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Advancing Aerospace Defense Equipment Operational Management in the Intelligent Era: An Integrated Model of AI-Enabled Decision-Making, Data Fusion, Multi-Domain Coordination, and Operational Resilience

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ABSTRACT

Aerospace defense equipment systems are characterized by a large number of heterogeneous elements, geographically extensive deployment, deeply interconnected operational relationships, and intense adversarial confrontation. Under such conditions, effective operational management is essential for integrating distributed equipment elements, optimizing resource utilization, accelerating decision-making, and enhancing overall operational effectiveness. The evolution of operational management has progressed from weapon-centric and platform-centric approaches toward network-centric architectures, reflecting the increasing importance of information integration, distributed coordination, and system-level operational effectiveness.

This study examines the conceptual foundations, evolutionary characteristics, and development of operational management for aerospace defense equipment systems, with particular emphasis on the transition toward intelligent and highly interconnected operational architectures. Building upon established operational-management practices, the study develops an integrated conceptual framework incorporating AI-enabled decision-making, multi-source data fusion, multi-domain coordination, and operational resilience. Within this framework, artificial intelligence is considered an enabling mechanism for accelerating decision support and adaptive planning; data fusion supports the generation of accurate and timely operational situational awareness; multi-domain coordination facilitates the integration of geographically dispersed sensors, command-and-control nodes, and defensive assets; and operational resilience provides the capacity to sustain system-level effectiveness under disruption, uncertainty, and adversarial interference.

The analysis further examines representative developments in foreign operational-management systems, particularly the U.S. Command and Control, Battle Management and Communications (C2BMC) system, Advanced Battle Management System (ABMS), and Distributed Battle Management (DBM) program. The evolution of these systems demonstrates a broader transition from relatively independent equipment management toward distributed, network-enabled, intelligent, adaptive, and resilient operational management. Based on these developments, this study proposes an integrated development perspective emphasizing intelligent decision-making, real-time data fusion, dynamic multi-domain coordination, adaptive resource allocation, and resilient system architecture.

The proposed framework provides a conceptual basis for improving the operational-management effectiveness of aerospace defense equipment systems in increasingly complex, information-intensive, and contested environments.

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1.INTRODUCTION

The third technological revolution, represented by advances in information technology, has accelerated production automation, modern management, technological modernization, and the modernization of national defense technologies [1,2]. Among these developments, **management modernization** has stimulated the emergence and practical application of modern management theories and methodologies, whereas **defense-technology modernization** has substantially enhanced the capabilities of individual weapon and equipment systems[3]. More importantly, it has facilitated the systematic integration of geographically distributed equipment elements into complex operational architectures, thereby generating system-level capabilities that exceed the functional boundaries of individual platforms [4].

The transition from isolated equipment capabilities toward integrated operational systems has consequently produced a new form of warfare characterized by system-level confrontation, distributed operational resources, rapid information exchange, and increasingly complex coordination relationships [5]. In such environments, the effectiveness of a defense system is no longer determined solely by the performance of individual weapons or platforms [6]. Rather, it increasingly depends on the ability to integrate sensing, communication, command and control, decision-making, resource allocation, and engagement functions into a coherent operational architecture [7].

Operational management represents one of the critical mechanisms through which individual equipment elements can be aggregated into complex operational systems and system-level capabilities. [8]. Its importance has therefore increased with the development of information-intensive and network-centric warfare. Conventional command-and-control approaches may become insufficient when the operational environment involves large numbers of heterogeneous assets, geographically dispersed deployment, rapidly changing threats, and compressed decision cycles[9]. These conditions create a growing requirement for automated decision support, real-time data fusion, dynamic resource allocation, and adaptive coordination [10].

The development of artificial intelligence provides an additional technological dimension to this transformation. AI-enabled decision-making can potentially support rapid assessment of large volumes of heterogeneous information, identify patterns in complex operational environments, and assist in generating adaptive decision options [11,12]. However, AI alone cannot ensure effective operational management. Its effectiveness depends on the quality and timeliness of **multi-source data fusion**, the interoperability of distributed operational elements, the effectiveness of **multi-domain coordination**, and the ability of the overall architecture to maintain functional continuity under uncertainty and disruption [13,14].

Accordingly, this study conceptualizes aerospace defense operational management as an integrated system rather than merely an information-technology application. The proposed framework combines four complementary dimensions: **AI-enabled decision-making, data fusion, multi-domain coordination, and operational resilience**. These dimensions are considered mutually reinforcing components of operational-management effectiveness.

Against this background, the present study examines the conceptual foundations and characteristics of operational management, reviews its historical evolution, analyzes representative foreign operational-management systems, and develops perspectives for the future development of aerospace defense equipment operational management. Particular attention is given to the evolution from weapon-centric management to platform-centric and network-centric architectures and, subsequently, toward intelligent and adaptive operational-management models.

2. Overview of Operational Management

2.1 Conceptual Foundations of Operational Management

The term **"battle management"** originated in U.S. military terminology and is commonly translated as operational or battlefield management [15]. The U.S. military defines battle management as management activities conducted under operational conditions on the basis of command, guidance, and direction provided by an appropriate authority [16]. From the perspective of modern management theory, management can be understood as a process comprising planning, organization, direction, coordination, and control [17].

In the context of missile-defense operations, the U.S. Missile Defense Agency has described battle management in terms of strategies expected to produce the most favorable outcomes and the set of tasks required to successfully implement the selected strategy. This definition highlights two fundamental dimensions of operational management: **decision selection** and **coordinated execution** [18, 19].

There is currently no single universally accepted definition of operational management within the domestic literature. *Military Management Science* defines operational management as the process of planning, organizing, leading, coordinating, and controlling operational forces, actions, and the battlefield in order to ensure the effective execution of operations and the efficient allocation and utilization of operational resources [20]. The *Chinese Military Encyclopedia* similarly describes operational management as the planning, organization, command, coordination, and control of military operational activities in accordance with relevant military regulations, with the objective of effectively allocating and utilizing operational resources and improving military operational capabilities [21].

These definitions indicate that operational management is fundamentally concerned with the transformation of dispersed operational resources into coordinated system-level capabilities. In this sense, it extends beyond conventional command-and-control functions and incorporates information processing, resource optimization, operational planning, coordination, and real-time adaptation.

Modern management integrates management science, behavioral science, and computing technologies, with particular emphasis on strategic management, decision-making, and comprehensive and systematic management [22]. Similarly, operational management emphasizes the integration of command-and-control science with advanced computing and information technologies. Its fundamental objective is to enhance the scientific and systematic nature of command and control through automated methods based on operational models [23].

The emergence of AI-enabled decision-making further expands this concept. Whereas traditional automated operational management primarily relies on predefined models, rules, and operational plans, intelligent operational management can incorporate adaptive analytical capabilities [24]. AI-based methods can support the interpretation of heterogeneous information, identify relationships among operational variables, and provide decision-support options within highly dynamic environments. Nevertheless, such capabilities should be regarded as an extension of operational-management mechanisms rather than a replacement for command authority and operational doctrine [25].

