

# Validating Mission Engineering for Dual-Use UAV Conceptual Design

## The LODAV e-VTOL Case Study

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**Abstract** - Managing complex stakeholder requirements in dual-use system development presents significant challenges as civil and defense objectives frequently conflict. This paper validates the Mission Engineering framework as an effective methodology for requirements management during conceptual design of a dual-use UAV program. The LODAV project, a dual-use e-VTOL UAV designed for remote island logistics and maritime surveillance in Japan, serves as the case study. Four analytical methods were applied: Context Diagram for stakeholder interface mapping, Design Structure Matrix for subsystem dependency analysis, MOE/MOP hierarchy for mission effectiveness metrics, and Degree of Commonality Index for design shareability quantification. Results show the ME framework successfully facilitated multi-stakeholder requirement integration, achieving an overall system DCI of 0.72 and supporting economic viability of dual-use development. Although LODAV did not reach operational deployment due to budget constraints, ME application during conceptual design demonstrated tangible benefits. These findings confirm ME as a valuable methodology for managing complex stakeholder environments in dual-use conceptual design.

**Keywords:** Mission Engineering, Dual-Use UAV, Requirements Management, Design Structure Matrix, Degree of Commonality Index

## I. INTRODUCTION

### A. Background and Motivation

Japan is characterized by a unique geographic challenge: of its 6,852 islands, 416 are permanently inhabited, yet 303 remain unconnected by bridge or regular air service [1]. These remote communities face escalating logistics costs, aging populations, and fragile supply chains that are increasingly vulnerable to natural disasters. At the same time, Japan's maritime security environment demands enhanced persistent surveillance capabilities across an expansive exclusive economic zone. These converging needs present a compelling case for dual-use Unmanned Aerial Vehicle (UAV) systems capable of serving both civilian logistics and defense surveillance missions within a single platform architecture.

Dual-use technology development—wherein a single system platform supports both civil and military/defense applications—has gained increasing attention in recent decades as a means of reducing redundant development costs, maximizing technology transfer benefits, and leveraging government-funded research across broader application domains [2]. However, dual-use development introduces a fundamentally more complex stakeholder environment than single-domain programs. Civil stakeholders prioritize safety certification, cost efficiency, and public acceptance, whereas defense stakeholders emphasize operational security, robustness under adversarial conditions, and information assurance. Reconciling these divergent requirement sets without sacrificing system performance in either domain is a non-trivial challenge.

### B. Mission Engineering Overview

Mission Engineering (ME) is a systems engineering methodology formally defined by the U.S. Department of Defense (DoD) as "the deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system concepts and technologies to achieve desired operational mission effects" [3]. Unlike traditional systems engineering, which typically begins with system requirements decomposition, ME starts at the mission level—identifying mission objectives, operational scenarios, and stakeholder needs before descending to system-level specifications.

Central to the ME process are two key quantitative constructs: Measures of Effectiveness (MOEs), which capture mission-level success criteria from the stakeholder's perspective, and Measures of Performance (MOPs), which quantify system capabilities required to achieve those MOEs. This hierarchical structure—from mission objectives through MOEs to MOPs and

ultimately to Key Performance Parameters (KPPs) and Technical Performance Measures (TPMs)—provides a traceable chain linking stakeholder intent to engineering specifications [3, 4]. This structured traceability is especially valuable in dual-use contexts where the same system must satisfy divergent mission objectives.

### C. Research Gap and Objective

While ME has been applied extensively in U.S. DoD acquisition programs and increasingly in commercial aerospace contexts, there remains a notable gap in published literature examining ME application specifically to dual-use UAV systems in the conceptual design phase [5, 6]. Most existing dual-use development studies focus on post-design commonality analysis or technology transfer frameworks rather than front-end requirements management [7, 8]. Furthermore, most ME case studies in the literature involve programs that reached operational deployment, leaving the question of whether ME delivers measurable value during conceptual design alone largely unanswered, even when full-scale deployment is not achieved. This paper addresses this gap through the LODAV project case study, a dual-use e-VTOL UAV development program that conducted rigorous conceptual design using ME methodology and proceeded to initial prototype testing phase but was ultimately halted before operational deployment due to budget constraints. The specific research contributions of this paper are: first, a validated ME process adaptation framework for dual-use UAV conceptual design; second, quantitative evidence of ME's effectiveness in multi-stakeholder requirement integration through DCI analysis; third, an integrated methodology combining Context Diagram, DSM, MOE/MOP hierarchy, and DCI analysis; and fourth, lessons learned applicable to future dual-use system development programs.

