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# RAMI and Data Governance for Fusion

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# 1 Introduction

Analyses of Reliability, Availability, Maintainability and Inspectability (RAMI) are a key enabler of the successful design and operation of a next-generation fusion facility, with wider relevance to other big science facilities. Our recent experience at IFMIF-DONES (Pinna et al., 2025; Arranz et al., 2025), together with the scientific literature, demonstrates that early and continuous integration of RAMI studies is essential to meet ambitious availability targets in *first-of-a-kind* plants with highly novel technologies and scarce operational data.

Initiated at the conceptual design stage and updated throughout the design cycle, RAMI studies provide quantitative guidance for allocating availability requirements across systems, identifying critical components, and defining the required redundancies, fault-tolerant modes and maintenance strategies. This perspective directly supports the transition from "design for performance" to "Design for Maintenance", in which layout, access routes, shielding, logistics and handling systems are planned from the outset to minimise mean downtime and reduce constraints associated with the radiological activation of components (Arranz et al., 2025).

Experience at DONES highlights the value of structured methodologies—Plant and Function Breakdown Structures (PBS/FBS), Failure Modes and Effects Analysis and Failure Modes, Effects and Criticality Analysis (FMEA/FMECA), Reliability Block Diagrams (RBDs) and system reliability approaches—combined with advanced tools such as virtual reality and sophisticated digital models to validate complex maintenance operations before construction (Pinna et al., 2025).

For a fusion facility, incorporating RAMI requirements into the system architecture and infrastructure layout from an early stage will mitigate technical risks, optimise life-cycle costs and enable a data-driven asset management policy aligned with international standards (ISO 19650, ISO 55000, ISO 14224). These principles are also applicable to other big science facilities.

# 2 Lessons learnt applicable to any fusion facility

A fusion facility would benefit from a RAMI design approach closely integrated with operation and maintenance from the earliest stages, drawing on the lessons learnt at DONES (Ibarra et al., 2019). The following sections highlight lessons from IFMIF-DONES relating to both RAMI analysis and information governance.

### RAMI, logistics and maintenance must be integrated

- At DONES, RAMI studies have been used to define maintenance policy (maintenance shutdowns, operational availability, PM/CM allocation, replacement and restoration criteria, etc.). However, maintenance assumptions (MTTR, *cooldown* times, accessibility and logistics) directly influence the availability results obtained from RAMI studies.
- The "*Maintenance Matrix*" centralises RAMI and maintenance information (safety classification, maintenance type, resources, frequency, duration and predecessor/successor activities), and was specifically conceived as a bridge between RAMI analysis and maintenance planning (Arranz et al., 2025).

### Define system-level PBS/FBS, FMEA and RBDs at an early stage

- At DONES, the first RAMI step was to define detailed Plant and Function Breakdown Structures (PBS/FBS), which underpin systematic FMEA and the development of reliability block diagrams for individual systems (accelerator, lithium, test cell, balance of plant, waste, etc.). At other comparable facilities, these analyses have been undertaken retrospectively as a form of "forensic engineering", preventing RAMI studies from influencing the design.
- This has enabled early identification of critical components (backplate, traps, pumps, HFTM welds, scrapers, etc.), availability bottlenecks and requirements for redundancy or spare-parts storage before the design is finalised.

### "Design for Maintenance" from the initial layout

- DONES has demonstrated that access points, openings, clearances, overhead cranes, floor loading and logistics routes strongly influence the feasibility of maintenance operations, particularly for large or activated components (target, SRF modules, beam dump, waste tanks, HVAC, etc.).
- Virtual reality logistics simulations have been used to validate maintenance and installation manoeuvres, detect collisions, refine overhead crane and omnidirectional platform (OMP) arrangements, and size workshops and spare-parts stores (Arranz et al., 2025; Benito-Fuentes et al., 2024; Rouret et al., 2023).

### Formalise a maintenance policy and a "*Maintenance Matrix*" during design

- At DONES, an explicit preventive maintenance policy has been defined: preventive/corrective categories, maintenance types according to plant state (*beam on/off*, lithium system running/stopped), classification as "*hands-on*" / "*hands-off*" / "*remote handling*", regulatory and safety requirements, etc.
- This is captured in the *Maintenance Matrix* (more than 1,200 activities), which links each item of equipment via the PBS to its specific task, frequency, duration, number of personnel, safety classification (*SIC1/2*), required shutdown type, personnel classification, layout priority, documentation links and the Maintenance Plan.