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Therefore, operational management should not be understood simply as the direct application of information technology. It depends fundamentally on the integration of **scientific modeling, operational knowledge, information processing, decision-making mechanisms, and organizational coordination**. The effectiveness of such a system is consequently determined not only by technological sophistication but also by the quality of data, interoperability among operational elements, coordination mechanisms, and system resilience.

2.2 Evolution of Operational Management

Operational management is a product of the integration of command-and-control science and information technologies. Its developmental stages have been closely associated with contemporary operational concepts and technological capabilities. With the continuous development of communication and computing technologies, and with the evolution of operational concepts and methods, operational management has progressed through several major stages, including **weapon-centric, platform-centric, and network-centric operational management** [26].

2.2.1 Weapon-Centric Stage

Operational management first emerged during the **1960s**, [27]. when the U.S. Air Force developed systems intended to support ground commanders in providing long-range target indications and voice guidance to airborne combat aircraft on the basis of information obtained through interconnected early-warning radars [28].

The primary objective was to assist pilots in detecting threats before adversaries and achieving accurate engagement. At this stage, system functionality was relatively limited and focused primarily on providing external guidance information to individual weapons or aircraft. The degree of integration between information and firepower was relatively low, resulting in a predominantly **weapon-centric architecture** [29].

From the perspective of the proposed integrated framework, this stage can be characterized by limited data fusion, relatively low coordination complexity, and weak system-level resilience. Operational effectiveness depended heavily on the performance of individual weapons and the quality of externally provided information.

2.2.2 Platform-Centric Stage

To meet the requirements of shipborne air-defense systems for simultaneously countering large numbers of aircraft, anti-ship missiles, and other multidirectional threats, the U.S. Navy developed the **Aegis combat management system** in the late 1960s [30].

The system integrated shipborne phased-array radar, missiles and launch systems, electronic warfare equipment, and other operational assets into a comprehensive platform-level architecture. It enabled the detection, tracking, identification, and engagement of hundreds of targets within extremely short time periods, thereby supporting integrated naval air-defense and missile-defense operations [31].

In contrast to the weapon-centric stage, the platform-centric architecture focused on a relatively confined physical platform such as a warship and enabled comprehensive management of operational elements and equipment resources within that platform. The integration between information and firepower became substantially stronger. [32].

This stage also established an important foundation for subsequent intelligent operational management. By integrating sensing, processing, decision support, and engagement resources within a common architecture, the platform-centric approach created the conditions for more advanced **data fusion and automated decision support** [32].

2.2.3 Network-Centric Stage

Beginning in the **1990s**, operational management became increasingly important within U.S. missile-defense systems. The United States subsequently developed systems such as the Ground-Based Midcourse Defense Command, Control, and Communications system (**GBMC3**) and the Command and Control, Battle Management, and Communications system (**C2BMC**) [33].

These systems enabled the integration of land-based, sea-based, and space-based operational elements distributed across geographically extensive areas. They supported operational planning and interception strategies while enabling the allocation of sensor resources, weapon resources, and command-and-control resources within compressed decision cycles [34].

The network-centric stage represented a major increase in the degree of system integration. Sensors and weapon systems distributed across large geographical areas could be connected through communication networks and coordinated as an integrated operational system. The resulting architecture demonstrated a high degree of information-firepower integration and represented a transition from platform-level optimization toward **system-of-systems operational management**) [35].

This transformation also corresponds directly to the variables introduced in the present study. Network-centric operational management increases the importance of **data fusion** because information originates from heterogeneous and geographically distributed sensors. It increases the importance of **multi-domain coordination** because operational elements may belong to different platforms and operational domains. Finally, the growing dependence on interconnected networks creates a corresponding requirement for **operational resilience** against communication disruption, information uncertainty, and adversarial interference.

2.3 Characteristics of Aerospace Defense Operational Management

The development history described above indicates that aerospace defense represents one of the most important application environments for operational management. Aerospace defense operations are highly time-sensitive defensive confrontations conducted after adversarial actions have been initiated. Compared with offensive missions, which may provide greater opportunities for deliberate command planning and operational maneuver, aerospace defense operations are characterized by severe temporal compression, rapidly changing threat conditions, and stringent requirements for real-time situational awareness, adaptive planning, and precision engagement[36].

From the perspective of a **“operational research–system design–model application–system integration”** forward-design process, aerospace defense operational management can be distinguished from conventional command-and-information systems by the following characteristics [37].

2.3.1 Unified Resource Allocation

Aerospace defense operations may involve aerodynamic targets, ballistic missiles, near-space weapons, and other heterogeneous threats. Threat directions may be uncertain, while target types and ranges may vary substantially. At the same time, aerospace defense requires high levels of

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information accuracy and timeliness, whereas electronic interference, deception, decoys, and other adversarial measures can consume substantial operational resources [38].

Consequently, multiple equipment types must be coordinated through integrated allocation of information, firepower, communications, and command-and-control resources. The objective is to satisfy the requirements of highly time-sensitive and strongly contested aerospace defense operations.

Within the proposed framework, **AI-enabled resource allocation** can serve as an advanced mechanism for supporting this process. Rather than relying exclusively on static allocation rules, intelligent decision-support mechanisms can evaluate changing operational conditions and assist in identifying feasible allocation options. The effectiveness of such mechanisms remains dependent on reliable data fusion and the interoperability of the underlying operational network.

2.3.2 Precision Situational Awareness and Multi-Source Data Fusion

Current and future aerospace threats may employ combinations of low observability, electromagnetic interference, accompanying decoys, and concentrated attacks. Consequently, aerospace defense operations may encounter high-speed, dense, intermittent, and highly disordered target environments [39].

Effective engagement requires the reconstruction and processing of dense air-and-space situational information under severe interference and within **sub-second cycles**. Comprehensive identification mechanisms combining decision-level and feature-level information processing can be used to distinguish decoys from genuine threats and confirm threat targets, thereby generating an engagement-level operational picture that satisfies identification and interception requirements[40].

This characteristic highlights the central role of **multi-source data fusion** in intelligent operational management. Data fusion should not be limited to combining sensor observations; it should support the transformation of heterogeneous observations into coherent operational situational awareness. In the proposed framework, the quality of the fused operational picture directly influences the reliability of AI-enabled decision-making and, consequently, operational-management effectiveness.

2.3.3 Predominantly Automated Engagement Management

Aerospace defense operations are characterized by severe spatial and temporal compression and extremely high time sensitivity. System response requirements are typically measured at the **second level**, making it difficult for purely human-centered command processes to respond effectively to rapidly evolving situations [41].

Operational-management systems can therefore integrate scientific models, predefined operational plans, engagement rules, and experiential knowledge to generate and update engagement sequences and operational rules in real time. Such systems can assist commanders in executing operational tasks in an appropriate sequence while supporting automated analysis, real-time decision-making, and intelligent resource scheduling [42].

The integration of AI-enabled decision-making provides an additional capability by allowing decision-support processes to respond to changing conditions rather than relying solely on fixed plans. However, the appropriate role of AI should remain embedded within a controlled human-command framework, particularly where operational decisions involve uncertainty, incomplete information, or rapidly changing threat conditions [43].

