Maintainability Lessons Learned

SLS Requirements

SLS-PLAN-013, Space Launch System (SLS) Program Safety and Mission Assurance (SMA)

4.4.3.6 Maintainability Assessment

The SLS Elements will perform Maintainability analyses and demonstrations to assess compliance with allocated Maintainability Technical Metrics Plans (TPMs) and to assure that maintenance activities can be successfully executed within the scope of the SLS maintenance concept. SLS Reliability and Maintainability (R&M) personnel will participate in Program/Element design reviews and will be responsible for the technical review of Element Maintainability assessment activities to assure that Maintainability is being properly considered in the system.

SLS Requirements

SLS-RQMT-014, Space Launch System (SLS) Program Safety and Mission Assurance (SMA) Requirements

5.3 Maintainability Engineering

The SLS R&M Program implements the following Maintainability engineering activities to assure ease of maintenance and to minimize system downtime and life cycle costs.

5.3.1 Maintainability Requirement Development and Allocation

The SLS Program shall develop quantitative Maintainability TPMs from the top-level Launch Availability TPM and allocate them to SLS Elements to influence the element designs (SLS-SMA-RM-018).

5.3.2 Maintainability Design Criteria

The SLS Elements shall assure the development and implementation of qualitative Maintainability design criteria to facilitate ease of corrective and preventive maintenance (SLS-SMA-RM-019).

5.3.3 Maintainability Modeling and Analysis

The SLS Elements shall develop Maintainability models and analyses concurrently with the SLS design process and jointly with design engineering (SLS-SMA-RM-020). Results shall be compared to maintainability TPMs in order to determine the adequacy of the design, provided as feedback to SLS design, used to support design trades, and as input to other related analyses (e.g., launch availability analysis, logistics support analysis, etc.) (SLS-SMA-RM-021).

The Maintainability models and analyses shall be updated throughout the SLS life cycle to incorporate updates in analytical and empirical data collected.

SLS Requirements

SLS-PLAN-047 SLSP Technical Metrics Plan (TMP)

4.4.4 Vehicle Level Maintenance Downtime
The Maintenance Downtime TPM assesses the degree to which the SLS is repairable to support additional launch attempts in the event of a launch scrub due to a hardware/software failure. Maintenance Downtime is inclusive of all time from the point a launch scrub is declared until the vehicle is ready to restart countdown for the follow-on launch attempt, exclusive of weather delays…. The vehicle TPM measures the percent of vehicle failures that occur after the start of launch countdown and result in a launch scrub that can be repaired with a maximum repair time of 240 hours. This TPM supports the vehicle maximum maintenance downtime of 480 hours.

4.4.5 Element Maintainability

The Element Maintainability TPMs are derived in support of the Launch Availability TPM and assess the degree to which the Element is repairable to support additional launch attempts in the event of a launch scrub due to hardware/software failure. For each Element, the Maintainability TPMs assess the percentage of Element failures that occur after start of launch countdown and result in a launch scrub that can be repaired within 240 hours in the Vehicle Assembly Building after roll back from the pad.

Shuttle Lessons Learned

As the Space Shuttle evolved, reality overcame dreams and visions, thus performance problems developed. These were of a wide variety, including payload to orbit capability, cost, operational complexity, refurbishment, and maintenance. When a project is faced with a performance issue (payload to orbit), there are three options available for dealing with the problem: (1) weight reduction (structures, consumables, propellant reserves, etc.), (2) performance enhancements (thrust, LSP, launch site, burn time, etc.), and (3) operational procedures and constraints (reduced requirements, environment reductions, etc.).

The Shuttle employed all three techniques in order to meet performance requirements. This was accomplished in a very innovative and balanced manner from the reduction of safety factors on the ET for well known loads to the High Performance Motor (HPM) SRM 3,000 performance enhancement, to the 104-percent power level SSME.

NASA Technical Paper 3653: A History of Aerospace Problems, Their Solutions, Their Lessons

Although the Space Shuttle is a marvelous and successful machine, there are some down sides. For example, as a result many sensitivities of not only the Shuttle system, but also its elements and components as well, it has led to costly launch delays, maintenance and refurbishment issues, operational hands-on labor (touch labor), and cost.