## II. MISSION ENGINEERING FRAMEWORK FOR DUAL-USE SYSTEMS

### A. Adapted ME Process for Dual-Use Development

The standard ME process follows a top-down hierarchy from national strategies through mission scenarios to system specifications [3]. For dual-use application, this paper proposes an adapted five-phase process: first, Dual-Domain Stakeholder Identification, where civil and defense stakeholders are systematically mapped using a Context Diagram; second, Mission Scenario Definition, where concurrent civil and defense operational scenarios are developed with explicit interface identification; third, MOE/MOP Hierarchy Construction, where effectiveness and performance metrics are defined for both mission domains with traceability maintained; fourth, Architecture Trade-Space Analysis, where candidate design architectures are evaluated against dual-domain requirements using DSM analysis; and fifth, Commonality Quantification, where the DCI is computed to quantify design shareability and economic viability. The adaptation of established systems engineering methodologies to novel dual-use contexts requires structured creative problem-solving approaches, which informed the five-phase ME process proposed in this study [9].

### B. Analytical Methods

In this study, four analytical methods are integrated in the proposed ME framework:

**Context Diagram:** A system-level representation showing all external entities interacting with the system-of-interest, together with the data flows and control signals crossing the system boundary [10]. In the dual-use context, the Context Diagram explicitly distinguishes civil and defense stakeholder interfaces, revealing potential conflicts and complementarities.

**Design Structure Matrix (DSM):** A square matrix representation of system elements and their mutual dependencies, first introduced by Steward [11] and later extended by Browning [12]. In the LODAV application, the DSM reveals coupling patterns between subsystems, enabling identification of shared modules across civil and defense missions. Coupling strength is quantified on a 0–3 ordinal scale representing no, weak, medium, and strong dependency.

**MOE/MOP Hierarchy:** A hierarchical decomposition of mission requirements from operational objectives (MOEs) to system-level specifications (MOPs, KPPs, TPMs), consistent with the DoD Architecture Framework (DoDAF) and the DAU Mission Engineering Guide [3]. For dual-use systems, separate MOE branches are constructed for civil and defense missions and then analyzed for shared MOP opportunities.

**Degree of Commonality Index (DCI):** A quantitative metric introduced by Thevenot and Simpson [13] to measure component sharing across product families. The DCI formula is expressed as:

$$DCI = \frac{\sum(q_j \times u_j)}{\sum q_j}$$

where  $q_j$  is the total usage count of component  $j$  across all product variants, and  $u_j$  is the commonality ratio (number of variants using component  $j$  divided by total number of variants). DCI ranges from 0 (completely unique components) to 1 (fully shared components). A  $DCI \geq 0.70$  is commonly adopted as a threshold indicating economically viable dual-use design [13].

### III. CASE STUDY: LODAV SYSTEM DEVELOPMENT

#### A. Project Overview

The LODAV (Long-Range Autonomous Vehicle) project was a Japanese dual-use e-VTOL UAV development initiative targeting two primary mission domains: autonomous cargo delivery to remote inhabited islands of Japan, and maritime surveillance and intelligence, surveillance, and reconnaissance (ISR) operations. The program was led by a graduate research institution and conducted under a collaborative framework with aerospace industry partners, with support from the air defense sector in applying Mission Engineering methodology to the program's conceptual design activities. The program commenced conceptual design activities in 2021 and was ultimately halted before operational deployment due to budget constraints.