2.3.4 Support for Networked Advanced Operational Methods

Operational practice indicates that network-centric operations provide an important means of responding to complex operational environments and extending the capability boundaries of systems and operational architectures. They can therefore be regarded as an advanced application form of operational-management systems[44].

To maximize the effectiveness of networked operations, operational-management systems should be designed together with the equipment under their control. Such architectures can support the dynamic combination of sensors, command-and-control nodes, and engagement assets, as well as dynamic closure of precision operational chains[45].

This approach enables command relationships to be adjusted according to operational requirements and permits system functions to be dynamically reorganized. The result is greater continuity in command coordination and operational management.

From the perspective of the present study, this characteristic constitutes the technological basis of **multi-domain coordination**. Dynamic coordination among distributed operational elements can enhance adaptability, reduce dependence on individual platforms, and improve system-level effectiveness.

2.3.5 Deep Interconnection of Operational Equipment

Aerospace defense operations impose stringent requirements on interception effectiveness. Because the number of interception opportunities and interception probabilities available to a single weapon system are limited, appropriate interception planning may require multiple interception opportunities across different phases of target flight [46].

Based on unified operational-effect objectives, incoming aerospace targets can be continuously tracked and detected while layered engagement resources are coordinated throughout the operational process. Such operations require close integration among successive operational stages [47].

Accordingly, aerospace defense systems require deep interconnection and relatively flat control across geographically and functionally distributed operational equipment. Such integration is essential for maintaining effective operation of the overall aerospace defense architecture[48].

In the proposed framework, this characteristic is closely related to **operational resilience**. A deeply interconnected architecture can provide alternative coordination pathways and distribute operational functions across multiple elements. However, increased interconnection also introduces additional dependencies and potential vulnerabilities. Therefore, resilience must be incorporated into the architecture from the design stage rather than treated solely as a post-deployment cybersecurity or recovery function.

3. Foreign Operational Management Systems

3.1 U.S. C2BMC System

In **2002**, the United States initiated the development of a missile-defense command-and-control architecture to accelerate the formation of integrated missile-defense capabilities. The **Command**

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and Control, Battle Management, and Communications (C2BMC) system was introduced as a new component of the U.S. missile-defense architecture[49,50].

The fundamental purpose of C2BMC was to integrate geographically distributed missile-defense equipment and transform individual capabilities into an integrated system-level missile-defense capability. The system has therefore been regarded as a capability multiplier for missile defense and as an important mechanism for supporting an integrated and layered missile-defense architecture [51].

C2BMC consists of baseline hardware and associated software and provides a series of customized capabilities for planning, monitoring, and operational decision support. It can be deployed in two different suite configurations: the **Combatant Command Command-and-Control (COCOM C2)** suite and the **Global Engagement Manager (GEM)** suite. [52].

The COCOM C2 suite emphasizes operational planning and situational awareness. It supports detailed planning during peacetime as well as dynamic planning before engagement and provides commanders with a unified operational picture. The GEM suite focuses more heavily on wartime operational management and can control multiple forward-deployed **THAAD** radars while providing advanced target-tracking, discrimination, and operational-management capabilities. [53].

The operational-management functions of C2BMC integrate the capabilities of the missile-defense architecture through engagement rules, operational planning, and operational-resource scheduling. The system can fuse detection information from multiple sensors to generate a common missile-defense operational picture, distribute high-precision ballistic-missile tracking data, develop interception plans, manage sensor resources, and monitor the engagement processes of missile-defense weapon systems [54].

The system also provides automated operational-management tools capable of supporting threat-level assessment, evaluation of weapon interception capabilities, and calculation of weapon-system engagement suitability. Depending on operational requirements, different operational elements may function relatively independently or operate in a highly coordinated manner [55].

To facilitate efficient coordination among different operational elements, the system provides three operational-management coordination modes [56]:

1. **Passive coordination mode**, in which coordination is based on previously planned engagement rules and firing strategies. Its principal advantage is that it minimizes the amount of information exchange required among different weapon systems.

2. **Point-to-point coordination mode**, in which different weapons actively coordinate through real-time information exchange.

3. **Centralized coordination mode**, in which cross-weapon coordination is conducted under the unified coordination of a higher-level commander.

These three modes illustrate an important evolution toward adaptive coordination. Passive coordination provides predictability and low communication requirements, whereas point-to-point and centralized coordination provide greater opportunities for real-time adaptation. From the perspective of the proposed framework, these modes can be interpreted as different mechanisms for implementing **multi-domain coordination and adaptive decision-making** under different information and command conditions.

At present, C2BMC has been deployed at more than **70 workstation sites** across strategic commands, theater commands, and missile-defense operational forces. Following the spiral development principle of **"design a little, develop a little, deploy a little, and learn more,"** the system has undergone multiple upgrades and capability expansions [57].

During the early development of C2BMC, substantial portions of weapon fire-control system software were reused to ensure interoperability with weapon systems, allowing the architecture to be constructed rapidly [58]. Over the subsequent **nearly 10 years**, the system completed the development and deployment of the **S6.4** version. This version initially established global situational-awareness capabilities and command-and-control functions for the Ground-Based Midcourse Defense system, **Standard Missile-3 (SM-3)** interceptors, and forward-deployed **AN/TPY-2** radars. It also supported simultaneous homeland and regional ballistic-missile-defense operations [59].

Fig() **Standard Missile-3 (SM-3)** [60].

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Fig () **Army/Navy Transportable Radar Surveillance (AN/TPY-2)** [61].

The system subsequently completed the development and deployment of **S8.2**, further improving global situational awareness and global engagement capabilities. It also introduced sensor management and control for long-range discrimination radars, expanded the Aegis BMD system's long-range engagement capabilities based on forward-radar information, and comprehensively enhanced support for interception engagements [62].

According to the U.S. missile-defense architecture development planning released in **October 2022**, the next stage of C2BMC development emphasizes integrated, full-process defense operational-management capabilities for ballistic missiles, near-space hypersonic weapons, cruise missiles, and other threats within the framework of **Joint All-Domain Command and Control (JADC2)**. [63].

