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A MODEL-BASED METHOD FOR MOSA-CONSTRAINED, VICTORY-INFORMED E/E ARCHITECTURE TRADE STUDIES

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ABSTRACT

Early electrical/electronic (E/E) architecture decisions in ground combat vehicles (GCVs) strongly influence lifecycle cost, upgradeability, survivability, cyber resilience, and integration risk across decades-long service lives. As Army programs transition from distributed E/E architectures toward zonal and software-defined vehicle concepts, the number of viable architectural options expands while the cost of late architectural change increases. This paper presents a detailed, model-based architecture evaluation methodology structured around Requirements–Functional–Logical–Physical (RFLP) principles, using Modular Open Systems Approach (MOSA) constraints as architectural requirements and VICTORY-aligned concepts as validation targets. The methodology emphasizes multi-variant architecture definition with large-scale reuse, early synthesis of wiring and network impacts, end-to-end traceability, change impact awareness, and continuity from architecture evaluation into detailed, multi-team design. The approach enables early, evidence-based comparison of architectural alternatives and preserves a traceable rationale to support modernization, sustainment, and future system evolution.

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1. INTRODUCTION

Objective

The objective of this paper is to define a repeatable, model-based methodology for evaluating alternative ground combat vehicle E/E architectures under Modular Open Systems Approach (MOSA) [1] constraints and VICTORY [2]-informed architectural validation targets, with emphasis on early trade-space exploration, quantitative comparison, and continuity from architecture evaluation into detailed design.

Ground combat vehicle architectures are experiencing a fundamental transition, driven by increased mission complexity, rapid growth in sensor and compute demands, expanded software functionality, and statutory requirements for openness and modularity. Historically, E/E architectures have evolved incrementally, resulting in highly distributed designs with large wiring mass, limited growth margin, and significant integration burden. At the same time, the cost of architectural change increases sharply as programs mature. Decisions made during early concept development can constrain integration flexibility and sustainment options for decades. These realities motivate the need for rigorous, quantitative, early-phase architecture evaluation methods that allow Army research organizations and acquisition stakeholders, including organizations such as DEVCOM Ground Vehicle Systems Center [3], to explore trade spaces, quantify architectural impacts, and reduce technical risk before committing to Programs of Record. The methodology emphasizes repeatability and transparency so results can be applied across programs and modernization increments.

2. ARCHITECTURE EVALUATION AS A FIRST-CLASS ENGINEERING ACTIVITY

In this methodology, architecture evaluation is treated as a first-class engineering activity rather than an informal precursor to detailed design. The objective is not to define a single “correct” architecture, but to systematically explore alternative architectural patterns and understand their implications. The methodology is structured around the Requirements–Functional–Logical–Physical (RFLP) [4] paradigm:

- Requirements (R): Architectural drivers derived from MOSA policy, survivability, cyber resilience, growth margin, and interoperability needs.
- Functional (F): Capability-oriented decomposition independent of hardware or vendor assumptions.
- Logical (L): Alternative realizations of functions and data flows, including distributed, zonal, and hybrid patterns.
- Physical (P): Realization in LRUs, zone controllers, networks, power distribution, and harnesses.

This separation allows architectural decisions to be evaluated objectively without premature commitment to physical implementation choices. [5] The approach is intended to be repeatable and adaptable, enabling consistent evaluation across vehicle variants, mission configurations, and modernization cycles, and even programs.