This case study builds upon the preliminary conceptual design work presented by Otani and Ohkami (2023) [5], who first introduced the dual-use e-VTOL concept and demonstrated the initial application of Mission Engineering methodology to the LODAV system architecture. The present study extends that foundational work by conducting a comprehensive validation analysis of the Mission Engineering approach, examining its effectiveness throughout the conceptual design phase, and evaluating the methodology's capability to manage the inherent complexity of dual-use requirements integration. While the original work focused on demonstrating the feasibility of applying Mission Engineering to dual-use UAV development, this research provides systematic validation of the methodology's performance against established systems engineering evaluation criteria. All LODAV system specifications, mission parameters, and design targets cited in this paper—including payload capacity, mission radius, and autonomy level—originate from that prior publication and are reproduced here solely to provide the necessary context for methodology validation.

The LODAV system concept envisions an electric vertical takeoff and landing (e-VTOL) platform with a distributed propulsion architecture, enabling vertical operations from unprepared sites on remote islands while achieving efficient fixed-wing-style cruise for extended-range missions. Key design targets included a payload capacity of 100 kg, a mission radius exceeding 500 km, and autonomous operations capability to Level 4 (full autonomy in defined operational domains). The platform was designed to be reconfigurable between civil cargo configuration and defense ISR configuration through modular payload bay design.

Despite completing a thorough conceptual design phase, including aerodynamic analysis, preliminary structural sizing, propulsion system selection, and mission simulation, the LODAV program was suspended in 2023 due to budget constraints. The program did not reach prototype fabrication or operational demonstration. However, the completeness of the conceptual design work—particularly the application of Mission Engineering methodology—provides substantial material for methodology validation.

#### B. Stakeholder Analysis and Context Diagram

The first ME analytical step applied to LODAV was a systematic stakeholder identification and context mapping exercise. Through structured interviews and document analysis, eleven primary stakeholder groups were identified across the civil and defense domains. Figure 1 presents the resulting Context Diagram, which maps all external entities interacting with the LODAV system and the nature of their information and operational interfaces.

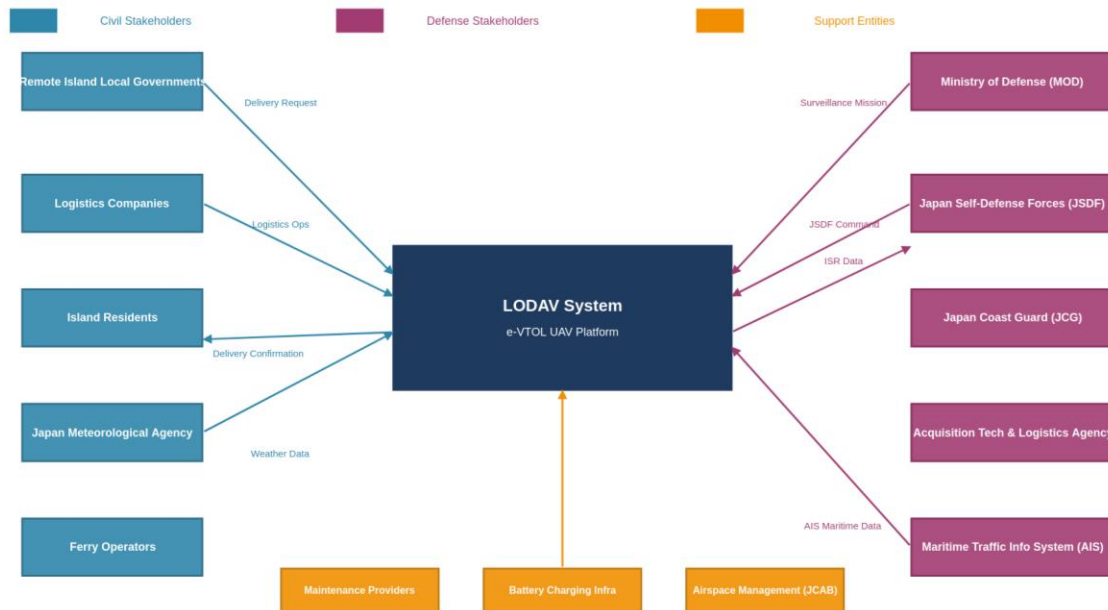


Figure 1: LODAV System Context Diagram showing Civil and Defense Stakeholder Interfaces

