IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 12 January 2024, accepted 25 January 2024, date of publication 5 February 2024, date of current version 16 February 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3362229

RESEARCH ARTICLE

Improved Technology Readiness Assessment Framework for System-of-Systems From a System Integration Perspective

JI-IN KOO AND SUK-JAE JEONG
Department of Defense Business, Kwangwoon University, Seoul 01897, South Korea
Corresponding author: Suk-Jae Jeong (sjjeong@kw.ac.kr)

The present Research has been conducted by the Research Grant of Kwangwoon University in 2021.

ABSTRACT The military of the Republic of Korea utilizes technology readiness assessment (TRA) to quantitatively evaluate the maturity of domestic technologies. TRA is a key tool for determining the research and development potential in the country. As TRA employs hardware (HW)-oriented technology readiness levels (TRLs), it is suitable for independently assessing individual technologies. However, it has limitations in terms of evaluation from a system-integration perspective. Additionally, the results of checklist-based assessments are highly likely to involve subjectivity, which may yield sparse quantitative insights. This study proposes an enhanced TRA framework in which TRA procedures and criteria are redefined from the system-integration perspective. A framework that can overcome the limitations of the current TRL and TRA frameworks and enable easier, more intuitive assessments is developed. The proposed framework distinguishes between a technology element and a critical technology element (CTE) in terms of HW, software (SW), and interface (IF) and redefines TRLs. Under this framework, TRA is performed according to the TRLs that are redefined in terms of HW, SW, and IF; considering risk management, the lowest evaluation value is used as the system maturity level. The proposed CTE selection method minimizes external evaluator interventions by considering the quantitative goals of the key required operational capabilities, development difficulties, and applications of commercial off-the-shelf technologies. The effectiveness of this framework is confirmed through a case study involving three systems of systems. The results of this study can inspire research at the framework level and contribute to the improvement of existing TRA systems.

INDEX TERMS Integration readiness level, system readiness level, technology readiness assessment, technology readiness level.

I. INTRODUCTION

Weapon systems are becoming increasingly intelligent, unmanned, and integrated into the system of systems (SoS). The weapon system acquisition policy of the South Korean military prioritizes domestic research and development (R&D) as well as the procurement of commercial products. Technology readiness assessment (TRA) is a crucial tool for quantitatively evaluating current domestic technological levels, judging the feasibility of domestic R&D, and managing the associated risks. Since its introduction to the South Korean military in the early 2000s, the TRA system has undergone continuous improvements to better align with the current domestic environment for weapon system R&D projects. However, the current TRA still relies on a hardware (HW)-oriented technology readiness level (TRL), which is suitable for assessing individual technologies but has limitations in evaluating the system readiness level (SRL). Moreover, checklist-based evaluations with ambiguous phrases frequently involve subjective judgments. Efforts have been made to address these limitations through research on the integration readiness level (IRL) and SRL; however, the results have not been formally institutionalized.

The associate editor coordinating the review of this manuscript and approving it for publication was Francisco J. Garcia-Penalvo.

This study proposes an improved TRA framework that overcomes the limitations of the current TRL and TRA by redefining the TRA procedures and criteria from the system-integration perspective of systems engineering (SE). In this study, a technology element (TE) refers to a specific and discrete component of a technology that can be assessed and measured for its maturity level. It represents a fundamental building block or aspect of a technological system. A critical technology element (CTE) refers to a specific technology component or aspect that is deemed critical for the successful development or operation of a system. CTEs have a substantial impact on the overall performance, schedule, cost, and risk of the system. The selection method for CTEs provides specific approaches for deriving and selecting TEs and CTEs from a system-integration perspective, starting with the development of a technical work breakdown structure (WBS). In particular, the proposed method utilizes certain quantifiable targets of the key required operational capabilities (ROCs), technological development difficulty levels, and application of commercial off-the-shelf (COTS) technologies to minimize the frequency of subjective judgments. For technology evaluation, TRA utilizes the TRL, which has been redefined in terms of HW, software (SW), and interfaces (IFs) from a system-integration perspective. We conducted case studies on the proposed framework and confirmed its practicality and substantial practical value. The major contributions of this study are summarized as follows:

- A TRA method focusing on the system-integration perspective based on SE is presented.
- External evaluator interventions are minimized using methodology-level TRA procedures.
- An intuitive and easy TRA method with consistent results is provided.
- Practical CTE selection procedures are provided.
- Experts familiar with system engineering can easily learn the TRA method.

