A Review of Capability-Based System Development Model Research

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Abstract. This paper outlines the development methods of a capability-based system with an emphasis on the key concepts of Capability Based Planning (CBP) and Capability Portfolio Management (CPM) by sorting out related research and application at home and abroad. It provides theoretical support for the construction of the system development model and makes prospects for capability-based system development.

Keywords: system development · capability-based planning · capability portfolio management

1 Introduction

System confrontation is the process of forming system capabilities through the interaction and interdependence of subsystems in multiple capability areas led by specific missions and tasks. Given the intricate and uncertain strategic environment and complex process of system development, the structural framework of each sub-system, risk response capability and future development direction shall be decided from the top-level planning perspective under the overall guidance of strategic capability. Thus, higher requirements are put forward for the system development to further enhance the system's capability.

2 Overview of the Capability-Based System Development

Capability refers to the ability to achieve the expected goal or result by using various means and methods through certain missions and tasks [1]. U.S. military capability elements include Doctrine, Organization, Training, Material, Leadership, Personnel, Facilities, and Policy (DOTMLPF-P) [2]. System capability is a high-level description of system requirements with relatively stable connotations and structures that do not change with the external strategic environment; therefore, it is an ideal way to guide army transformation, integrated joint warfare, and weapon development based on system capability.

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2.1 The Vision of Capability-Based System Development

In the 1990s, the U.S. military's weapon development turned increasingly fragmented and fell into an isolated state, unable to converge into an overall joint warfare capability to address the complexity and uncertainty of warfare threats. As a result, the U.S. Department of Defense (DoD) first introduced the concept of a "Capabilities-Based Approach" [3] to guide defense planning in 2001 in the Quadrennial Defense Review, which stated that the traction model for defense planning should shift from "threat-based" to "capabilities-based". Since then, the U.S. Army has been guided by a "capability-based" approach to army building, military transformation, equipment acquisition, and other aspects of defense construction.

Figure 1 details the application of a "capability-based" approach to requirements acquisition, assessment, planning, and acquisition to further the military transformation and the national defense construction.

The vision of capability-based system development is based on joint forces from a top-level design perspective, as summarized below [4].

(a) Capability-based system development addresses specific capability requirements and responds to inherent and external uncertainties, finding answers to the question "what projects need to be completed" rather than "how to complete the projects";

(b) Capability-based system development is a "top-down" decision-making process. Under the constraints of the national defense budget, the project planning process is promoted downward through the mapping between the capability requirements and the military mission to achieve a balanced development of costs, risks, capabilities and other dimensions; and.

(c) The portfolio under multiple threats and scenarios shall be taken into consideration for capability-based system development to obtain flexible, adaptable and robust development solutions.

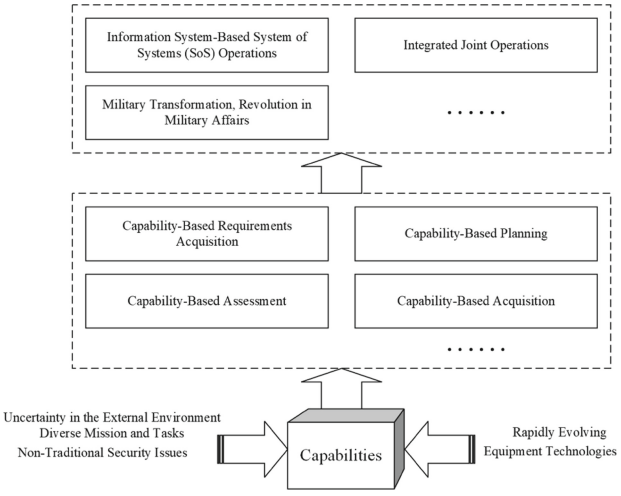

Fig. 1. Capabilities-Based Approach

2.2 Capability Based Planning (CBP)

The capabilities-based approach runs through all domains and stages of national defense construction, and has evolved into the Capability Based Approach (CBA) and Capability Based Planning (CBP). CBA underpins the U.S. Army's Joint Capabilities Integration and Development System (JCIDS) [5] and serves to assess capability requirements, capability gaps, operational risk, etc. CBP involves the planning of a portfolio of capability requirements from a top-level planning and design perspective within the constraints of the defense budget, resulting in a system development program capable of responding to threats and challenges. The approach is widely used to direct the selection, development and planning of weapon and equipment portfolios [6]. Following the ongoing development and application of CBP, in 2003, the U.S. improved and upgraded the Weapon Investment and Acquisition Decision Support System, which consists of JCIDS, the Planning, Programming, Budgeting, and Execution (PPBE), and the Defense Acquisition System (DAS) [4].

2.3 Capability Portfolio Management (CPM)

One of the loopholes and shortcomings of the "capability-based" approach that continues to grow and evolve is the lack of quantitative data to support the decision-making and planning process. With a view to making it more convincing, the U.S. DoD, therefore, proposed Capability Portfolio Management (CPM) [7] to guide weapon portfolio planning by taking a cue from the sector of economics by adding a quantitative analysis process. As opposed to CBP which stresses the standardization of system and process, CPM aims to optimize the decision making and resource allocation, and to complete the integration, synchronization and coordination of capability requirements and DOTMLPF-P in a capability portfolio [8].