The Context Diagram reveals several critical interface characteristics. Civil stakeholders—including remote island local governments, logistics companies, island residents, Japan Meteorological Agency (JMA), and ferry operators—primarily interface with LODAV through delivery requests, logistics operational data, and weather information. Defense stakeholders—including the Ministry of Defense (MOD), Japan Self-Defense Forces (JSDF), Japan Coast Guard (JCG), and the Acquisition, Technology and Logistics Agency (ATLA)—interface through surveillance mission tasking, command signals, and maritime traffic information.

A key insight from the Context Diagram analysis was the identification of three categories of interfaces: civil-exclusive interfaces requiring no special security measures; defense-exclusive interfaces requiring encrypted communication and access control; and shared infrastructure interfaces—particularly airspace management (JCAB), battery charging infrastructure, and maintenance providers—that serve both mission domains. This tripartite classification directly informed the subsystem architecture decisions described in Section III.D.

Table 1 summarizes the key stakeholder requirements extracted from the Context Diagram analysis, highlighting the areas of alignment and conflict between civil and defense needs. Civil stakeholders require JCAB type certification and public safety compliance, necessitating formal safety analysis methodologies. Model-based safety analysis approaches provide structured frameworks for identifying hazards and verifying safety requirements during conceptual design, complementing the ME-based requirement integration methodology applied in this study. At the national level, the Japan Civil Aviation Bureau has established specific safety guidelines for unmanned aircraft operations, which define the certification requirements that the civil logistics configuration of LODAV must satisfy for Beyond Visual Line of Sight (BVLOS) operations over remote island routes. The civil safety certification requirement (JCAB type certification) implies a structured safety analysis process consistent with model-based safety analysis methodologies [14, 15].

Requirement Category	Civil Stakeholder Needs	Defense Stakeholder Needs	Alignment
Range / Endurance	≥500 km range, all-weather operation	≥500 km range, ≥6 hr loiter	✓ High
Payload	≥100 kg cargo, flexible bay	EO/IR sensors, modular ISR suite	Δ Medium
Autonomy	Level 4, BVLOS certified	Level 4, C2 override capability	Δ Medium
Communication	4G/LTE, Satellite, 10 Mbps	Crypto-secure SATCOM, ECCM	X Low
Safety / Cert.	JCAB type cert., public safety	MIL-SPEC reliability, EMI	Δ Medium
Cost Model	≤30% vs ferry per delivery	Life-cycle cost < ¥1B JPY	✓ High
Operability	Island base ops, minimal crew	Remote base, organic maintenance	✓ High

Table 1: Civil vs. Defense Stakeholder Requirements Comparison (✓ High Alignment, Δ Medium, X Low)

### C. DSM Analysis of LODAV Subsystems

Following the stakeholder analysis, a Design Structure Matrix was constructed to map the dependency relationships among ten identified LODAV subsystems. The subsystems were classified into civil-shared, defense-specific, and jointly-used categories based on the Context Diagram analysis. Figure 2 presents the resulting DSM, with coupling strength coded on a 0–3 ordinal scale.