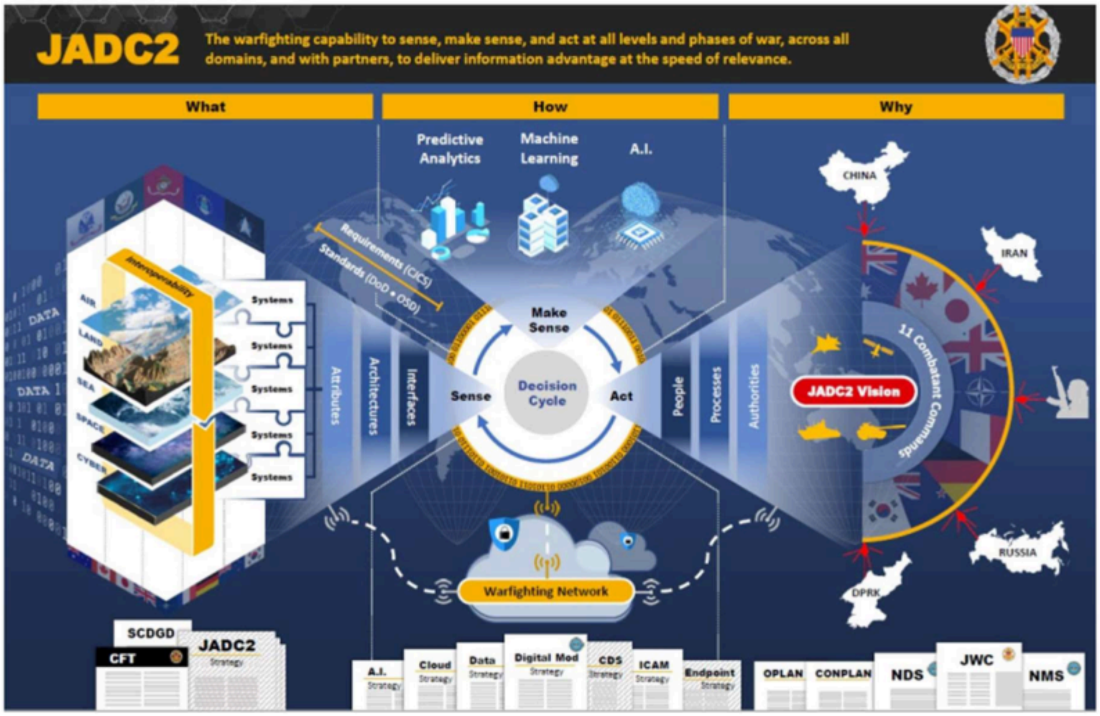

Figure ( ) JADC2 Placemat [64].

Within the JADC2 framework, the development direction emphasizes improvements in operational-management systems, the construction of high-capacity and low-latency global missile-defense command-and-control networks, and simultaneous enhancement of network-security capabilities [65].

This development trajectory suggests that complex system-of-systems architectures tend to follow a pattern of **capability development followed by broader system integration**. It also demonstrates a transition from network-centric operational management toward more intelligent, adaptive, and resilient architectures in which information integration, multi-domain coordination, decision support, and network resilience become increasingly interconnected.

3.2 U.S. Advanced Battle Management System (ABMS)

The **Advanced Battle Management System (ABMS)** represents a next-generation distributed operational-management and command-and-control architecture developed by the United States for future warfare. Its intended purpose is to provide multi-domain operational management and command-and-control capabilities under contested and denied environments [66].

In **2016**, the U.S. Air Force first introduced the concept of an advanced battle management system for highly contested operational environments in its *Air Superiority 2030 Flight Plan*. In **2017**, the U.S. Air Force initiated formal ABMS planning, initially positioning the system as a means of replacing and modernizing the capabilities of the **Airborne Warning and Control System (AWACS)**. [66].

In **2018**, in response to the revised defense strategy and its increased emphasis on major-power competition, the U.S. Department of Defense and Air Force reassessed the requirements for the

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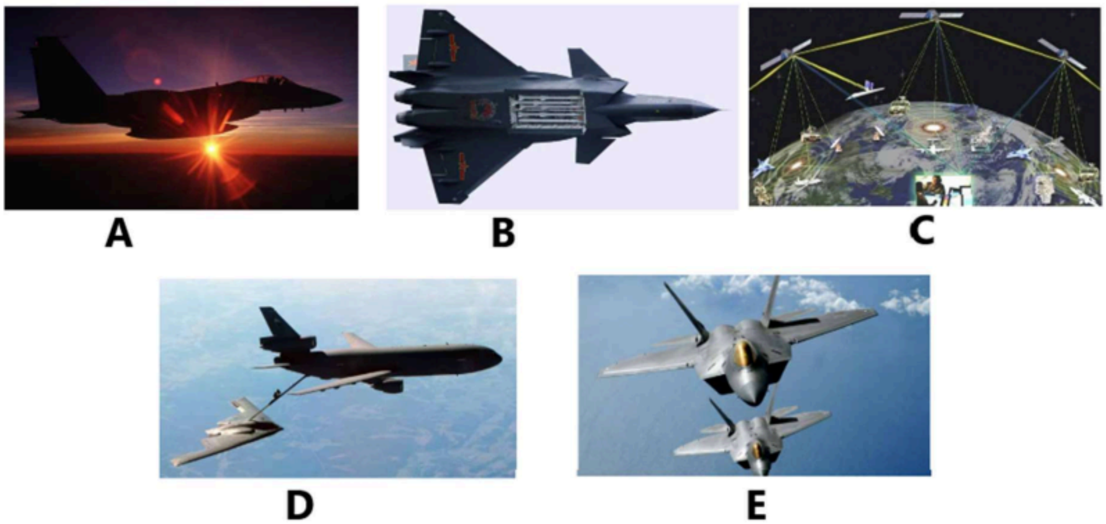
advanced battle management concept. The system was subsequently envisioned not merely as a replacement for E-3 and E-8C aircraft but as a broader **family of multi-domain command-and-control systems**. [67].



[68].Source: Air Superiority 2030 Flight Plan Enterprise Capability Collaboration Team , May 2016, https://www.af.mil/portals/1/documents/airpower/air%20superiority%202030%20flight%20plan.pdf

The ABMS concept was subsequently defined as the U.S. Air Force's solution for developing **multi-domain command-and-control capabilities in highly contested environments**, and in **2019** it was incorporated into the broader concept of **Joint All-Domain Command and Control (JADC2)**. [69].

The ABMS architecture is intended to establish an ecosystem composed of distributed sensors, data-fusion capabilities, and data-transport networks. Supported by cloud-based computing and artificial intelligence, this ecosystem is designed to provide commanders with enhanced decision support while reducing the duration of the **observe–orient–decide–act (OODA) cycle** and accelerating the operational engagement chain [70].

This architecture is particularly relevant to the present study because it illustrates a transition from conventional centralized operational management toward an **AI-enabled, data-centric, and distributed decision-support architecture**. Within such an architecture, artificial intelligence is not considered an isolated technological component; rather, it operates in conjunction with data fusion, distributed computing, communication networks, and human decision authority.

In **2022**, building on the results of previous demonstration experiments and technology-development activities, the U.S. Air Force initiated development activities associated with **Capability Release 1**, including airborne edge nodes, cloud-based command-and-control systems, and digital infrastructure. It also established the **ABMS Digital Infrastructure Consortium** [71].

The U.S. Air Force subsequently used analytical tools to examine deficiencies in existing command-and-control and operational-management capabilities and to identify areas requiring improvement. Based on these assessments, several fundamental principles were established for ABMS development [72].

3.2.1 Separation of Command and Control Functions Under Specific Conditions

The first principle is that command-and-control architectures should support an appropriate separation between command and control under exceptional circumstances. In highly time-sensitive situations, such as the arrival of cruise-missile threats, decisions may need to be made and executed without requiring direct involvement from a commander at every stage [73].

From the perspective of intelligent operational management, this principle introduces an important distinction between **command intent** and **execution-level control**. AI-enabled decision-support mechanisms and automated operational-management functions can assist in translating predefined mission objectives and authorized rules into rapid operational responses [73].