The Shuttle as a system is, therefore, very complex, requiring much touch-labor to operate, and is limited in performance by its constraints; yet it is indeed a remarkable machine, a marvel, a wonder. Future systems, however, need a different approach that is reliable, cost efficient, and, therefore, robust.

Cost, operations, manufacturability, and supportability must be a fundamental part of the design equation. Metrics must be developed to support:

Cost and operational efficiency requires a multipronged approach

(1) Calculated risk-taking/management that obviously includes a detailed assessment of consequences must be a part of this risk-taking

(2) Product improvement that reduces cost and improves operations; reduction of the number of parts, simplicity, and robustness are parts of this equation

(3) Development of criteria; all this must be accomplished without violating basic physics and while using good engineering practices.

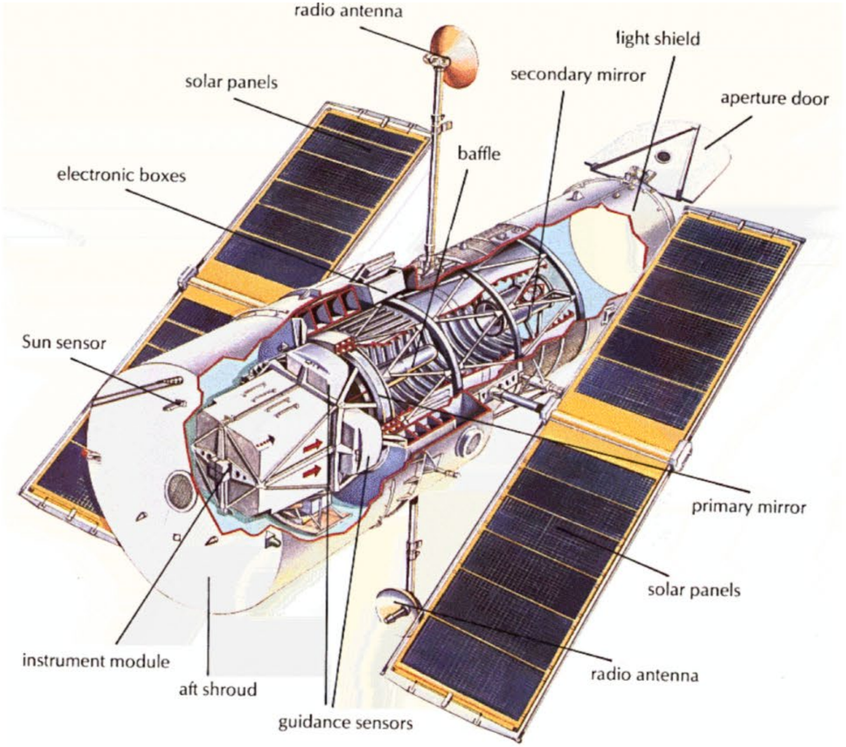
Shuttle Lessons Learned

"While the Shuttle's capabilities are extensive and varied, it has proven to be extremely expensive to use, unreliable in its logistics, and operationally fragile."

Testimony of Michael D. Griffin Hearing on the Future of Human Space Flight Committee on Science Rayburn House Office Building Room 2318 16 Oct 2003

Hubble Space Telescope

Maintainability concepts were included early in the life cycle, where maintenance planning and optimum ORU usage in design saved the program significant costs when on-orbit repairs became necessary.