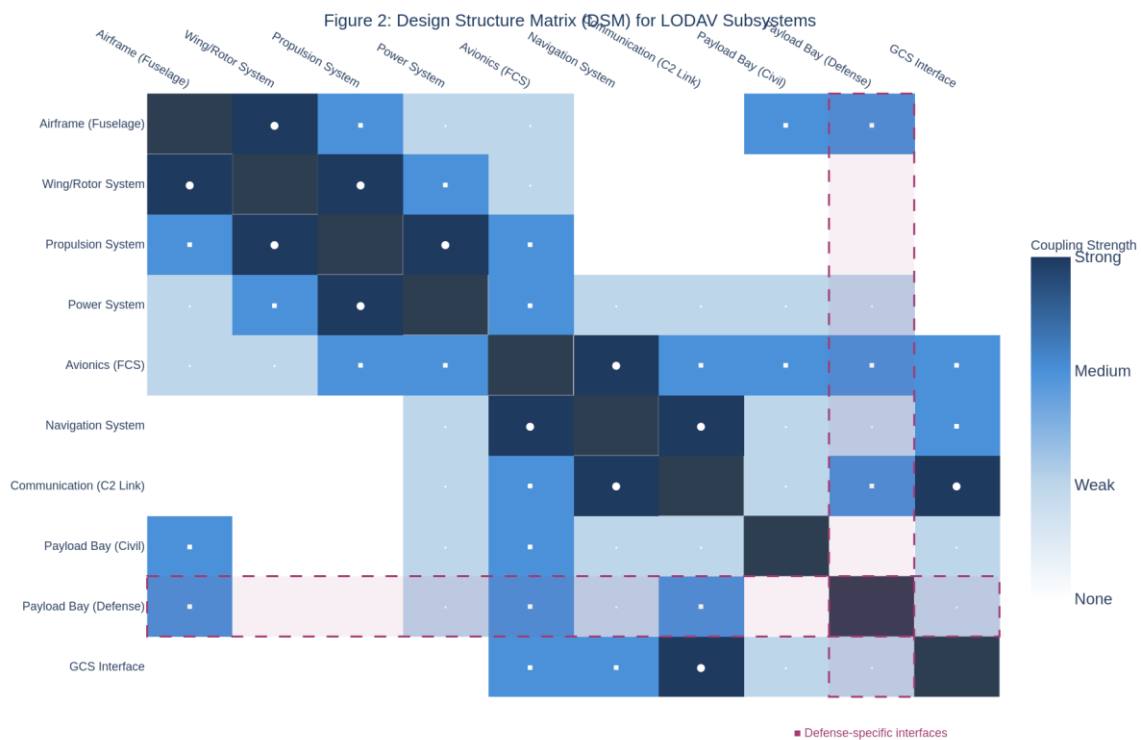


Figure 2: Design Structure Matrix (DSM) for LODAV Subsystems (● Strong, ■ Medium, · Weak Coupling)

The DSM analysis reveals three primary module clusters: the structural-propulsion cluster comprising the Airframe, Wing/Rotor System, and Propulsion System, which exhibit strong mutual coupling and are shared across both mission domains; the avionics-navigation-communication cluster, which forms a tightly coupled information processing core that is also substantially shared; and the mission-specific payload clusters, where the civil cargo bay and defense ISR payload bay show low coupling to each other but both couple to the shared avionics and power systems.

A particularly important finding from the DSM analysis was the identification of the Communication System as a critical interface subsystem. In the civil mission, the communication system interfaces with commercial cellular and satellite networks using unencrypted protocols. In the defense mission, it must transition to crypto-secure operation with electronic counter-countermeasures (ECCM) capability. This dual-requirement creates a design tension that was only made explicit through the DSM analysis—a key demonstration of the ME framework's value in surfacing hidden complexity during conceptual design.

### D. MOE/MOP Hierarchy Construction

Based on the stakeholder requirements extracted from the Context Diagram analysis, a comprehensive MOE/MOP hierarchy was developed for both civil and defense mission branches. Figure 3 presents the resulting hierarchy, which spans from top-level dual-use mission success criteria through MOEs and MOPs to KPPs and TPMs.