3. MULTI-VARIANT ARCHITECTURE DEFINITION WITH LARGE-SCALE REUSE

A core requirement of the evaluation approach is the ability to define and compare multiple architecture variants, ideally within a single authoritative model. Rather than duplicating models for each candidate architecture, common requirements, functional decompositions, logical services, and physical assets are reused across all variants. Variation is introduced in a controlled manner through explicit architectural decisions, such as:

- Number and placement of vehicle zones
- Allocation of I/O aggregation and compute resources
- Network topology and gateway strategy
- Redundancy and fault-containment approaches

4. EARLY SYNTHESIS OF WIRING LENGTH, WEIGHT, AND COST

Detailed harness CAD definition is not required to understand architectural wiring impacts. Using physical placement of LRUs and zone controllers, connectivity definitions, and zonal aggregation strategies, wiring length can be synthesized early in the evaluation process. From synthesized wiring length, additional metrics can be estimated, including copper mass and relative cost proxies based on conductor gauge and connector count. Because synthesis is performed per architecture variant, analysts can, for example, directly compare the wiring reduction benefits of zonal architectures against increases in redundancy, survivability provisions, or controller count. This is particularly important for ground vehicles, where wiring mass, routing complexity, and maintainability have significant lifecycle implications.

5. NETWORK UTILIZATION ESTIMATION WITHOUT MESSAGE-LEVEL DESIGN

Full, message-level network definitions are often impractical during early architecture evaluation. Requiring detailed protocol design too early can bias architectural decisions and increase modeling effort without gaining proportional insight. Instead, network loading can be estimated using logical communication paths, signal grouping, data size ranges, and update-rate classes (e.g., low, medium, high frequency). These abstractions enable estimation of bus-specific utilization trends for CAN, Ethernet, or other networks. The resulting utilization estimates support comparison of architectural options, identification of potential bottlenecks, and assessment of gateway loading, while deferring detailed message design until architectural decisions stabilize.

6. END-TO-END TRACEABILITY AND ARCHITECTURAL IMPACT ANALYSIS

Because the model explicitly relates LRUs to their I/O endpoints and allocated functions, and functions to data flows and service interactions, impact assessment can be performed quickly and consistently. Affected functions and services can be identified through rule-based queries rather than manual analysis, ensuring completeness while reducing dependence on expert interpretation.

This traceable structure also supports configuration governance and lifecycle management by preserving architectural relationships and enabling rapid reassessment when requirements, mission equipment, or cybersecurity constraints evolve.

7. MOSA CONSTRAINTS AND VICTORY VALIDATION TARGETS

MOSA is treated as a set of explicit architectural constraints governing modularity, interface openness, replaceability, and future competition. These constraints are captured as requirements and allocated across RFLP layers, ensuring they influence architectural structure rather than being addressed through procedural controls. VICTORY [2] concepts are used as validation targets for data-centric integration, shared infrastructure, and decoupling of data producers and consumers. Architectures are evaluated for degree of alignment with these concepts rather than binary compliance decisions, consistent with exploratory evaluation objectives.

8. CONTINUITY FROM ARCHITECTURE EVALUATION TO DETAILED DESIGN

Continuity is a key feature and benefit of this methodology. Once an architecture variant is selected, it is promoted to an authoritative baseline rather than discarded. The same model structure is then progressively enriched as design maturity increases. Enrichment activities may include introduction of message-level network definitions, refinement of power distribution and protection strategies, allocation of software components to compute resources, and detailed harness optimization. Architectural intent, trade study rationale, and traceability are preserved throughout this transition, allowing detailed designers access to the source of the decisions informing the baseline architecture they are working with.