In Section II, key issues related to the topic are identified by analyzing the TRA system and related studies. Section III presents the proposed TRA framework addressing these challenges. Section IV presents a case study conducted for verifying the effectiveness of the framework. Finally, Section V concludes the paper.

II. RELATED REGULATIONS

A. REGULATIONS AND POLICIES RELATED TO TRA

According to the Orders for the Development of War Capabilities, the military of the Republic of Korea (ROK) prioritizes domestic development and COTS item purchases for acquiring weapon systems [1]. Since 2021, the Defense Acquisition Program Administration (DAPA) has been promoting priority acquisition policies for Korean products to support the domestic defense industry and elevate defense science and technology capabilities [2]. Following the establishment of the DAPA in 2006, it ratified institutional foundations for the TRA of the ROK military in the erstwhile Defense Acquisition Program (ACT). Until 2011, this TRA program was utilized in various projects; however, the absence of specific guidelines in this assessment has limited its use as a basis for determining whether to proceed with the projects. Nevertheless, in 2011, the DAPA actively promoted the use of TRA to prevent project failures owing to insufficient technological maturity, establishing it as a key decision-making tool for domestic R&D projects [3]. Consequently, TRA was conducted according to the Technical Maturity Evaluation Work Guidelines (2019) set by the DAPA.

This version of TRA was applied to precedent studies, exploratory developments, integrated exploratory and system developments, advanced concept technology demonstrations, and critical technology research and test development projects.

The assessment was performed in the following sequence: 1) preliminary work, 2) CTE selection, and 3) assessment [4]. The National Aeronautics and Space Administration (NASA) [5], Department of Defense (DoD) [6], and Government Accountability Office (GAO) have provided valuable guidelines for performing TRA [7]. All of these guides emphasized the importance of clear CTE selection and objective TRA evaluations involving independent expert teams. The DoD initiated the streamlining of acquisition program procedures in 2011; consequently, TRA was conducted only for major defense acquisition programs (MDAPs) and projects with technological risks. The DoD TRA guide has reduced the mandatory requirement to achieve TRLs at all major milestones and now limits TRA execution only to Milestone B of a MDAP. While NASA and DoD did not use a specific definition for SW TRLs, the GAO recognized the difference between HW and SW TRLs and included a definition for SW TRLs in its guide.

B. LITERATURE ON TRA

The TRL metric was initially developed by Sadin et al. [8] of NASA in 1974 using a seven-level scale. The current TRL framework was established in 1990 using a nine-level scale and was formalized by Mankins in 1995 [9]. Subsequently, the TRL metric of NASA has been adopted extensively by various US government agencies, such as the DoD, Department of Energy, and Department of Transportation, as well as by European space agencies.

However, concerns have been raised regarding the limitations of relying solely on this nine-level TRL metric for TRA. For example, Cornford and Sarsfield [10] highlighted the demerits and challenges of assessing technological maturity using the TRL metric established by NASA: 1) it provides subjective assessments; 2) it is not focused on system-to-system integration; 3) it is focused on HW and not SW; 4) it is not well integrated into cost and risk modeling; and 5) it is lacking in definitions for terminologies.

Research on technology integration began with the proposal of the integrated technology analysis methodology and integrated technology index (ITI) as indicators of technology

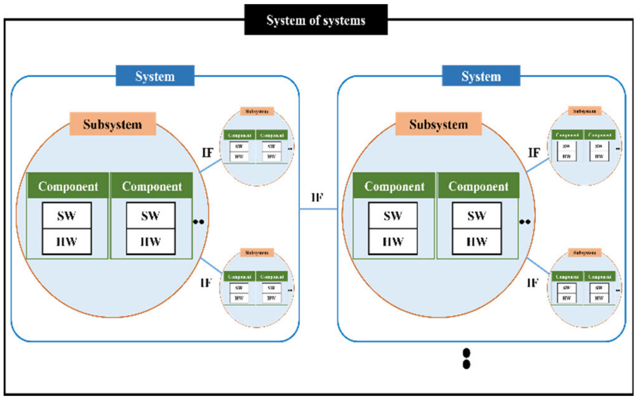

FIGURE 1. Structure of a system of systems (SOS). SW: software; HW: hardware; IF: interface.