Such separation does not imply the elimination of human authority. Instead, it represents a functional allocation in which commanders establish objectives, constraints, priorities, and engagement authorities, while operational-management systems provide increasingly automated support for time-sensitive execution [73].

3.2.2 Decentralization of Operational Management

The second principle is the decentralization of operational-management functions. Rather than maintaining dependence on centralized platforms such as the E-3, ABMS emphasizes the utilization of **cross-domain and multi-source sensor data**. [74].

This represents a significant transition from platform-centered management toward distributed information processing. It also increases the importance of **data fusion**, because operational decisions must increasingly be based on information originating from heterogeneous sensors distributed across different platforms and operational domains. [74].

In the proposed framework, decentralized data processing can improve operational adaptability by allowing individual nodes to retain useful local capabilities while contributing relevant information to a broader operational picture.

3.2.3 Integrated Design Across Operational-Management Levels

The third principle emphasizes the integrated design of operational-management systems across different command levels. This includes horizontal integration among ground, air, maritime components, and operational commands, as well as vertical integration among different execution echelons across land, maritime, and air domains. [75].

Such integration is intended to enhance system survivability and operational continuity. From the perspective of the present study, this principle corresponds directly to **multi-domain coordination** and **operational resilience**. [75].

A resilient operational architecture should not depend exclusively on a single command node, communication pathway, or information source. Instead, it should distribute appropriate functions across multiple nodes while maintaining sufficient interoperability to support coordinated operations. [75].

3.2.4 Distributed Command and Operational Management

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The United States has also continued to explore distributed forms of command and operational management. An **ABMS Request for Information issued in November 2022** provided an initial conceptualization of the application of distributed architectures[76].

The conceptual architecture indicates that distributed operational-management systems can retain independent operational-management functions while improving overall information and decision-making advantages through support-and-supported relationships among operational elements[76].

This distinction is important. A distributed architecture should not simply decompose a centralized system into isolated functional components. Rather, each operational node should retain an appropriate degree of autonomous functionality while remaining capable of cooperating with other nodes when required.

Accordingly, distributed operational management can be understood as an architectural mechanism for balancing **local autonomy, global coordination, information availability, and resilience**.

3.3 U.S. Distributed Battle Management (DBM) Program

To address potential future threats, the U.S. military has explored concepts for future manned–unmanned collaborative operational systems in which manned and unmanned platforms, weapons, sensors, and electronic-warfare systems are connected through stable satellite and tactical communication links [77].

Such an architecture can provide operational personnel with greater flexibility in selecting and organizing operational resources. However, the rapid multiplication of platforms and operational elements also introduces additional complexity and places greater demands on operational management.

Future potential conflicts may additionally involve environments in which communication capabilities are degraded, disrupted, or unavailable. Such conditions can adversely affect coordination among platforms and the sharing of operational situational awareness.

In response to these challenges, the **U.S. Defense Advanced Research Projects Agency (DARPA)** initiated the **Distributed Battle Management (DBM)** program in **2014**. The program sought to develop appropriate control algorithms, airborne decision-support software, and advanced human–machine interaction technologies for cockpit environments [78]..

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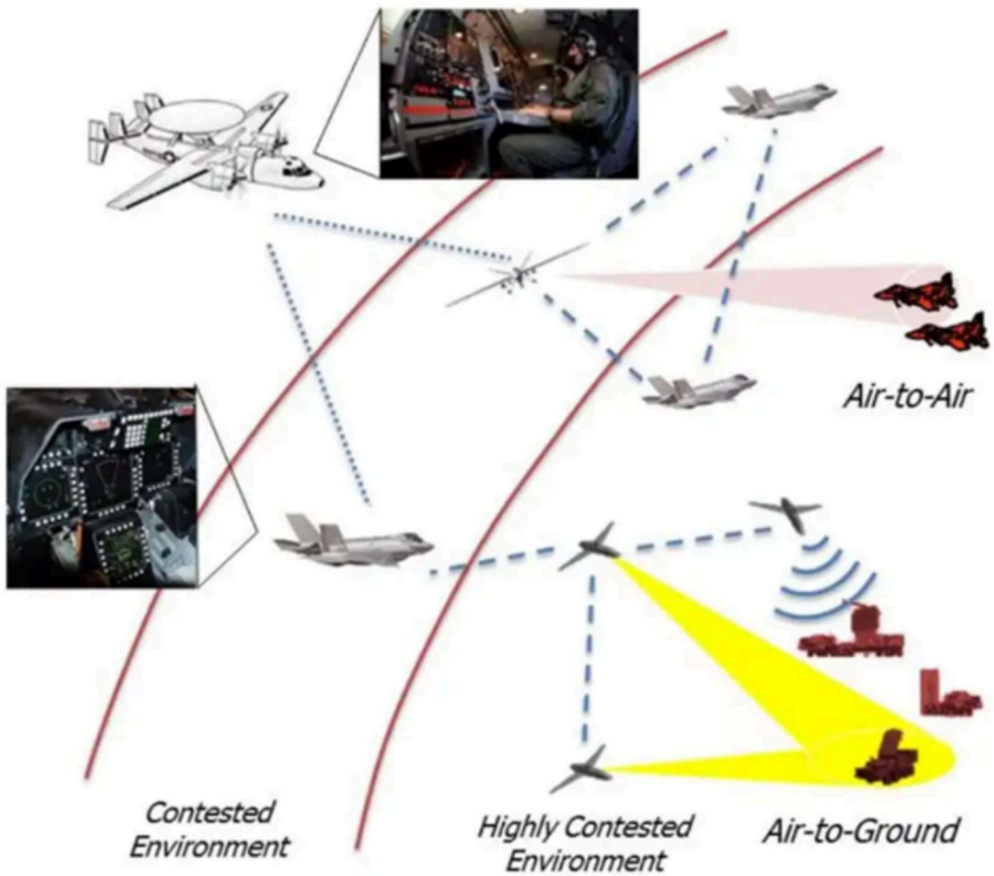

Source: [78].

"*The scenario presented in DARPA's Distributed Battle Management (DBM) BOA foresees the DBM developing decision aids for airborne battle managers and pilots in tactical aircraft, as well as autonomy for unmanned systems, in order to manage complex kill chains for air-to-air and air-to-ground missions in a contested environment. DARPA illustration*" [78].

The objective was to enhance **distributed adaptive planning and control** and situational-awareness capabilities and to support airborne battle managers and pilots in performing air-to-air and air-to-ground missions under highly contested conditions [79].

The DBM program primarily focused on automated decision-support tools capable of supporting distributed adaptive planning and control and distributed situational awareness . These capabilities were intended to assist decision-makers in managing increasingly complex systems, including unmanned systems and other distributed capabilities, under communication-denied conditions. The system also incorporated mechanisms for estimating threat scale and potential losses of friendly aircraft [79].

3.3.1 Distributed Adaptive Planning and Control

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Distributed adaptive planning and control are intended to assist pilots and battle managers in managing aircraft, weapons, and sensors in real time under communication-constrained conditions while maintaining alignment with commander's intent [80].