### Formalise a framework for data governance

Our experience reveals a common pattern in complex technical programmes: when information governance is not defined from the outset, the organisation generates data and documents without a common system to make them reusable, comparable and traceable. The result is structural technical debt that accumulates silently and is later paid for through rework, ad hoc integrations, duplication, loss of confidence in data, and constraints on automating and scaling analytics and AI.

Two levels with distinct impacts should be distinguished:

#### 1) Absence of a governance policy (what "must exist" and what is mandatory)

Policy is the foundational layer: it defines *the minimum elements* that must exist, *who is accountable*, *what is mandatory* and *the criteria information must meet* to be considered valid within the programme (design, construction, O&M, research, development and innovation).

Without a policy, each initiative makes well-intentioned local decisions, and the programme ends up with incompatible "micro-systems". Examples include:

- No asset taxonomy: No policy defines the requirement for a taxonomy or its minimum requirements (unique identification, hierarchy, attributes and coding rules). Different projects represent the same asset in different ways, breaking traceability across disciplines.
- Document and data management treated as an outcome rather than a requirement: Without an explicit policy, governance amounts to good intentions. Each team optimises its deliverable without ensuring interoperability across the programme.

In summary, without a policy, there is no "internal agreement" on how information should be structured. Technical debt starts here, as information assets are created that are subsequently costly to standardise.

2) Consequent absence of a governance strategy (how it is implemented and operated)

While policy defines *what* is required and *what must be done*, strategy defines *how*: the target architecture, platform decisions, data management patterns, operating model and the route by which the organisation produces and uses data consistently.

Without a strategy, even where isolated examples of good practice exist, solutions become piecemeal and divergent. This is evident in:

- No defined analytics strategy: Neither the approach to be used (a data lake or another solution) nor its role in RAMI and maintenance applications is specified. Each subproject designs its own repository with its own transformations and criteria.
- Infrastructure decisions not established (hosting, servers and location): Neither the server hosting location nor the operating model (service levels, security and continuity) is defined. Quick fixes proliferate that are difficult to sustain or scale.
- No standardised management methodology (e.g. Medallion): How data are organised and evolve within the repository is not defined. Raw and transformed data are mixed, reducing reproducibility and increasing the validation effort required for RAMI analysis.
- No agreed organisational model for data (e.g. Data Mesh): No approach based on domains, clear responsibilities and reusable data products is established. Integrations are addressed case by case, without developing a sustained data product capability.

In summary, without a strategy, each project (design, construction, maintenance, research, development and innovation) develops different methodologies and approaches to generate and manage information. This creates a legacy of unstructured and inconsistent information that inevitably reduces opportunities for reuse, limits analytics and AI, and increases the cost of any future consolidation.

Recommendation for a fusion facility:

The constructive lessons learnt from DONES and LIPAc are clear: in programmes of this scale, governance cannot be an optional extra or a retrospective deliverable. This avoidable structural technical debt (common in long-established organisations predating the maturity of these methodologies) should be prevented from the outset by explicitly defining:

- Policy: the requirement for an asset taxonomy (and the requirements it must meet), and the mandatory minimum elements of governance, documentation and data.
- Strategy: the data architecture and operating model (e.g. a *data lake* or another solution), infrastructure decisions (*hosting*), and a management methodology (e.g. Medallion) and/or an approach based on domains and *data products* (e.g. Data Mesh) to ensure consistency and scalability.

# 3 Immediate needs for the RAMI Analysis Plan of a fusion facility

Based on these lessons, the priorities for formalising a RAMI Analysis Plan for a fusion facility would be:

1. Define the PBS/FBS and the organisation-wide data model
    - Develop the PBS of the fusion facility (plant–system–subsystem–equipment–component) and its associated *Function Breakdown Structure* as a common basis for RAMI, maintenance, BIM and logistics.
    - Align this hierarchy with an equipment taxonomy compatible with ISO 14224 (equipment types, functions, and reliability and maintenance data classes).