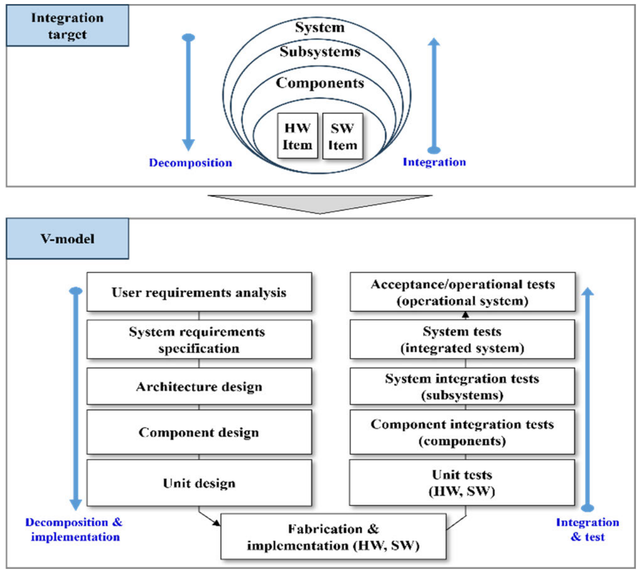

FIGURE 2. Major activities in systems engineering (SE).

integration by Mankins [11]. However, the ITI has limitations from the system-integration perspective. In response, the UK Ministry of Defense developed technology insertion metrics and applied integration maturity levels to assess integration maturity.

Gove [12] developed the IRL to assess the IF maturity among CTEs to overcome the demerits of the TRL, which measures the maturity of a piece of technology. This metric not only measured the IF maturity between CTEs, but also provided directions for improving the integration perspective with other technologies. Subsequently, this metric was expanded from a seven-level scale to a nine-level scale. Sauser et al. [13] proposed a five-level SRL, which is a system-level technological maturity metric derived from a matrix using TRL and IRL metrics.

Mankins [11] introduced the R&D degree of difficulty (R&D3) as the difficulty level in maturing individual technologies, whereas Bilbro [14] proposed the advanced degree of difficulty (AD2), which is similar to R&D3. Olechowski et al. [15] analyzed the application of TRL in various industries worldwide and identified 15 improvement challenges in terms of system complexity, planning and review, and assessment feasibility. Tomaschek et al. [16] surveyed TRL practitioners from diverse industries globally and identified four high-priority improvement challenges: system complexity, technology integration representation, IF maturity, and system-level maturity.

Tompkins et al. [17] proposed an approach that employed a design structure matrix (DSM) to assess the SRL of complex systems. Additionally, they presented a framework for incorporating the current SRL calculation method into the DSM tool. Doukas [18] discussed the applications and opportunities for high-temperature superconducting transmission system links, summarized the major technical challenges to be overcome by the academic community, and used TRLs to assess the technical readiness of alternating current and direct current options.

Petrovic and Hossain [19] developed a fuel-cell technology readiness level (FCTRL) assessment tool for application to fuel-cell technologies. This method comprised seven levels of maturity, with three sublevels (i.e., questions) at each level. The FCTRL methodology was developed for experts, engineers, and professionals who need to evaluate fuel-cell technologies for integration into existing systems and applications, as well as for those with a general interest in fuel cells and renewable energy systems [19].

Jesus and Chagas Jr. [20] developed a methodology for applying IRLs using architectural views through a design structure and domain-mapping matrices. They also provided suggestions for holistic systems analysis and managerial communication applications using this method, and recommended a rationale for assessing the IRLs of legacy systems [20].

C. ENGINEERING ACTIVITIES OF MAJOR SYSTEMS: SYSTEM-INTEGRATION PERSPECTIVE

The weapons system of the ROK military has been developed based on SE. An SoS can be decomposed into the elements system, subsystem, components, and HW/SW, as illustrated in Fig. 1.

Integration within a complex system is realized through IF connections between these levels following a top-down approach. The integration targets and engineering activities in the R&D of the SE-based weapons system are illustrated in Fig. 2.