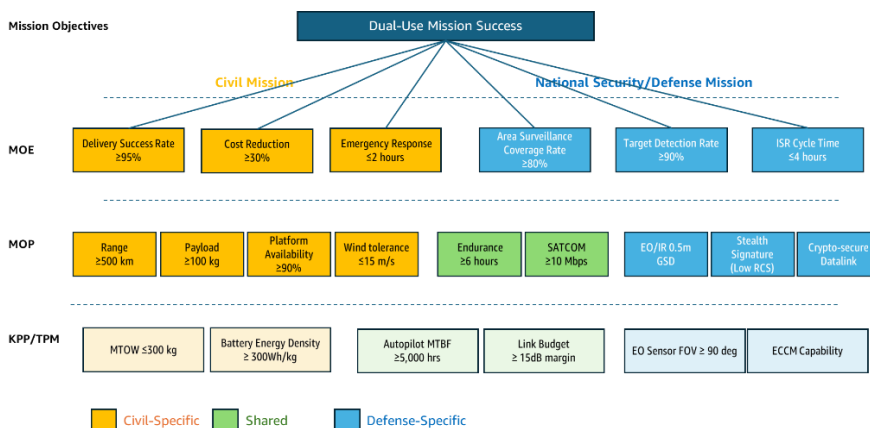


Figure 3: MOE/MOP Hierarchy for LODAV Dual-Use Missions

The civil mission branch defines three top-level MOEs: a delivery success rate of  $\geq 95\%$ , a cost reduction of  $\geq 30\%$  relative to conventional ferry services, and an emergency response capability of  $\leq 2$  hours. These MOEs cascade to MOPs including mission range ( $\geq 500$  km), payload capacity ( $\geq 100$  kg), platform availability ( $\geq 90\%$ ), and wind tolerance ( $\leq 15$  m/s).

The defense mission branch defines three top-level MOEs: area surveillance coverage rate ( $\geq 80\%$ ), target detection rate ( $\geq 90\%$ ), and ISR collection cycle time ( $\leq 4$  hours). These cascade to MOPs including endurance ( $\geq 6$  hours of loiter), satellite communication bandwidth ( $\geq 10$  Mbps), electro-optical/infrared sensor resolution (0.5 m ground sample distance), and electronic protection capability.

A critical insight from the MOE/MOP analysis was the identification of six shared MOPs applicable to both mission branches: range, endurance, autopilot reliability, power management, navigation accuracy, and structural survivability. These shared MOPs represent the ME-driven identification of the common design basis—the subset of system performance requirements that must be met by both mission configurations simultaneously. This directly informs the subsequent DCI analysis by defining the theoretical maximum commonality achievable.

Level	Metric	Civil Value	Defense Value	Shared?	Traceability
MOE	Mission success rate	$\geq 95\%$	$\geq 90\%$	✓ Yes	Delivery/ISR cycle completion
MOE	Cost effectiveness	$\leq 30\%$ vs ferry	$\leq 3B$ LCC	✓ Yes	Per-delivery unit cost
MOP	Mission radius	$\geq 500$ km	$\geq 500$ km	✓ Shared	Airframe + Propulsion
MOP	Payload mass	$\geq 100$ kg cargo	$\sim 80$ kg ISR suite	△ Partial	Payload Bay design
MOP	Endurance	$\geq 5$ hr	$\geq 6$ hr loiter	✓ Shared	Power + Airframe
MOP	Communication	LTE/SATCOM 10 Mbps	Crypto-SATCOM ECCM	✗ Unique	Comms subsystem
KPP	MTOW	$\leq 300$ kg	$\leq 300$ kg	✓ Shared	Structural sizing
KPP	Autopilot MTBF	$\geq 5,000$ hr	$\geq 5,000$ hr	✓ Shared	Avionics selection

Table 2: MOE/MOP Summary for LODAV Civil and Defense Missions

### E. DCI Analysis Results

DCI analysis compared the Bill of Materials (BOM) structure of LODAV-C (civil logistics) and LODAV-D (defense ISR) across nine functional subsystem categories using the Thevenot-Simpson formula [13]. Airframe Structure achieved the highest commonality (DCI = 0.95), with Propulsion (0.88) and Power System (0.92) similarly high. Avionics (0.82) reflects shared COTS autopilot platforms. Navigation System (0.75) and GCS Interface (0.70) sit at the high-commonality threshold, with defense configurations requiring INS hardening and security modules respectively. Communication System (0.63) falls in the medium range, consistent with DSM findings. Civil Payload Bay (0.40) and Defense Payload Bay (0.15) show low commonality by design; the modular bay architecture prevents this from propagating to the core platform. The overall system DCI of 0.72 exceeds the 0.70 economic viability threshold, confirming that the ME-guided conceptual design achieved viable dual-use commonality without prototype fabrication.