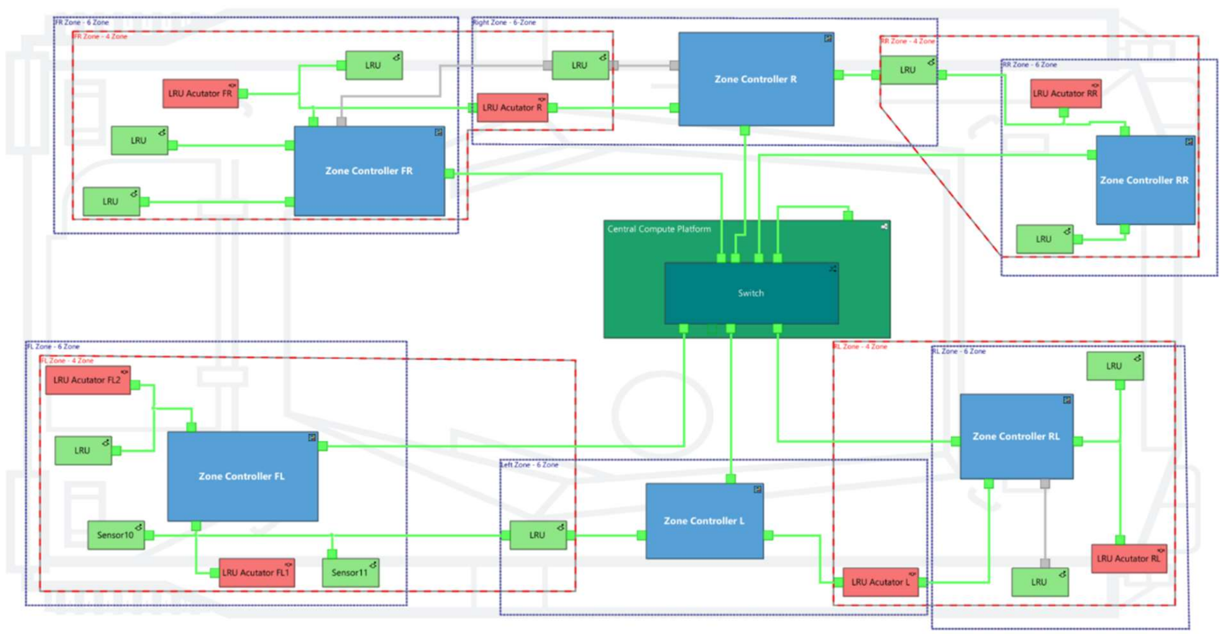

Figure 1. Superset 150% Model

9. CHANGE CONTROL, TICKETING, AND ATTRIBUTE-LEVEL TRACEABILITY

As architecture definition transitions into detailed design, the volume and granularity of change increase significantly. Effective evaluation environments must therefore support formal change control and task management. Changes are initiated through ticketed engineering tasks and captured at the level of specific model objects and attributes. For each change, traceability is maintained to the initiating task, affected artifacts, responsible user, and time and date of modification. This enables auditable architectural evolution and supports independent technical review.

10. EXAMPLE VIGNETTE: 4-ZONE VS 6-ZONE ARCHITECTURE TRADE STUDY

A notional trade study comparing 4-zone and 6-zone E/E architectures illustrates application of the evaluation methodology. Both variants share a common requirements baseline, functional decomposition, and logical service definitions. Differences are limited to zoning strategy, placement of aggregation controllers, distribution of compute resources, and associated network topology.

Using a single reusable model structure, analysts define both variants as controlled subsets of a common 150% architectural design space. Figure 1 shows the superset architecture containing all LRUs, candidate zone boundaries, network elements, and service allocations. Figures 2 and 3 show the derived 4-zone and 6-zone candidate architectures. Because both variants originate from the same model, observed differences result from architectural decisions rather than modeling inconsistencies.

Early evaluation may reveal several qualitative distinctions that guide where deeper analysis is required. These observations help identify which aspects of the architecture are most sensitive to zoning strategy, controller placement, and service allocation. Quantitative metrics are then used