The left-hand side of the V-model represents a top-down perspective, where the requirements are analyzed, designed, and implemented. Requirements focusing on the key ROCs are established based on operational concepts. The well-defined requirements from the analysis phase are allocated to the HW/SW component design during the design phase. Developers implement HW and SW according to the requirements reflected in the design during the implementation phase. From a system-integration perspective, system-level requirements drive the identification and incorporation of internal and external interfaces into designs. The interfaces are developed according to the design during the implementation phase. The target of system integration is HW/SW components. The interfaces can be categorized as follows: HW-HW, HW-SW, and SW-SW.

The right-hand side of the V-model represents the bottom-up perspective, where the verification activities (system integration test, development, and operational test) progress through a unit test of the HW/SW components, followed by stepwise integration and verification (in the reverse order) up to the subsystem and system levels. The unit test ensures that the developed HW/SW components manufactured and implemented as designed, and the integration perspective focuses on the verification and validation of IFs through stepwise integration and verification processes to confirm the fulfillment of the requirements. From the system-integration perspective, the targets of integration are the HW and SW components, while the IFs serve as a means of integrating them. Therefore, in the context of TRA, the TE, CTE, and TRA need to be distinguished from the perspectives of HW, SW, and IF, and each should be evaluated accordingly.

D. IDENTIFICATION OF KEY ISSUES

The TRA adopted by the ROK military was institutionalized in 2006 and is currently a key decision-making tool in determining the domestic R&D of weapons systems [3]. However, several contentious issues remain unresolved. In this study, we identified two key issues in the CTE selection and TRLs/TRA.

First, the following issues may arise in the selection of a CTE. If a specific CTE is excessively prioritized, the concentration of resources required for important technologies will become dispersed. However, if the CTE is under-identified or overlooked, it may fail to meet the requirements, thereby hindering the success of the project [7]. The CTE selection method used in Korea consists of a checklist method that includes abstract terms, which introduces subjectivity and facilitates potential interventions. Therefore, the validity of CTEs is frequently debated in CTE selection meetings. To resolve this issue, the criteria for CTE selection should be clarified and the selection process should be broken down at the methodological level to minimize the subjective interpretations prevalent under the current checklist approach.

The proposed CTE selection method minimizes external evaluator interventions by considering the quantitative goals of the key required operational capabilities, development difficulties, and applications of COTS technologies.

At present, TEs and CTEs are not identified separately in terms of HW, SW, and IF technologies. To perform TRA from a system-integration perspective, the TEs and CTEs need to be distinguished from the perspectives of these technologies.

Second, from the perspective of the TRL/TRA, the nine-level TRL, which is used in almost all jurisdictions domestically and internationally, is only specialized for individual

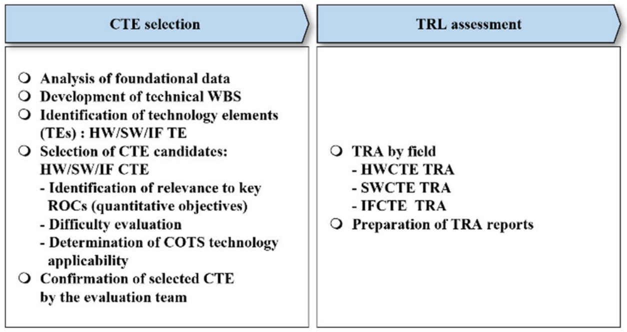

FIGURE 3. Proposed high-level technology readiness assessment (TRA) framework. CTE: critical technology element; TRL: technology readiness level; WBS: work breakdown structure; TE: technical element; ROC: required operational capability; COTS: commercial off-the-shelf; HWCTE: hardware CTE; SWCTE: software CTE; IFCTE: interface CTE.

technologies. As mentioned previously, it has several limitations [10]. Research on IRL and SRL has been conducted to address these limitations; however, the results have not been institutionalized yet. The IRL identifies the IF technologies between individual CTEs and evaluates the maturity of the IF technologies. From the SE system-integration perspective, this aspect must be reinforced and detailed procedures must be presented for defining the integration target, identifying the IF, and deriving the technology that is required for the IF.