3 Research Status of Capability-Based System Development Model

3.1 Overseas Research Status

The concept of capability-based first emerged in foreign countries and has led to certain research results. Rios et al. [9] proposed a quantitative assessment framework for portfolio problems in intelligence information systems; Snyder et al. [10] designed a portfolio analysis tool to quantitatively assess capability requirements for U.S. Air Force operational capabilities, and then completed capability-based resource allocation; Dahmann et al. [11] proposed a systems engineering approach to defense acquisition in order to improve the robustness of the acquisition process; Flynn [12] conducted a study on capability portfolio analysis and concluded that capability portfolio analysis facilitates the defense acquisition process. Davis et al. [13], a senior researcher at RAND, proposed a set of analytical methodologies for generating, evaluating and screening alternative capability portfolio scenarios and developed the Building Blocks To Composite Options Tool (BCOT) and the Portfolio Analysis Tool (PAT), as shown in Fig. 2.

Snyder et al. [14] quantified capacity and constructed a "cost-capacity" robust model for resource allocation; Chow et al. [15] proposed a model for evaluating desired capabilities under cost and budget uncertainty; Hiromoto [16] proposed a capability portfolio

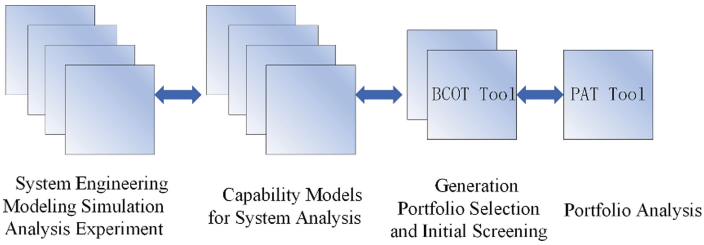

Fig. 2. Davis Portfolio Analysis

management concept that minimizes the budget while ensuring the capability; Iacobucci [17] constructed a framework for the study of weapon system portfolios based on capability portfolio analysis; Davendralingam et al. [18] introduced Markowitz portfolio theory in the defense acquisition decision making process; Schaffner et al. [19] constructed trade-off spaces within the constraints of budget and capability requirements and chose among alternatives based on factors such as capability, cost, and time; and Neitzke et al. [20] constructed a "benefit-cost-risk" model and a weighted utility function based on capacity.

3.2 Domestic Research Status

Domestic scholars have conducted some research on weapon portfolio planning and selection by adopting the capability-based approach. Xiong et al. [21] described the weapon capability space, constructed a multi-objective optimization model for the weapon capability portfolio under the constraints of time and cost, and applied genetic algorithms for model solving; Zhou [22] studied the model construction and algorithm solution for the multi-objective and multi-stage planning of weapon portfolio by adopting the top-level design methods of CBP and CPM; Dou [23] applied portfolio decision making to the weapon portfolio selection process and gave a set of research methods for weapon portfolio selection and decision analysis for large-scale optimization; and Zhang [24] studied the planning selection of weapons in multi-capability areas from the perspective of the top-level design of weapons portfolio planning.

4 Application of Capability-Based System Development Model

4.1 Foreign Application Status

In 2017, NATO released the Alternative Analysis (AltA) to address planning, policy, and procedural issues targeting strategies, politics and operations. AltA provides military decision makers with a more macro perspective and a more holistic understanding through the application of independence, critical thinking, and alternative viewpoints. AltA has been shown to reduce decision risk, offer the possibility of innovative solutions, and provide more timely decision support for decision makers.

In 2020, NATO's Supreme Allied Commander Transformation Headquarters proposed a "Computer-Assisted Military Capability Planning Oriented Chess Rehearsal"

methodology designed to validate the concept of applying qualitative expert systems to develop capability requirements in computer-assisted chess rehearsals to reduce adjudicator bias and risk associated with decision making.

In 2011, the UK Ministry of Defence developed the "NITEWORKS" project to address strategic capability tradeoffs, as shown in Fig. 3. It primarily involved modeling and experimenting with capabilities, requirements, risks, and options within the constraints of the national strategic vision and military budget, and finding compromises and balances in capability building paths at the mission-dependent level and the strategic option level. The trade-off space analysis enables efficient use of resources, provides better decision support to decision makers, and reduces operational risk.

In 2021, MITRE Corporation proposed the research framework of "Mission Engineering - Integrated Decision Support Key & Evaluation Framework - Digital Engineering" (ME-IDSK & EF-DE) at the ITEA Symposium, as shown in Fig. 4, proposing a mission-centered, capability assessment-based decision support concept. In this framework, Mission Engineering (ME) provides the operational context of the mission and technology gaps, Digital Engineering (DE) provides the complexity and relevance of the management data and model resources, and the two are linked to form a system engineering paradigm of "diamond model", with the Integrated Decision Support Key & Evaluation Framework (IDSK&EF) for capability testing and experimental evaluation to enable concept-to-capability decision support, and ultimately provides information support for DoD technology realization, prototyping, and acquisition decisions.