- Integrate the PBS/FBS into the asset management model in accordance with ISO 55000 (a life-cycle perspective encompassing risk, value, cost and asset performance) (ISO 55000, 2014).

2. Design and create the Maintenance Matrix for the fusion facility (version 1.0)
    - Use the DONES Maintenance Matrix as a conceptual template and adapt it to the fusion facility, retaining key fields: PBS code, equipment/component, task, maintenance type, frequency, duration, resources, safety classification, access type, predecessor/successor activities, etc.
    - Structure the matrix in line with ISO 14224 good practice so that maintenance and failure data can be reused in RAMI analysis (RBDs, FMEA/FMECA, Petri nets) and in the asset management system (Saleh et al., 2023).
    - Plan its integration with an organisation-wide CMMS from the outset, so that the matrix evolves from a static design into a live database populated by operational data.

3. Implement BIM and the CDE as the digital repository for the fusion facility (ISO 19650)
    - Adopt BIM from the conceptual stage, specifying in the information requirements (EIR/AIR) that RAMI and maintenance properties must be included for all maintainable elements.
    - Establish a Common Data Environment (CDE) as the single repository for BIM models, technical documentation, the Maintenance Matrix, RAMI data and operational records, following ISO 19650 principles (version control, information states, traceability and security) (ISO 19650-1, 2018).
    - Define dedicated BIM property sets for RAMI and maintenance (PBS ID, criticality, failure modes, reference MTBF/MTTR, maintenance type, frequency, duration, number of personnel, safety classification, access type, links to procedures, etc.), so that the BIM model acts as the “structured container” for this information.

4. Establish a data governance model compatible with RAMI and maintenance
    - Establish a set of roles:
        - ✓ asset information/BIM manager (for ISO 19650 and the CDE),
        - ✓ asset management/RAMI manager (for ISO 55000),
        - ✓ reliability and maintenance data quality manager (aligned with ISO 14224).
    - Define organisation-wide processes for:
        - ✓ generating, reviewing and approving RAMI and maintenance data at each stage (design, construction and operation);
        - ✓ quality control, auditing and regular updating of the PBS, Maintenance Matrix, BIM model and CMMS;
        - ✓ access management, information security and change traceability.
    - Establish clear policies for unique coding, naming and identification (GUIDs/IDs) to ensure consistency across the PBS, BIM, Maintenance Matrix, CMMS and RAMI models.

5. Plan a phased, data-linked RAMI analysis programme
    - Pre-conceptual/conceptual design:
        - ✓ set operational and inherent availability requirements for each system;
        - ✓ identify key uncertainties (failure data, cooling times, accessibility, radiological cooldown and logistics) and how these will be captured as structured data.
    - Basic design:
        - ✓ develop FMEA/FMECA based on the PBS/FBS, recording functions, failure modes and consequences in a database aligned with ISO 14224;
        - ✓ build RBDs for critical systems, using this database and the Maintenance Matrix as the main inputs.
    - Detailed design and transition to operation:
        - ✓ freeze version 1.0 of the Maintenance Matrix for the fusion facility and the BIM property sets for RAMI and maintenance, and integrate them with the CMMS and CDE;
        - ✓ define how actual operation and maintenance data will be fed back regularly into the RAMI models, the Matrix and BIM as part of the ISO 55000 asset management system.

6. Integrate design, layout and logistics with RAMI and the digital repository
    - Link layout decisions (rooms, clearances, routes, lifts and workshops) to Maintenance Matrix activities and BIM models, so that any design change is automatically assessed in terms of accessibility, intervention times and resources.
    - Plan the use of virtual twins and VR based on the BIM model to validate maintenance and logistics manoeuvres, consistently using the same IDs and data held in the CDE and the Matrix to avoid duplication of models and information (Benito-Fuentes et al., 2024).

These measures explicitly anchor the RAMI Analysis Plan for the fusion facility in an organisation-wide data governance model supported by BIM and ISO standards, making the digital repository of the fusion facility the operational core of all design, maintenance and asset management decisions. The same framework can be adapted to other big science facilities.

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