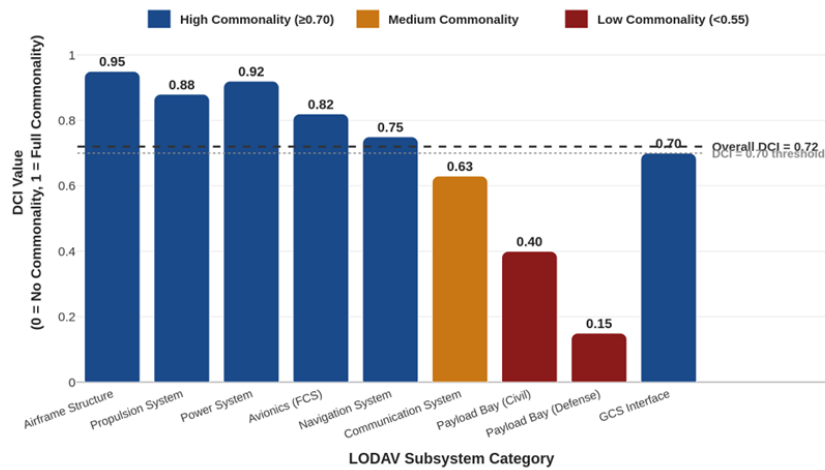


Figure 4: DCI Analysis Results by Subsystem Category for LODAV (Overall DCI = 0.72)

Subsystem Category	DCI	LODAV-C (Civil) Parts	LODAV-D (Defense) Parts	Shared Components	Key Difference
Airframe Structure	0.95	18	18	Fuselage, wings, landing gear	None (fully shared)
Power System	0.92	12	12	Battery pack, BMS, inverters	EMP hardening (D only)
Propulsion System	0.88	16	16	Motors, ESCs, propellers	Low-RCS blades (D only)
Avionics (FCS)	0.82	9	11	FCC, IMU, air data sensors	Hardened CPU (D only)
Navigation System	0.75	5	7	GPS/INS module, GNSS antenna	INS hardening, GPS anti-jam (D)
GCS Interface	0.70	7	9	MAVLink core, C2 software	Secure enclave (D only)
Communication System	0.63	6	8	SATCOM terminal, LTE modem	Crypto module, ECCM filter (D)
Payload Bay (Civil)	0.40	14	0	Bay structure, quick-release system	Cargo restraints (C only)
Payload Bay (Defense)	0.15	0	11	Bay structure interface only	EO/IR sensors, SAR (D only)
<b>OVERALL SYSTEM DCI</b>	<b>0.72</b>	<b>87</b>	<b>92</b>	<b>67 shared components</b>	<b>Meets DCI ≥ 0.70 target</b>

Table 3: LODAV DCI Analysis Results by Subsystem Category

## IV. DISCUSSION

### A. ME Effectiveness in Dual-Use Conceptual Design

The LODAV case study demonstrates four measurable benefits of Mission Engineering in dual-use conceptual design. First, stakeholder requirement transparency was achieved through the Context Diagram, which identified eleven stakeholder groups and three critical requirement conflicts including communication security versus commercial access, EMP hardening versus weight budget, and operational security versus airspace integration. These conflicts would have remained latent until later stages at higher resolution cost. Second, architectural decision support was provided by DSM analysis, which quantified low coupling between mission-specific payloads and the shared platform core. This objective evidence enabled confident investment in modular payload bay architecture as the primary civil-defense switching mechanism. Third, quantitative design validation was achieved through DCI analysis, which yielded an overall commonality index of 0.72. This exceeded the 0.70 economic viability threshold and provided evidence-based justification for dual-use investment during conceptual design before hardware fabrication. This represents a distinctive ME strength. Fourth, requirements traceability was established through the MOE/MOP hierarchy, which created clear traceability from mission objectives to technical specifications. Six shared MOPs were identified, providing architectural rationale for high platform core commonality and preventing ad hoc trade-off decisions.