The functions include task and target assignment, resource deployment, weapon–target matching, and sensor scheduling. The operational-management system provides support to weapon operators and pilots in operational environments while allowing unmanned systems, where appropriately authorized, to autonomously select methods for accomplishing assigned tasks[80].

Within the integrated model proposed in this study, distributed adaptive planning represents a major application domain for **AI-enabled decision-making**. The importance of AI arises from the need to process multiple operational variables simultaneously and to generate decision-support alternatives under rapidly changing conditions.

However, effective intelligent decision-making requires reliable information inputs, appropriate operational models, clearly defined decision constraints, and mechanisms for maintaining consistency among distributed decisions. Consequently, AI-enabled decision-making should be considered part of a broader operational-management architecture rather than an independent capability.

3.3.2 Distributed Situational Awareness

Under communication-constrained conditions, DBM software is designed to monitor the status of communication links and selectively transmit important information according to predefined priority criteria. This approach prevents low-priority information from consuming limited communication-channel resources and helps ensure that critical operational information can be transmitted and processed in a timely manner [81].

The system can also process target information locally at the terminal level, thereby reducing the amount of information that needs to be transmitted. Furthermore, it can fuse multi-source information originating from different platforms and support distributed situational-awareness sharing [81]..

Such processing can support the determination of friendly and opposing-force locations, target identification, and assessment of target status, thereby providing information required for distributed adaptive planning and control. This capability demonstrates the strategic importance of **data fusion at the edge**. Rather than requiring all information to be transferred to a centralized processing location, selected information can be processed locally and transformed into operationally meaningful data before transmission. [81].

From a resilience perspective, this approach reduces dependence on continuous high-bandwidth connectivity. Consequently, distributed data fusion can contribute simultaneously to **decision-making efficiency, communication efficiency, multi-domain coordination, and operational resilience**.

3.4 Comparative Synthesis of C2BMC, ABMS, and DBM

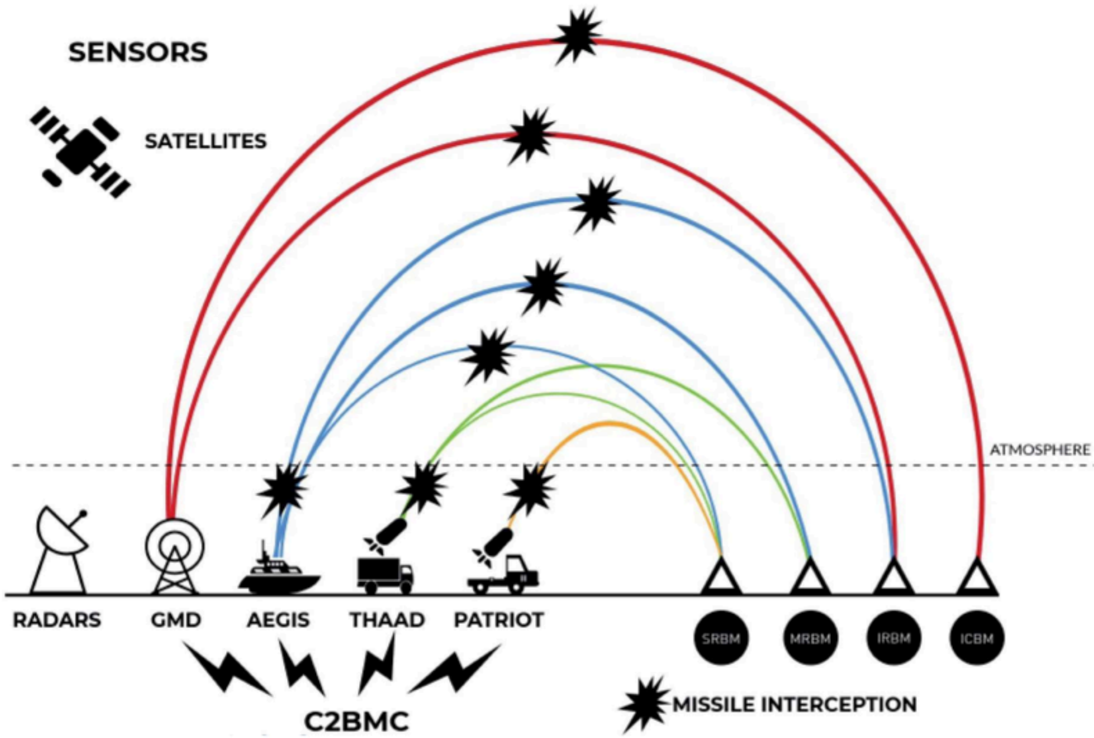

Fig () Components of the BMD system. [82].

The development trajectories of the U.S. **C2BMC system, ABMS, and DBM program** reveal several common characteristics in the evolution of operational management [83,84,85].

First, these systems maintain the principle of **information–firepower integration** while progressively increasing the degree of distributed information processing and operational coordination.

Second, they demonstrate the value of a **spiral development model**, in which operational-management capabilities are developed, tested, deployed, evaluated, and subsequently expanded through successive iterations.

Third, the development of specialized operational-management systems can precede their broader integration into increasingly comprehensive system-of-systems architectures. This can be characterized as a **"develop first, integrate subsequently"** approach.

Fourth, increasing attention is being given to an appropriate functional separation between **command and control**, allowing command authorities to focus on intent, priorities, and high-level decisions while operational-management systems provide increasingly sophisticated execution-level support.

Finally, the emergence of distributed operational management demonstrates a growing requirement for operational continuity under degraded communication and contested conditions.

Taken together, these developments indicate a transition from conventional centralized management toward an architecture characterized by **AI-enabled decision support, multi-source data fusion, distributed multi-domain coordination, and operational resilience**.

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These developments provide useful conceptual references for the future development of aerospace defense command-and-control and operational-management systems.

Source: [86].

4. Perspectives on the Development of Operational Management

4.1 Adhering to Operationally Oriented System-Level Forward Design

The integrated use of information and firepower represents one of the fundamental functions of operational management. Experience from the development of the U.S. C2BMC system demonstrates that aerospace defense operations frequently span multiple operational regions and require extremely high levels of information accuracy and timeliness. Accordingly, an integrated mechanism for managing information and engagement resources is required to coordinate heterogeneous operational assets within a common operational architecture[87].

Integrated information–firepower management can take advantage of the relatively predictable characteristics of certain ballistic trajectories and the geographically distributed nature of aerospace defense operations. Before engagement, sensors, interceptors, and other operational resources can be organized according to anticipated threat conditions. During an engagement, trajectory estimates can be updated continuously and corresponding sensor-observation and interception plans can be dynamically adjusted [88].