An SRL quantifies the overall technological maturity of a system using a matrix that includes both the TRL and IRL. As the SRL is also based on HW-oriented TRL, it does not differentiate among HW, SW, and IF technologies. From the perspective of system integration, HW, SW, and IF TRLs must be segregated to perform their respective TRAs. The SRL is more useful and meaningful for comparing overall maturity between systems. However, because TRA is primarily focused on risk management using immature technologies, utilizing the lowest technological maturity among HW, SW, and IF CTEs for system-level maturity is more reasonable.

As mentioned previously, the contemporary TRA adopts a checklist approach that is prone to evaluator subjectivity and does not evaluate HW and SW separately. Clarification and refinement of the checklist items will be helpful steps. However, if each level can be delineated by distinguishing the output level and verification environment of each indicator, an intuitive evaluation can be performed using only the TRL indicators.

III. TRA FRAMEWORK FROM A SYSTEM-INTEGRATION PERSPECTIVE

A. OVERVIEW OF THE TRA FRAMEWORK

The proposed TRA framework is illustrated in Fig. 3. It consists of two stages: CTE selection and TRL evaluation (existing preliminary preparation activities have been excluded from the research scope).

In the CTE selection stage, candidate CTEs were identified from the results of basic data analysis, and an evaluation team

Items	Existing	Proposed
TRL index	❍ Using HW-oriented single TRL	❍ Application of HW/SW/IF TRLs from a system integration perspective
TE identification	❍ Intuitive identification of single-type TE at the component level of the technical WBS	❍ Identification based on the technical WBS in the following sequence: ① Identification of the HWTE and SWTE using the HW and SW configuration items ② Identification of the IFTE after identifying the interface among the HW and SW components
CTE selection	❍ Selection of single-type CTEs based on a checklist - Selection as CTE if one or more essential items and at least one optional item are obtained	❍ Process-oriented, system integration-centric CTE selection, as follows: ① Selection of key ROC (quantitative objectives)-related TEs as candidates for CTE (1st) ② Additional selection of CTE (1st) considering development difficulties associated with non-key ROC TEs ③ Among the CTE candidates (1st), the TE applicable to COTS technology is excluded as a CTE candidate
Performing TRA	❍ Performing TRA using HW-oriented TRL and checklist	❍ Performing TRA using HW/SW/IF TRLs ❍ Process enhancement to minimize evaluation ambiguities

FIGURE 4. Differences between proposed and existing frameworks.

comprising experts finalized the CTEs during meetings. The CTE selection process at a higher level is not significantly different from that at the regular level.

However, significant differences exist among the lower-level activities. The selection of CTEs was based on the results of TE identification, which involved identifying key technologies related to the ROC (quantitative targets), assessing technology difficulties, and considering applications of COTS technologies. Furthermore, from the perspective of system integration, the TE and CTE were identified separately in terms of HW, SW, and IF technologies. The TRA for the CTE was performed in each domain using the redefined TRLs from the perspectives of HW, SW, and IF.

Subsequently, a TRA report that documented the evaluation results for the HW, SW, and IF CTEs was prepared. System-level maturity was defined as the lowest technological maturity level from a risk-management perspective. Maturity plans for immature technologies were developed for CTEs that did not meet the criteria for key milestones in the current acquisition phase.

The differences between the proposed and existing approaches are depicted in Fig. 4.

B. SELECTION OF CTEs

The detailed process of CTE selection is illustrated in Fig. 5.

First, a technical WBS was developed based on an analysis of foundational data. Then, the technical WBS was structured into system–subsystem–component–HW/SW items. The HWTE and SWTE required for each structured HW/SW configuration item were identified and the HWTE and SWTE were defined. Then, the IF between the HW/SW configuration items of the components was identified through an operational concept analysis. Thereafter, the definition for the IFTE, which is the technology required to implement the identified IF, was written. Based on the analysis of quantitative metrics related to the key quantitative objective criteria (ROCs), CTE candidates (first round) were selected for the identified HW/SW/IF TE.