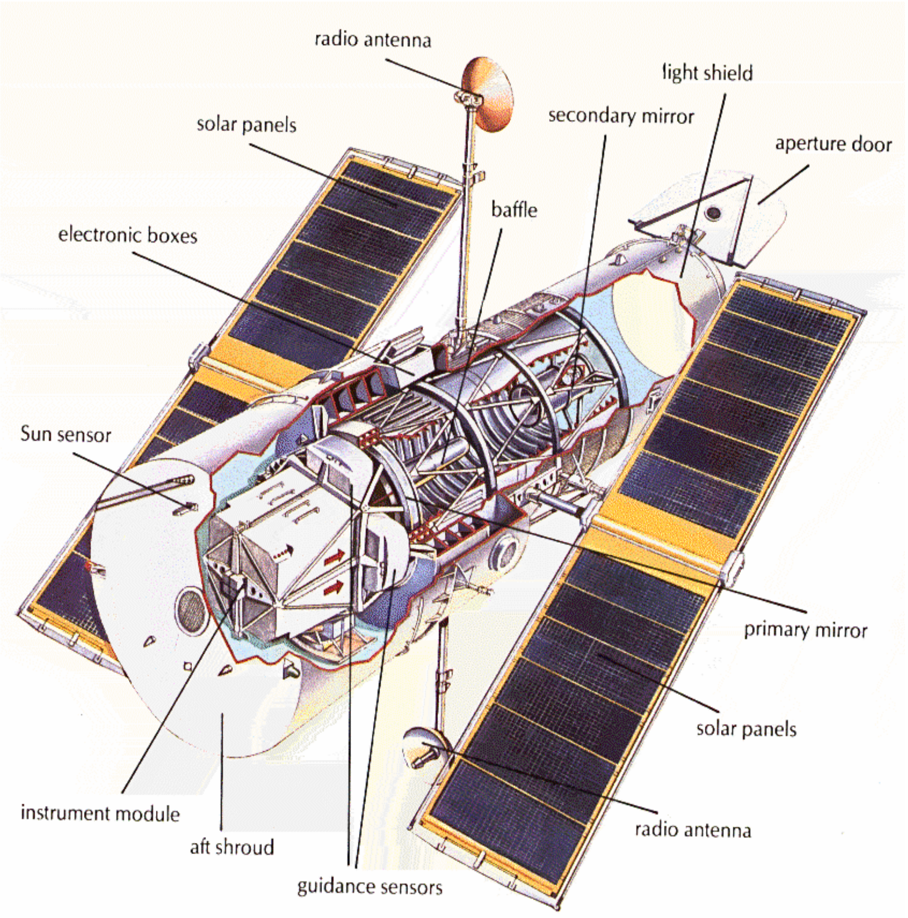


HST was designed with replaceable cameras and guidance sensors. Provisions were also made for change-out of limited life components (e.g. gyroscopes, batteries, and reaction wheels). Servicing missions were planned every three years using the Space Shuttle. In this way the initial expense of developing and launching the HST would be amortized over a longer lifetime while providing a consistent level of scientific return by incorporating the latest technologies.

Benefits of Implementing Maintainability on NASA Programs

Implementation of Maintainability principles can reduce risk by increasing operational availability and reducing life cycle costs.

- Enhanced system readiness/availability
- Reduced downtime
- Supportable systems
- Ease of troubleshooting and repair
- System growth opportunities
- Hardware/software modifications
- Interchangeability
- Modular designs
- Decreased storage considerations
- Reduced maintenance manpower
- Reduced operational costs
- Compatibility with other Programs
- Reduced management overhead



Hubble Space Telescope was designed for Maintainability and serviceability. Launched in 1990, it is still functioning today.

Hubble Space Telescope

Hubble is the only telescope designed to be maintained in space by astronauts. Five Space Shuttle missions have repaired, upgraded, and replaced systems on the telescope, including all five of the main instruments.

The fifth mission was canceled on safety grounds following the Columbia disaster (2003), but NASA Administrator Michael D. Griffin approved the fifth servicing mission which was completed in 2009. The telescope is operating as of 2019 and could last until 2030-2040.

HST Lesson Learned

Was the Life Cycle Support dimension of the Program effectively planned and executed?

This dimension was integral from day one (concept and design phases) and the results speak for themselves. The Hubble Space Telescope (HST) probably represents the benchmark for building in system sustainment (Reliability, Maintainability, provision for technology upgrade, built-in redundancy, etc.), all with provision for human execution of functions critical to servicing missions. With four successful service missions complete, including one initially not planned for the primary mirror repair, the benefits of design-for-sustainment, or life cycle support, throughout all phases of the Program becomes quite evident. Had this not been the case, it is not likely that the unanticipated, unplanned mirror repair could have even been attempted, let alone been totally successful.