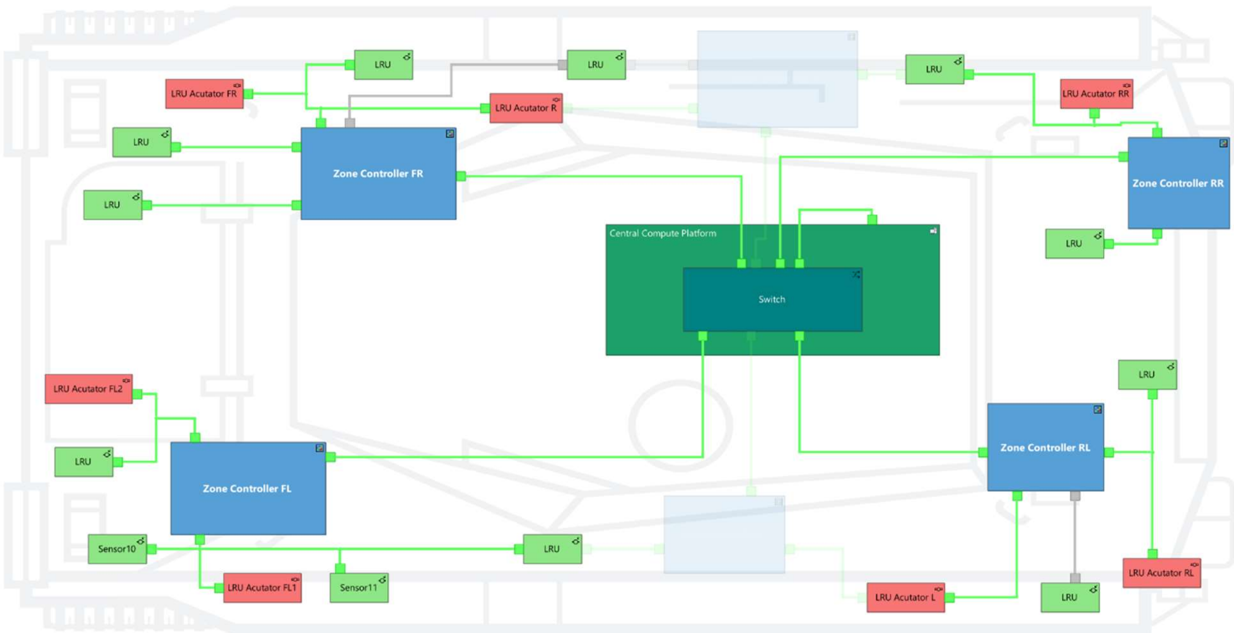

Figure 2. 4-Zone Architecture Variant (derived from Superset 150% Model)

to provide objective evidence for comparison.

10.1. Qualitative Distinctions

These qualitative observations guide evaluation focus areas; quantitative metrics provide objective evidence for comparison.

Wiring and Physical Integration

- The 6-zone architecture localizes I/O aggregation, reducing routing corridor congestion.
- The 4-zone architecture concentrates routing bundles, increasing bundle density and potential maintainability challenges.

Fault Containment and Survivability

- Smaller zones reduce failure blast radius and improve graceful degradation.
- Fault isolation boundaries align more closely with mission-critical subsystems.
- Larger zones increase the number of functions affected by localized damage or power faults.

Network and Compute Distribution

- Additional zone controllers introduce more aggregation points and gateway processing boundaries.
- Fewer zones reduce controller count but increase traffic concentration and dependency on backbone connectivity.

Growth Margin and Mission Kit Integration

- Smaller zones provide more insertion points for future sensors, actuators and mission equipment.
- Larger zones may require more extensive modifications to support equivalent mission equipment growth.

Lifecycle and Sustainment Considerations

- Localized wiring and modular boundaries can improve maintenance accessibility.
- Additional controllers increase spare part diversity but may reduce repair scope when failures occur.

10.2. Quantitative Evaluation Criteria

Quantitative criteria provide objective evidence to support architecture selection. These metrics can be synthesized early in the evaluation process without requiring full harness CAD definition or message-level network design. Values are derived from