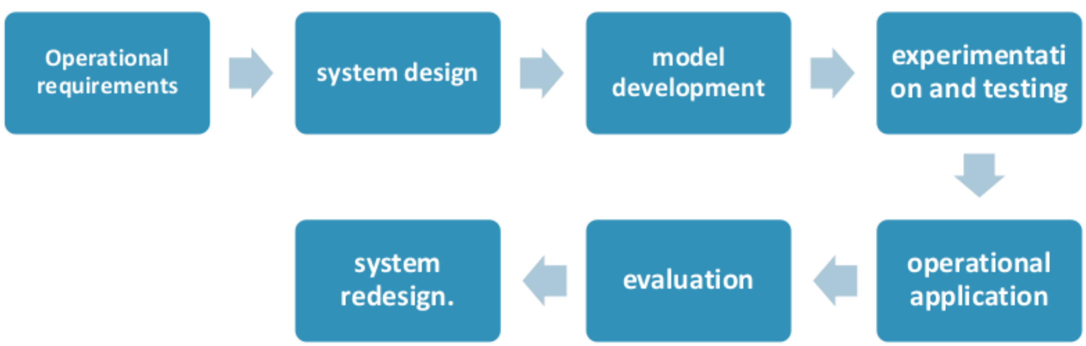
From an operational-management perspective, this process represents a transition from **static resource allocation toward adaptive resource management**. AI-enabled decision-support mechanisms and data-fusion capabilities can potentially contribute to this transition by processing continuously updated information and supporting the generation of alternative resource-allocation options [88].

Under conditions involving multiple simultaneous threats, appropriate planning and dynamic coordination can reduce potential resource conflicts and improve the utilization of limited operational resources. The ultimate objective is to maximize system-level operational effectiveness rather than optimizing individual equipment elements independently.

For future high-intensity and technology-intensive warfare environments, operational-management systems should therefore be developed through **system-level top-down design**, with overall operational effectiveness as the primary objective. Multi-level and integrated operational-management capabilities should be iteratively developed to support coordinated command and control across different operational domains.

An operationally oriented development philosophy should adopt a **"develop while researching, test while developing, and employ while testing"** spiral model. Operational-management activities can provide feedback on the characteristics of operational missions, thereby improving scientific understanding of operational requirements and feeding that knowledge back into system-level design.

This creates a continuous feedback loop:



Such a cycle can support continuous improvement in operational-management capabilities while maintaining alignment between technological development and operational requirements.

4.2 Integrating Joint and Domain-Specific Operational Management

Given the complexity of joint operational systems, an important question concerns whether a single operational-management system can immediately assume responsibility for all resources across all operational domains.

The development of **JADC2, ABMS, and C2BMC** suggests that joint operational management and domain-specific operational management can develop simultaneously. On the one hand, top-level architectural design and integration can establish common principles, interfaces, and technical constraints for joint operations. On the other hand, specialized operational-management systems can be developed independently within particular operational domains [89].

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This development pattern can be interpreted as a characteristic evolution of complex system-of-systems architectures: **specialized capabilities are developed first and subsequently integrated into broader architectures**.

The advantage of this approach is that domain-specific systems can be developed, tested, and evaluated within relatively well-defined operational environments before being incorporated into more complex joint architectures.

For future aerospace defense operational-management development, a feasible approach is therefore to establish a common top-level architectural framework and technical governance mechanism while allowing domain-specific operational-management systems to undergo independent development and experimentation.

Once their interfaces, data structures, interoperability mechanisms, and operational-management functions have been sufficiently validated, these domain-specific capabilities can be progressively integrated into broader joint operational-management architectures.

This approach also supports the proposed **multi-domain coordination** variable because coordination is not treated simply as organizational cooperation. Instead, it is supported by compatible data structures, interoperable technical interfaces, distributed decision-support mechanisms, and common operational-management standards.

4.3 Appropriate Functional Separation Between Command and Control

The development principles associated with the U.S. ABMS system demonstrate increasing attention to an appropriate functional separation between command and control. This approach recognizes that operational management maintains functional interfaces with command, planning, intelligence, and other mission functions [90].

The separation of command and control can facilitate a more precise division between **command judgment** and **execution-oriented operational management**. Commanders can concentrate on assessing the operational environment, establishing objectives, determining priorities, and expressing mission intent, while operational-management systems provide specialized support for execution and resource coordination.

Within an intelligent operational-management framework, this distinction becomes particularly important because automated systems may process information and generate decision-support recommendations much faster than traditional human-centered processes.

However, intelligent operational management should remain bounded by explicit command authority, operational rules, and predefined constraints. The objective is not to replace command judgment but to allow information systems to perform computationally intensive coordination and decision-support functions in a manner consistent with authorized mission intent.

Such an organizational model can support **mission-oriented command**, in which higher-level intent provides the overall direction while distributed operational nodes maintain sufficient autonomy to respond to rapidly changing local conditions.

This approach is particularly relevant to complex aerospace defense environments because it can combine centralized intent with distributed execution and thereby improve adaptability without requiring every operational decision to pass through a single command node.

4.4 Exploring Intelligent Distributed Operational Management

The United States is actively exploring distributed forms of command and operational management and has proposed initial concepts for applying distributed architectures., a distributed architecture does not necessarily imply that operational-management functions should be completely separated and dispersed [91].

Instead, each individual system can retain independent operational-management capabilities while improving overall information and decision-making effectiveness through **support-and-supported relationships** among distributed nodes [91]..

Distributed operational management represents an effective organizational approach for managing large-scale and complex operational environments. A major requirement is that the system should maintain an appropriate degree of operational continuity even when communications are constrained, degraded, or interrupted [91]..

A completely decomposed architecture may increase dependence on ideal communication conditions. If every operational function depends on continuous connectivity to a central node, communication degradation or interruption can result in significant reductions in system-level effectiveness [92].

This creates a potential vulnerability for highly interconnected operational systems and may reduce their ability to maintain sustained operational performance under contested conditions [92].

Accordingly, future development should emphasize **self-consistent distributed operational management**. Distributed command-and-control nodes should possess sufficient local decision-making capability to generate coherent decision options while maintaining consistency with the decisions of other nodes.

The fundamental requirement is not simply independent decision-making but **coordinated autonomy**. Distributed decisions should remain mutually compatible, avoid unnecessary conflicts, and collectively provide adequate operational coverage.

This principle directly corresponds to the proposed concept of **operational resilience**. A resilient architecture should be capable of degrading gracefully rather than experiencing abrupt functional collapse when individual communication links, sensors, computing nodes, or other components become unavailable [93].

The integration of AI-enabled decision-making and distributed data fusion can further strengthen this model. Local nodes can process available information, identify relevant operational changes, and generate decision-support options while exchanging only the information necessary for broader coordination.

Thus, intelligent distributed operational management can be conceptualized as a balance among four requirements [94]:

1. **Local autonomy**, allowing individual nodes to retain useful operational functions;
2. **Data fusion**, allowing heterogeneous information to be transformed into coherent situational awareness;
3. **Multi-domain coordination**, allowing distributed nodes to cooperate across organizational and operational boundaries; and

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4. **Operational resilience**, allowing the overall system to maintain useful capabilities under degraded conditions.

5. Integrated Development Framework

Based on the preceding analysis, an integrated conceptual framework can be established to explain the development of aerospace defense equipment operational management in the intelligent era.

The framework considers **operational-management effectiveness** as the overarching outcome and identifies four mutually reinforcing dimensions:

5.1 AI-Enabled Decision-Making

AI-enabled decision-making represents the intelligent analytical layer of the operational-management architecture. It supports rapid processing of heterogeneous information, adaptive assessment, decision-support generation, and dynamic operational planning.