Challenges

- Creating the "Design for R&M" environment to support the Agency's ambitious safety and affordability goals.
- Providing young R&M engineers adequate training and support to fill the gap created by staff attrition.
- Having the right mix of R&M engineering skills to support:
  - Technology development environment
  - Reliability, Maintainability, and Supportability (RMS) for long duration manned missions beyond Low-Earth Orbit
- Creating an integrated RMS operating analysis environment.
- Embedding R&M engineers in the design community.
- Establishing a centralized database for R&M analysis and predictions.

Logistics Lessons Learned in NASA Space Flight Interplanetary Supply Chain Management and Logistics Architectures

Top 7 Lessons Learned

The following seven lessons represent the review of nine separate data sources for lessons learned across Programs, Centers, and activities. This list is an attempt to look across perspectives to derive a root lesson and address the root causes.

1. Stowage is the most mentioned lesson in all databases. The lesson is that there should be design influence or specification to provide for stowage volume. The resulting problems from lack of stowage specification include growing time demands for the crew, loss of accountability, loss of access to operational space, limits to housekeeping, weakened morale, and an increased requirement for re-supply.

    Reconfigurable stowage volume is recommended.

    For high turnover, small items, pantry stowage is recommended (i.e. resupply the pantry, not the items in it).

    A system for naming and numbering stowage volumes should be established and maintained.

    Entryways, docking compartments, and other interconnections must take into account pass-through and cargo transfer operations.

2. The inventory system should be based on a common logistics system, shared by multiple organizations, to decrease the problem of differing values for like items across systems. Configuration management is enhanced with this type of system architecture, as well. Additionally, a single inventory system lends itself to a common naming system.

Logistics Lessons Learned in NASA Space Flight Interplanetary Supply Chain Management and Logistics Architectures

3. Packing lists and manifests do not make good manual accounting systems. Parent-child relationships are fluid and need to be intuitively handled by a system updated by the movement of both parents and children.

4. Commonality should be a prime consideration for all vehicles, systems, components, and software in order to minimize training requirements, optimize Maintainability, reduce development and sparing costs, and increase operational flexibility. Failure to do this increases the logistics footprint.

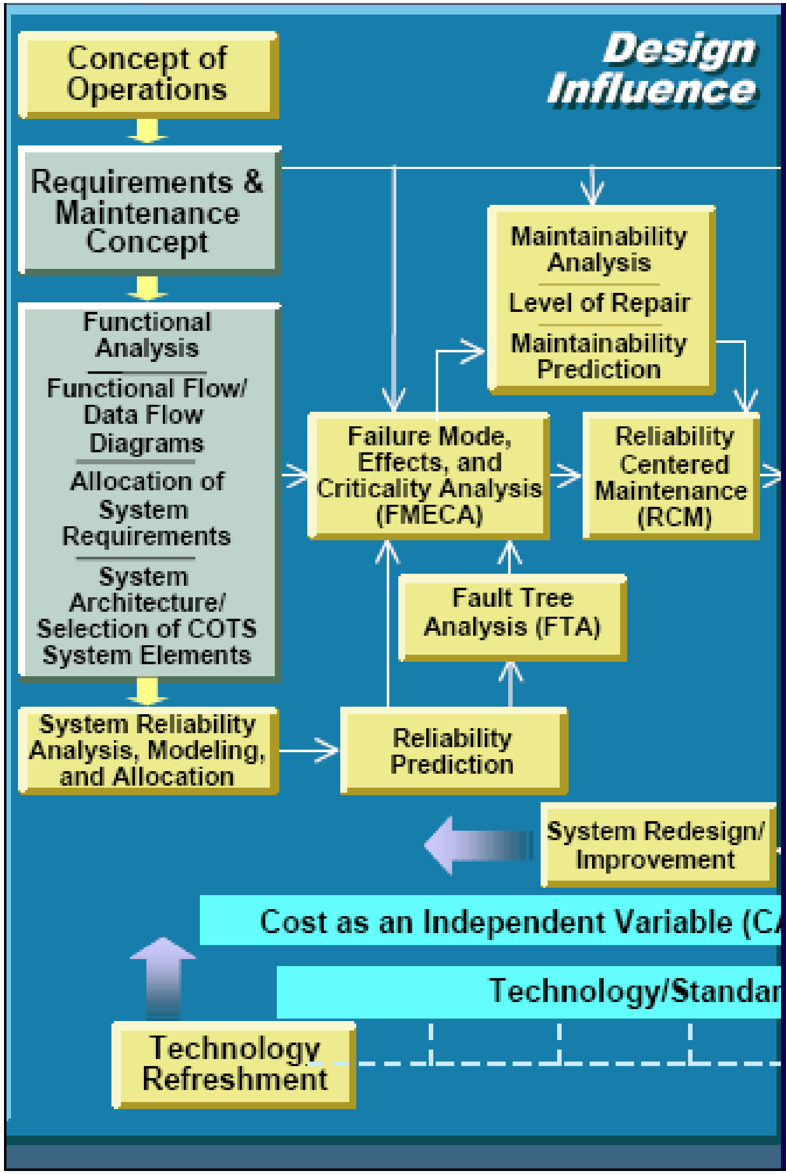
5. Design for maintenance should be a primary consideration in reducing the logistics footprint. Smaller parts may be possible for repairs, consistent with the ability to test the sufficiency of the repair and the tools and training provided to the crew. An optimization is preferable, taking into account tools, time, packaging, stowage, and life cycle cost.