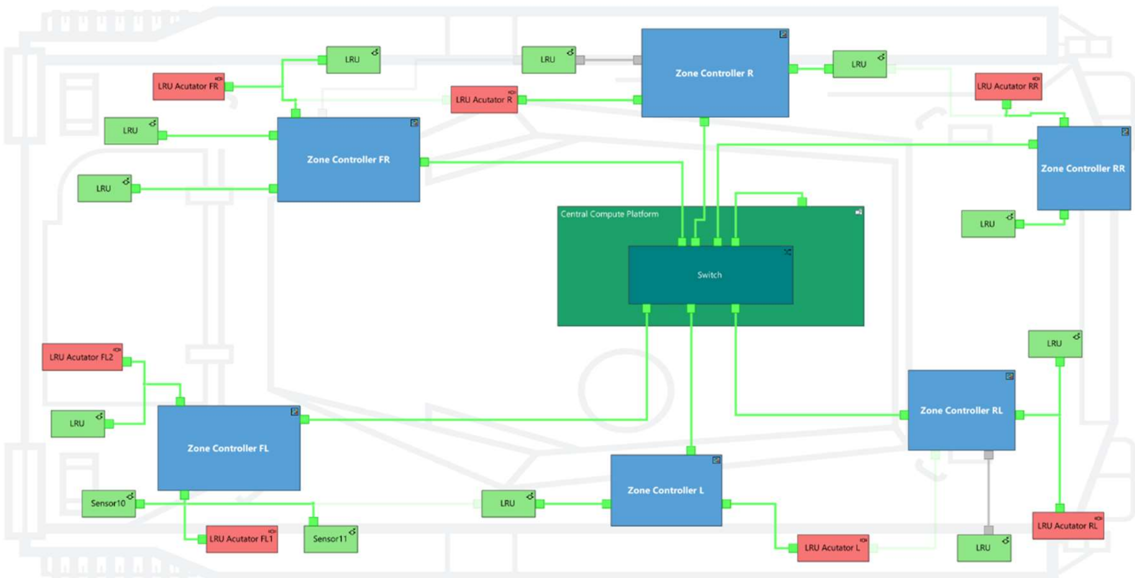

Figure 2. 6-Zone Architecture Variant (derived from Superset 150% Model)

documented assumptions regarding LRU placement, service interactions, zoning boundaries, and representative data-rate classes and network protocol overhead assumptions (e.g., framing, encapsulation, and scheduling factors).

Where precise values are not available, normalized indices and parametric sensitivity analysis provide comparative insight while preserving transparency of assumptions. Appendix A summarizes the approach used to derive the representative metrics shown below.

Representative evaluation criteria include:

Wiring and Interconnect Metrics

- Total harness length (estimated)
- Backbone harness length
- Intra-zone harness length by zone
- Connector count and distribution
- Harness mass and cost proxies derived from length and connector factors

Table 1. Wiring and Interconnect Metrics Comparison

Metric	4-Zone	6-Zone
Total harness length (index)	1.00	0.82
Backbone harness length (index)	0.75	1.10
Intra-zone wiring length (index)	1.00	0.68
Connector count	1.00	0.88
Harness mass proxy	1.00	0.80
Bundle density proxy	High	Moderate

Network Utilization and Topological Load

- Estimated average and peak utilization per subnet
- Backbone cross-zone traffic share
- Zone egress traffic distribution
- Headroom and oversubscription indicators
- Gateway traversal counts for critical flows

Table 2. Network Utilization & Traffic Distribution

Metric	4-Zone	6-Zone
Avg backbone utilization	42%	55%
Peak backbone utilization	68%	72%
Headroom	32%	28%
Cross-zone traffic share	46%	38%
Max critical gateway traversals	2	3

Metric	4-Zone	6-Zone
Zone egress traffic variance	High	Moderate

Architecture Complexity and Allocation
LRU / Zone Controller counts

- Distribution of compute and service allocation
- Cross-zone service dependency count
- Interface density and coupling indicators

Table 3. Architecture Complexity & Allocation

Metric	4-Zone	6-Zone
LRU count	1.00	1.00
Zone controller count	4	6
Central compute nodes	1	1
Cross-zone dependencies	High	Moderate
Interface density index	1.00	0.85
Compute distribution balance	Moderate	Improved