Its contribution is particularly important when operational conditions change faster than conventional human-centered decision processes can accommodate. However, AI-based decision support should remain subject to operational rules, command authority, mission objectives, and appropriate human oversight.

5.2 Multi-Source Data Fusion

Data fusion constitutes the information foundation of intelligent operational management. It transforms heterogeneous observations from distributed sensors and operational platforms into a coherent operational picture.

High-quality data fusion improves situational awareness and provides more reliable information for decision-support mechanisms. Conversely, poor-quality, delayed, incomplete, or inconsistent information can constrain the effectiveness of even highly advanced decision-support technologies.

5.3 Multi-Domain Coordination

Multi-domain coordination represents the organizational and technical mechanism through which distributed operational elements cooperate. It encompasses horizontal coordination among different operational components and vertical coordination across different command and execution levels.

Effective multi-domain coordination requires interoperable systems, compatible information structures, flexible command relationships, and mechanisms for dynamic resource allocation.

5.4 Operational Resilience

Operational resilience represents the ability of the operational-management architecture to maintain useful system-level capabilities under disruption, uncertainty, degraded communications, or partial loss of operational resources.

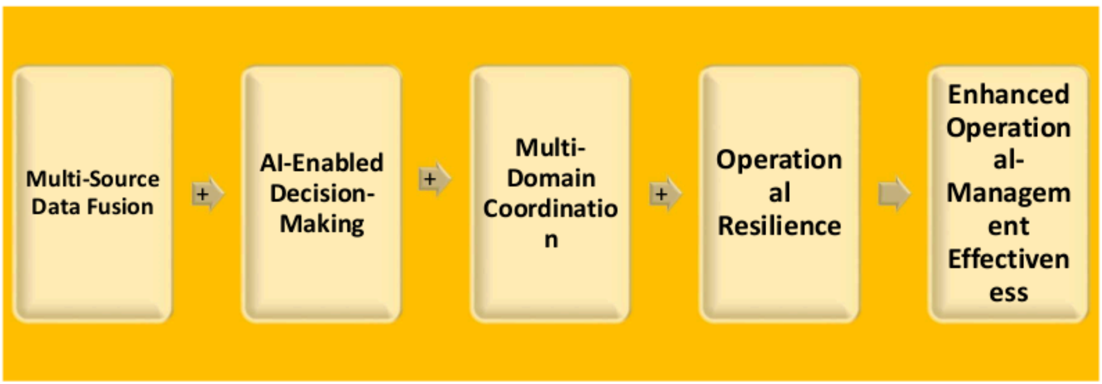
Resilience is particularly important for distributed systems because increased connectivity creates both opportunities for coordination and dependencies that may become vulnerabilities under contested conditions.

5.5 Relationship Among the Four Dimensions

The four dimensions should not be regarded as independent variables operating in isolation. Rather, they form a mutually reinforcing architecture.

At the same time, resilience can feed back into data fusion and decision-making by determining which information and functions remain available under degraded conditions. Thus, the proposed framework is fundamentally **dynamic and iterative** rather than linear.

The framework can therefore be expressed conceptually as:



This integrated perspective extends conventional operational-management theory by linking information processing, intelligent decision support, distributed coordination, and resilience within a single system-level framework.

6. Development Priorities for Future Aerospace Defense Operational Management

Based on the analysis, future development should focus on several mutually connected priorities.

First, operational-management systems should be developed through **operationally oriented top-down system design**. Technological development should begin with operational requirements and system-level effectiveness rather than isolated technological capabilities.

Second, **AI-enabled decision-making** should be progressively integrated into planning, situational assessment, resource allocation, and decision-support processes. AI should function as an

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augmentation mechanism that enhances human decision-making rather than as an isolated technological solution.

Third, **multi-source data fusion** should become a core architectural capability. The objective should be to transform heterogeneous information into coherent, timely, and operationally meaningful situational awareness.

Fourth, **multi-domain coordination** should be incorporated into system architecture from the beginning. Rather than attempting to integrate independently developed systems only after completion, interoperability requirements, common data structures, and interface standards should be established during the top-level design phase.

Fifth, **operational resilience** should be treated as a fundamental design objective. Distributed operational-management systems should retain useful capabilities when communication networks, sensors, command nodes, or computing resources are degraded or unavailable.

Sixth, development should continue through a **spiral model of research, experimentation, deployment, evaluation, and redesign**. Such a process allows operational-management systems to evolve in response to changes in technology, operational concepts, and threat environments.

Finally, future architectures should seek a balanced relationship between **centralized intent and distributed autonomy**. Centralized structures can establish common objectives and priorities, while distributed nodes can provide local processing, adaptive decision support, and operational continuity.

7. Conclusion

As with the theories and methodologies of modern management, operational management seeks to integrate the scientific principles of command and control with the efficiency of information technologies. It should therefore not be regarded merely as the direct application of information technology. Its effectiveness also depends on scientific modeling, operational knowledge, organizational design, data quality, and practical understanding of operational requirements.

Experience from domestic and international developments indicates that operational management constitutes both a **product and an implementation vehicle of system-level forward design**. At the same time, operational-management practice can provide feedback to system-level design, thereby establishing a continuous cycle of iterative capability development.

The evolution from weapon-centric to platform-centric and subsequently network-centric operational management demonstrates a progressive increase in the importance of system integration, distributed coordination, and information–firepower integration. More recent developments represented by C2BMC, ABMS, and DBM indicate an additional transition toward distributed, intelligent, adaptive, and resilient architectures.

Within this transition, four capabilities have become increasingly important: **AI-enabled decision-making, multi-source data fusion, multi-domain coordination, and operational resilience**. AI can enhance decision-support speed and analytical capacity; data fusion can improve the consistency and timeliness of operational situational awareness; multi-domain coordination can integrate distributed operational resources; and resilience can enable the system to maintain functional continuity under uncertainty, disruption, and contested conditions.

Future aerospace defense operational management should therefore move beyond the objective of simply connecting more equipment and exchanging more information. The central development objective should be the creation of an **intelligent, adaptive, distributed, and resilient operational-management architecture** capable of converting heterogeneous resources and information into coordinated system-level effectiveness.

A particularly important development direction is the integration of **top-down system design with bottom-up iterative experimentation**. Through continuous cycles of modeling, development, testing, operational application, evaluation, and redesign, operational-management systems can progressively improve their ability to respond to complex operational environments.

At the architectural level, future systems should seek an appropriate balance between centralized coordination and distributed autonomy. Centralized structures can provide common objectives, priorities, and system-level coordination, whereas distributed nodes can provide local processing, adaptive decision support, and operational continuity when communications are degraded.

Consequently, the future evolution of aerospace defense operational management can be conceptualized as a transition:

This trajectory reflects a broader transformation in which operational effectiveness increasingly depends not on the performance of isolated equipment elements, but on the ability of the overall system to **sense, fuse, decide, coordinate, adapt, and sustain operations as an integrated whole**.

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