### B. Dual-Use Development Challenges

Three characteristic challenges emerged that ME helped manage but did not fully resolve. First, organizational impedance exists because civil and defense program offices operate under fundamentally different acquisition processes, classification requirements, and decision timelines. ME-structured integration reduced but did not eliminate the iteration overhead inherent in dual-authority governance. Second, security-performance trade-offs were evident in the Communication System, which achieved only  $DCI = 0.63$ , the lowest among shared subsystems. This reflects fundamental incompatibility between open commercial protocols and encrypted anti-jam defense protocols. ME identified this tension clearly but could not eliminate it. Resolution required a software-defined radio architecture with selectable protocol stacks, adding complexity absent in single-domain designs. Third, funding authority ambiguity was demonstrated by program termination due to budget constraints. This reflects a systemic dual-use challenge of absent clear primary funding ownership. When neither civil nor defense budgets have sole program ownership, competing cost reduction claims threaten continuity. ME provides technical viability foundations but cannot resolve governance gaps.

### C. Validation Scope and Limitations

This validation is explicitly scoped to conceptual design. MOE/MOP values and DCI results reflect design intent established through ME processes, not operational measurement. The absence of prototype hardware and flight test data means performance predictions remain unvalidated against physical reality—an inherent limitation of programs terminated at conceptual design. Additionally, DCI analysis was conducted at subsystem level rather than component level, reflecting available design detail. Component-level analysis at preliminary design phase might reveal additional commonality opportunities not visible at current granularity. Future work extending ME application to subsequent design phases is recommended.

### D. Implications for Future Dual-Use Programs

Three actionable recommendations emerge from this study. First, apply the full ME analytical suite sequentially from program inception. The suite includes Context Diagram, DSM, MOE/MOP hierarchy, and DCI. Integrated application of these four tools produces comprehensive dual-use design space understanding. Second, establish explicit DCI targets in program requirements at start rather than computing retrospectively. Quantitative commonality targets guide architecture decisions throughout conceptual design. Third, ensure dual-use governance structures include explicit mechanisms for joint civil-defense decision authority. This addresses organizational impedances that ME methodology alone cannot resolve. The adaptation of established ME methodology to novel dual-use contexts itself represents an exercise in practical systems engineering innovation. Future programs should treat the ME framework not as a rigid prescription but as a creative problem-solving foundation, adapting its analytical tools to the specific stakeholder complexity and mission diversity of each dual-use development context.

## V. CONCLUSION

This paper validated the Mission Engineering framework as an effective methodology for managing complex, multi-stakeholder requirements during dual-use UAV conceptual design. Through the LODAV case study, four ME analytical methods—Context Diagram, Design Structure Matrix, MOE/MOP hierarchy, and Degree of Commonality Index—were applied and evaluated. Key findings demonstrate measurable ME value: Context Diagram analysis identified 11 stakeholder groups and three latent requirement conflicts that would have emerged as costly late-stage changes; DSM analysis identified modular payload bay architecture as the optimal civil-defense switching mechanism based on objective coupling data; MOE/MOP hierarchy identified six shared performance requirements providing the theoretical foundation for high platform commonality; and DCI analysis quantified overall system commonality of 0.72, exceeding the 0.70 economic viability threshold. Critically, although LODAV did not advance to operational deployment, the ME methodology delivered value during conceptual design alone—surfacing hidden complexity, supporting architectural decisions, quantifying design viability, and establishing traceable requirements. This validates ME as valuable not only as a full-lifecycle methodology but as a standalone conceptual design tool for dual-use systems. Future research directions include: extending ME analysis to preliminary design phase to validate DCI predictions against component-level data; applying the four-method framework to other dual-use domains such as maritime vessels and satellite systems; and developing companion governance frameworks for dual-use acquisition that complement the technical ME methodology validated here.

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