on the output analysis.
- Automatic check for inconsistencies in the data input.
- Unique identifier numbers recorded and traceable from inputs to outputs.
- Overall reduction on manual works reducing errors and streamlining the production of RAM works.

The following list details the input parameters:

- Reliability & Costs Database: this database centralizes the information regarding component failure rate, failure rate data source and failure modes. It also provides information for component costs, consumable costs and hourly costs associated with the various personal skill levels.
- General Information: this list consolidates per component type information as weight, size, turnaround time and life expectancy.

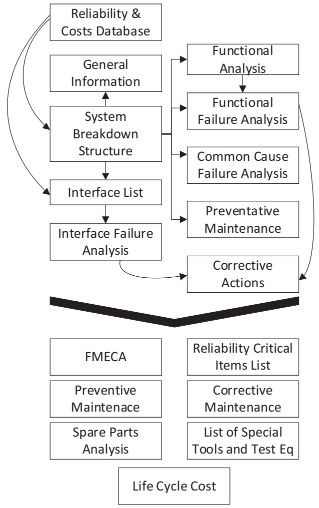

Fig. 3. Overview of the Data Management Tool.

- Interface List: lists the main internal and external interfaces of the system to be analyzed.

- Functional Analysis (FA): this analysis is carried out for each item in the System Breakdown Structure (i.e. system, subsystem, sub-subsystem, equipment, and component). It covers the primary function, list of secondary functions, conditions for degraded modes of operation and for system unavailability, list of interfaces, list of sub-items (sub-system, equipment, or component), quantities and redundancy.
- Functional Failure Analysis (FFA): this analysis is carried out for each item in the System Breakdown Structure (i.e. system, subsystem, sub-subsystem, equipment, and component). It covers for each of the functions of a given item the failure modes, mode apportionment factors, causes, effects, escalation, consequences for RAM (Minor, Major, and Significant) and Safety, effects on interfacing systems, operational means of detection, operational response, design and non-design mitigations, and the corrective action to rectify the failure.
- Common Cause Failure Analysis (CCFA): it is performed to assess potential common cause failures linked to physical, functional, or process causes, identifying consequences and proposing mitigations. The analysis is prompted using a checklist derived from IEC 61508-6 (1997).
- Interface Failure Analysis (IFA): follows the same approach as FFA however targets the analysis of failures of interfaces.
- Corrective Maintenance (CM): each CM identified in each Functional and Interface Failure Analysis for all component types is summarized in this list. Details regarding MTTR and its breakdown (i,e., diagnosis, repair, test, and restore times) are recorded alongside the required personal hours for the various skill levels (EN 13306 (2017)) list of components and consumables used in the repair tasks and special tools and testing equipment that are required.
- Preventative Maintenance (PM): PM tasks are developed and can incorporate various components in a single task. It covers task type, description, components covered, frequency, required personal hours for the various skill levels, components and consumables used (if any) in the repair tasks and special tools and testing equipment that are required.

The following list details the outputs:

- FMECA: based on the Reliability Database, System Breakdown Structure, list of Interfaces, Functional and Interface Failure Analysis, and Corrective Actions list, alongside the applicable risk matrix and the criteria for the classification of reliability critical items list the FMECA is produced.
- Reliability Critical Items List (RCIL): a list of Reliability Critical Items is extracted from the FMECA based on the criteria for identification.
- Preventative Maintenance (PM): a consolidated list of PM activities, frequencies, resources and quantity of locations to be deployed is provided. This becomes a relevant input for LCC, for the definition of the Maintenance Plan to be applied once the system starts operation.
- Corrective Maintenance (CM): a consolidated list of CM activities, frequencies, resources and quantity of locations to be deployed is provided. This becomes a relevant input for LCC and for supporting the definition of the quantity and size of maintenance teams.
- Spare Parts Analysis: a quantity of spares is calculated considering the spare demand rate from CM and PM, the Turnaround time and the expected level of confidence for each item.
- List of Special Tools and Test Equipment: a summary of special tools and test equipment is produced, identifying the expected average usage hours per year, which supports the definition of the quantity required.
- Life Cycle Cost (LCC): a simplified life cycle analysis is performed summarizing costs for Special Tools, Spare Parts and Corrective and Preventative Maintenance throughout the life cycle of the system.

4. Benefits of an Integrated RAM Approach

With the application of an integrated RAM approach throughout the design of Metro Systems, it is possible to conduct RAM studies alongside the design development, allowing the

RAM outputs to influence the design and procurement decisions. It allows the identification of RAM requirements to be transferred to the design, supply chain and operation and maintenance, preparing the grounds to allow the systems to perform as expected. During the pre-operation and operation stages, those requirements will have to be formally demonstrated with evidence. At the same stages, the FRACAS process will be in place to record, analyze, define corrective actions and monitor reliability growth. Additionally, the RAM approach is organized in a way that the plans, guidelines and studies evolve during the design, increasing the level of granularity and details through the process. The main benefits of an integrated RAM approach for the System design can be summarized as follows:

- Having an integrated approach with a clear framework, methodologies, and guidelines set out from the start of the design and cascaded down to the various contractors (subsystem owners).
- Assurance from the early design stages that the proposed subsystem architecture can achieve the expected level of RAM performance.
- Early identification of weaknesses and vulnerabilities in the proposed design.
- Procurement RAM requirements are being allocated to the suppliers.
- Supporting items such as the number of spare parts, special tools, preventative maintenance plan and human resources required are identified.
- Implementation of a FRACAS to follow up on the observed performance of equipment and components, supporting the identification of systematic failures in the early stages of testing and commissioning.
- Definition of clear criteria for acceptance or rejection of component level performance during the various demonstration stages.

This model and processes have been rolled out on multiple projects by the RAM team overtime. The integrated RAM framework was deployed at the early stage of concept design and passed onto contractors and suppliers to apply during the life cycle stages. It resulted in the achievement of the RAM objectives during the whole Design Phase and a successful integration of RAM management into Railway Systems Level. It demonstrates that a systematic and an integrated framework approach, processes and techniques can help railway organisations establish and implement RAM management throughout the life cycle.

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