Change Impact and Modularity

- Traceable change impact radius (affected artifacts per architectural change)
- Service-to-node fan-in/fan-out indicators
- Degree of cross-zone dependency affecting upgrade scope
- Configuration change propagation paths supporting governance and auditability

Table 4. Change Impact & Modularity Indicators

Metric	4-Zone	6-Zone
Avg impacted functions per change	1.00	0.72
Cross-zone change propagation	Frequent	Reduced
Service-to-node fan-out	High	Moderate
Upgrade scope locality	Moderate	Improved
Governance trace path complexity	Higher	Lower

Reliability and Fault Containment Proxies

- Failure blast radius index for loss of a zone controller or backbone segment
- Percentage of critical functions contained within a single zone boundary
- Repair scope proxy reflecting modular replacement boundaries
- Number of functions affected by loss of a zone controller or power segment, derived through model traceability

Table 5. Reliability & Fault Containment Proxies

Metric	4-Zone	6-Zone
Functions affected by loss of one zone controller (index)	1.00	0.63
Critical functions contained within one zone	68%	84%
Failure blast radius index	High	Moderate
Repair scope (modules replaced)	Larger	Smaller
Fault isolation boundary alignment	Moderate	Improved

The results illustrate the trade space between wiring efficiency, survivability, backbone aggregation load, and architectural modularity. Increased zoning improves fault containment, wiring localization, and upgrade flexibility, while introducing additional aggregation points and modest increases in backbone utilization.

Because the model explicitly relates LRUs to their I/O endpoints and allocated functions, and functions to data flows and service interactions, impact assessment can be performed rapidly and consistently. Rather than relying on manual analysis, affected functions and services can be extracted directly from the model using rule-based queries, ensuring completeness while

reducing reliance on manual expert judgment.
This traceable structure also supports configuration governance and lifecycle management by providing a durable record of model relationships and enabling rapid reassessment when requirements, mission equipment, or cybersecurity constraints evolve.

11. CONCLUSIONS

Rigorous architecture evaluation is essential for managing the increasing complexity of ground combat vehicle E/E systems. By combining RFLP discipline, MOSA constraints, VICTORY-informed validation, and variant-aware modeling, the methodology described in this paper enables early exploration of architectural trade spaces supported by quantitative evidence.

The approach allows multiple candidate architectures to be evaluated within a single reusable model, supports synthesis of wiring, network, and modularity metrics before detailed design, and preserves traceability needed for change impact analysis, governance, and lifecycle continuity.

Treating architecture evaluation as a repeatable, model-based engineering activity reduces technical risk, provides defensible rationale for architectural decisions, and enables selected architectures to transition directly into detailed design without loss of intent. This aligns with the needs of Army research organizations and acquisition stakeholders responsible for long-lived, upgradable ground vehicle systems.

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14. ACRONYMS

Acronym	Definition
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CAD	Computer-Aided Design
DEVCOM	Combat Capabilities Development Command
E/E	Electrical / Electronic
EW	Electronic Warfare
GCV	Ground Combat Vehicle
GVSC	Ground Vehicle Systems Center
GVSETS	Ground Vehicle Systems Engineering and Technology Symposium
IEEE	Institute of Electrical and Electronics Engineers

Acronym	Definition
INCOSE	International Council on Systems Engineering
I/O	Input / Output
LRU	Line Replaceable Unit
MBSE	Model-Based Systems Engineering
MOSA	Modular Open Systems Approach
NDIA	National Defense Industrial Association
OMG	Object Management Group
PoR	Program of Record
RFLP	Requirements–Functional–Logical–Physical
SAE	SAE International
USG	United States Government
VICTORY	Vehicular Integration for C4ISR/EW Interoperability

15. Appendix

Derivation of Representative Evaluation Metrics

The comparative values presented in Tables 1–5 are derived from a representative vehicle layout and documented architectural assumptions. This appendix summarizes a methodology used to generate normalized metrics during early architecture evaluation. The intent is not to provide precise design values, but to illustrate repeatable techniques for comparative assessment prior to detailed design.