6. Standards should be planned and applied to system development. Multiple standards applied to the same area increase the logistics footprint. A simple example of this is standard and metric tools. In most cases, where there are multiple standards, there is an interface required, and the interface then requires support. Corollary to this is the use of Commercial Off The Shelf (COTS) hardware. Unless it is delivered built to an existing standard, it automatically becomes a source of extra support requirements.

7. Return logistics should be taken into account in the design. The packaging requirements, pressurization, and reparability/disposability for the return or destructive reentry of items should be known and modeled. Trash growth and disposal should be modeled as part of the crew timeline.

Traditional R&M Roles and Responsibilities

RMS Engineering Process



Reliability Tasks:
- Concept of Operation Definition/Mission Profile/Design Reference Mission
- Reliability Requirements Analysis and Allocation
- Reliability Modeling and Analysis
- Reliability Prediction
- Failure Mode, Effects, and Criticality Analysis
- Fault Tree Analysis

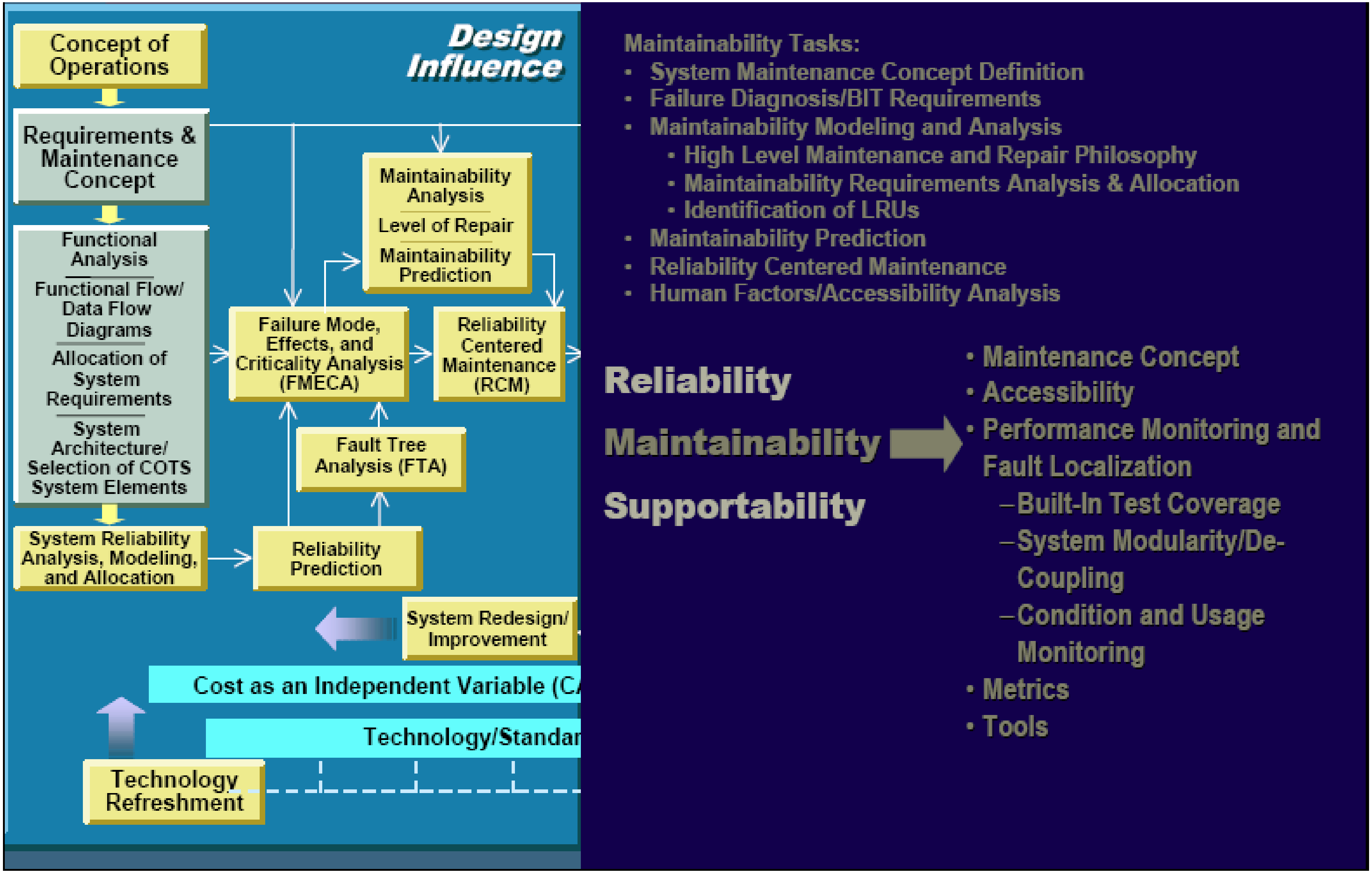
Reliability

Maintainability

Supportability

- Redundancy
- Reconfigurability
- De-Rating
- System Criticality Assessment
  - Single Points of Failure
  - Degraded Modes of Operation
- Metrics
- Tools

RMS Engineering Process



Design Influence

Concept of Operations

Requirements & Maintenance Concept

Functional Analysis

Functional Flow/ Data Flow Diagrams

Allocation of System Requirements

System Architecture/ Selection of COTS System Elements

System Reliability Analysis, Modeling, and Allocation

Reliability Prediction

Fault Tree Analysis (FTA)

Failure Mode, Effects, and Criticality Analysis (FMECA)

Maintainability Analysis

Level of Repair

Maintainability Prediction

Reliability Centered Maintenance (RCM)

System Redesign/ Improvement

Cost as an Independent Variable (C

Technology/Standar

Technology Refreshment

Maintainability Tasks:

- System Maintenance Concept Definition
- Failure Diagnosis/BIT Requirements
- Maintainability Modeling and Analysis
  - High Level Maintenance and Repair Philosophy
  - Maintainability Requirements Analysis & Allocation
  - Identification of LRUs
- Maintainability Prediction
- Reliability Centered Maintenance
- Human Factors/Accessibility Analysis