In 2019, the U.S. RAND Corporation developed the Multi-Purpose Assessment of Force Flow (MPAFF) to provide a quantitative assessment of force structure and force capabilities. This tool allows for a rapid and adequate assessment of risks and budgets for various force structures, readiness policies, and force generation policies to mitigate financial pressures.

In 2022, the RAND Corporation conducted a comprehensive review of the theory of Urban Green Space (UGS) by interviewing experts and reviewing data. UGS exploration enables judgments by decision makers, researchers, and others on the soundness of strategic options, and operational options, and also provides the Defense Advanced

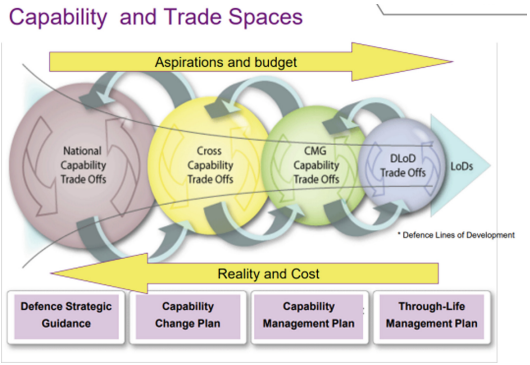

Fig. 3. NITEWORKS Project

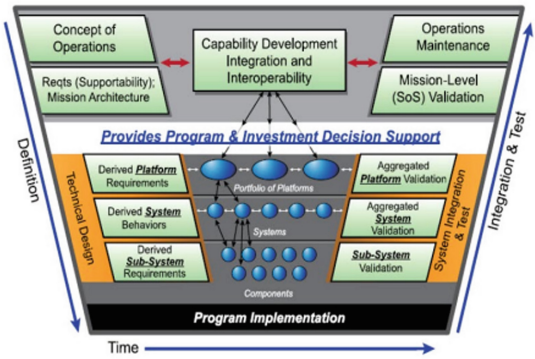

Fig. 4. ME-IDSK&EF-DE Research Framework

Research Projects Agency (DARPA) with information to assist in building investments that support assessment, interaction, and adaptation capabilities.

In 2022, the Center for Strategic and Budgetary Assessments (CSBA) released a model to study China's strategic portfolio, the China Strategic Choices Tool (SCT). The tool develops investment and disinvestment estimates from multiple areas and levels, addresses the trade-offs between our military's high-level resource allocation, force structure decisions, and military modernization, and facilitates the U.S. DoD's policy-level understanding and assessment of the budgetary choices, relative trade-offs, and constraints of our military modernization.

4.2 Domestic Application Status

Not many domestic scholars have studied the development of the system, but currently, the scholars are developing the "nine-grid" exercise system, also known as the strategic decoding grid platform. The system is designed to meet the major capability assessment needs of large missions, multi-domains, multi-threads, multi-systems, and multi-linkages that have a significant impact on the strategic landscape. Based on Huawei's "PPBEA" four-step strategic management chain, this system focuses on the decoding of strategic capabilities and the optimal transformation of the "strategic capability concept" to "strategic management control", so as to realize the rehearsal in future scenarios.

5 Research Trends in the Capability-Based System Development

The capability-based system development has now achieved better research and application at home and abroad, especially in the field of equipment acquisition. There are however still some issues that need to be further studied for system development.

(1) A top-down, scientific and quantitative operation and management approach is needed for the overall planning, forming a set of the overall framework for system development to support decision makers in integrated planning, maximizing system capabilities, building forward-looking system development programs, and further responding

to diversified system capability needs, and diverse and complex strategic environments and new challenges;

(2) The integrated decision-making approach shall consider the inherent uncertainty of the system more comprehensively. It is to analyze, manage and control the inherent uncertainties from the perspective of top-level planning, while considering the requirements of maximizing the development of overall capabilities and saving defense funds, i.e., weighing the multi-dimensional and multi-faceted influencing factors of overall capabilities, development risks and funding budgets in the system development in an integrated manner.

(3) In response to the external uncertainties in the system development, a robust planning scheme is further constructed. The traditional planning model adopts a static modeling approach from our perspective and mindset, which fails to fully take into account the adversarial relationship with the adversary and is prone to closed doors. Robust planning solutions, therefore, need to be generated in the initial stages of system development to enable the system to sustainably accomplish holistic, dynamic, and adversarial missions and tasks.

6 Conclusion

This paper concludes the basic principles of capability-based system development, sorts out the research status of CBP and CPM related theories, summarizes the application status of the capability-based system development model, and prospects the research direction and development trend of capability-based system development model, which is of great significance to further enhance strategic capability.

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