A.1 Assumed Vehicle Topology and Component Distribution

A notional ground vehicle layout is defined to support comparative evaluation. The model includes:

- representative LRU placement aligned with major vehicle regions
- typical sensor and actuator distributions for mobility, survivability, mission equipment, and crew systems
- candidate zone boundaries consistent with physical proximity and functional grouping
- representative interactions between subsystems

These assumptions provide a consistent basis for comparing architectural variants.

A.2 Wiring and Interconnect Metrics

Harness Length Estimation

Harness length is estimated using geometric distance approximations between connected components. For each connection:

```
Estimated Length = routing factor × straight-line distance
```

Where:

- `straight-line distance` is derived from component placement
- `routing factor` (typically 1.2–1.5) accounts for routing constraints and harness paths

Total harness length is computed as the sum of:

- endpoint-to-zone controller connections
- zone controller to backbone connections
- power distribution runs (if modeled)

Normalized indices are generated by comparing totals across architecture variants.

Connector Count

Connector count is derived from:

- LRU interface counts
- zone controller interface aggregation
- backbone segment terminations

Connector reduction often correlates with zonal aggregation strategies.

Harness Mass Proxy

Harness mass is estimated using:

```
Mass ∝ Σ (length × conductor weight factor)
```

Where `conductor weight factor` represents relative gauge classes (e.g., signal vs. power).

A.3 Network Utilization Estimation

Detailed message databases are not required for early evaluation. Instead, utilization is estimated using service interaction profiles.

Data-Rate Class Assignment

Service interactions are grouped into representative classes:

- Low-rate (status, control)
- Medium-rate (diagnostics, coordination)
- High-rate (video, sensor streams)

Each class is assigned a representative data rate range.

Protocol Overhead Considerations

Utilization estimates include network protocol overhead assumptions such as:

- framing and encapsulation overhead
- transport headers
- scheduling and time-sensitive networking factors

Link Utilization Estimation

For each network segment:

```
Segment Load = Σ (interaction data rate × overhead factor)
Utilization = Segment Load / Link Capacity
```

Cross-zone interactions are used to estimate backbone traffic share and aggregation load.

A.4 Architecture Complexity and Coupling Metrics

Cross-Zone Dependency Count

Dependencies are counted when services or data flows traverse zone boundaries. Higher counts indicate increased coupling and backbone reliance.

Interface Density

Interface density is approximated using:

```
Interface Density Index = total interfaces / compute nodes
```

This provides a comparative indicator of integration complexity.

A.5 Change Impact and Modularity Metrics

Change impact metrics are derived from model traceability relationships linking:

- requirements to functions
- functions to logical services and data flows
- services to physical nodes and I/O endpoints

Impact radius is estimated by identifying artifacts affected by changes to:

- zone boundaries
- service allocations
- node assignments

Because trace relationships are explicit, affected artifacts can be extracted through rule-based queries, enabling consistent and repeatable impact assessment.

A.6 Reliability and Fault Containment Proxies

Failure Blast Radius

Failure blast radius is estimated by identifying functions dependent on:

- a specific zone controller
- a backbone segment
- a power distribution element

This metric indicates the functional scope affected by localized failures.

Critical Function Containment

Critical functions are evaluated to determine whether they remain within a single zone boundary or require cross-zone dependencies. Higher containment improves survivability and graceful degradation.

A.7 Use of Normalized Indices

Where precise values are unavailable, normalized indices are used to compare architectures.

```
Normalized Value = Variant Metric / Baseline Metric
```

Normalized comparisons:

- preserve confidentiality
- emphasize relative architectural impacts
- support sensitivity analysis

A.8 Sensitivity Considerations

Evaluation results may vary based on:

- zone boundary placement
- controller location
- service allocation strategies
- network technology selection
- mission equipment integration

Sensitivity analysis helps identify architectural decisions with the greatest influence on system performance and survivability.