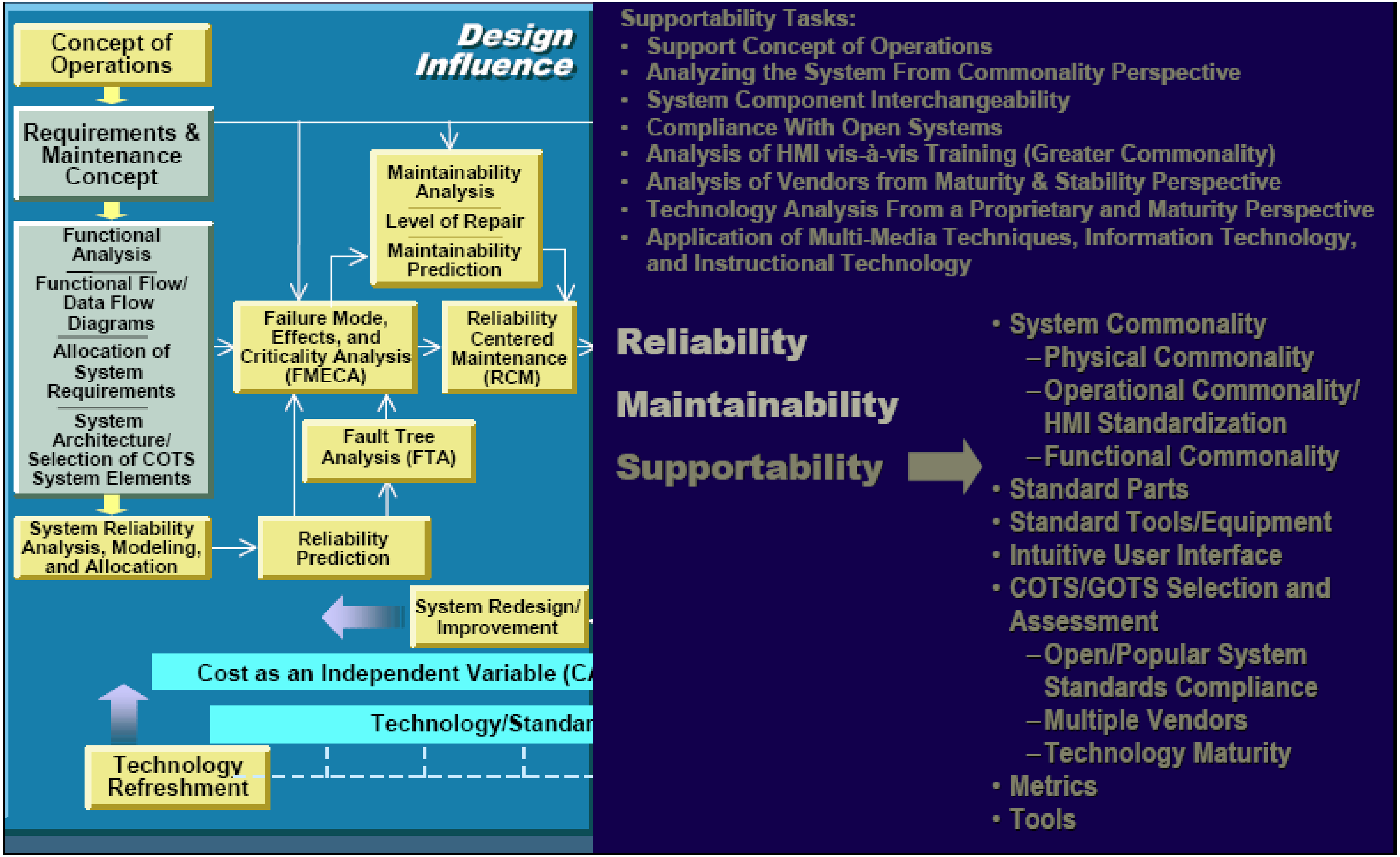
Reliability

Maintainability

Supportability

- Maintenance Concept
- Accessibility
- Performance Monitoring and Fault Localization
  - Built-In Test Coverage
  - System Modularity/De-Coupling
  - Condition and Usage Monitoring
- Metrics
- Tools

RMS Engineering Process



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Maintainability Prediction

Failure Mode, Effects, and Criticality Analysis (FMECA)

Reliability Centered Maintenance (RCM)

Fault Tree Analysis (FTA)

Reliability Prediction

System Redesign/ Improvement

Cost as an Independent Variable (C

Technology/Standar

Technology Refreshment

Supportability Tasks:
- Support Concept of Operations
- Analyzing the System From Commonality Perspective
- System Component Interchangeability
- Compliance With Open Systems
- Analysis of HMI vis-à-vis Training (Greater Commonality)
- Analysis of Vendors from Maturity & Stability Perspective
- Technology Analysis From a Proprietary and Maturity Perspective
- Application of Multi-Media Techniques, Information Technology, and Instructional Technology

Reliability

Maintainability

Supportability

- System Commonality
  - Physical Commonality
  - Operational Commonality/ HMI Standardization
  - Functional Commonality
- Standard Parts
- Standard Tools/Equipment
- Intuitive User Interface
- COTS/GOTS Selection and Assessment
  - Open/Popular System Standards Compliance
  - Multiple Vendors
  - Technology Maturity
- Metrics
- Tools