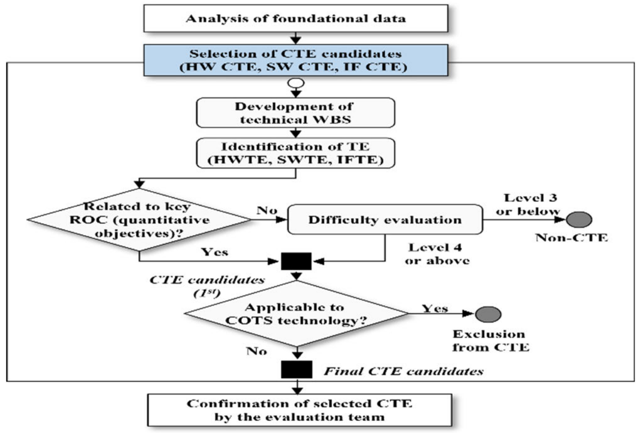

FIGURE 5. Procedure for CTE selection.

Difficulty	Definition of difficulty level
1	Existing technologies
2	Existing technology that needs partial modifications
3	New technology that can be developed sufficiently by utilizing existing technologies
4	New technology that only slightly resembles existing technologies, raising the need for new developments
5	Entirely new technology that does not resemble existing technologies

FIGURE 6. Different difficulty levels in technology development.

The key ROC quantitative metrics were performance criteria that need to be satisfied; they impact the scheduling and cost most significantly. The approach to determining the relevance between key ROC quantitative metrics and TEs was similar to that of allocating requirements to the HW/SW components in SE-based R&D. Technical difficulty assessment (TDA) was conducted for TEs that did not correspond to key ROCs, and TEs with difficulty levels of four or higher were added to the pool of CTE candidates (first round). Metrics were used for different levels of the TDA, which are shown in Fig. 6.

The TDA metrics were redefined versions of the AD2 metrics proposed by Bilbro [14]. The higher the level of unfamiliarity with a new technology, the higher the difficulty level. Technologies with high difficulty levels pose higher risks, thereby significantly impacting the performance, cost, and schedule of a project.

Finally, technologies that could be obtained through COTS were excluded from the list of CTE candidates (first round), and the final CTE was selected. Applying COTS technologies not only aligns with domestic acquisition policies, but

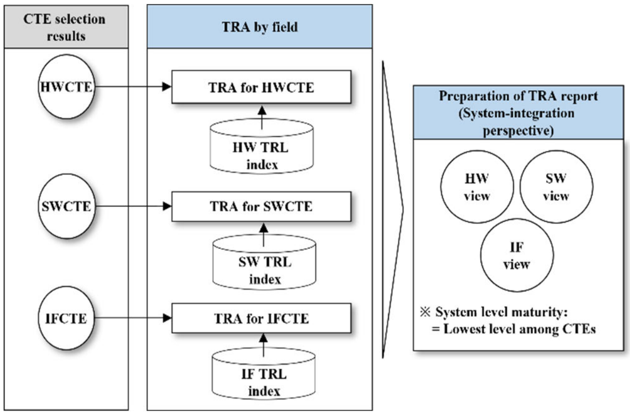

FIGURE 7. Procedure for TRA.

HW TRL	Definition	Validation environment	HW output
1	Understanding the basic principles	Paper	-
2	Formulation of technological concept	Paper	-
3	Proof of concept	Laboratory	-
4	Technology demonstration	Laboratory	Breadboard (low fidelity)
5	Test-level HW demonstration	Laboratory	Brassboard (medium fidelity)
6	Prototype-HW demonstration	Similar operating environment	Prototype (high fidelity)
7	Integration and verification of the HW in the subsystem facility	Similar operating environment	Level of integration into subsystems
8	Integration into the system and validated HW	Operational environment	Level of integration into the target system
9	Proven operations	Operational environment	Level of integration into the target system

FIGURE 8. HWTRLs.

also reduces the risks associated with a project by utilizing validated technologies.

The selected CTE was categorized as a hardware CTE (HWCTE), a software CTE (SWCTE), or an interface CTE (IFCTE).

C. ASSESSMENT OF TRLs

Evaluation of the TRL of the final CTE was performed based on the redefined hardware TRL (HWTRL), software TRL (SWTRL), and interface TRL (IFTRL) metrics, as illustrated in Fig. 7. Each TRL was redefined based on existing research and guidelines.

1) HWTRL

The HWTRL is a metric that evaluates the technological maturity of the HW. It was redefined based on the current nine-level TRL (Fig. 8) [4], [5], [6], [7].

Levels 1–3 and 9 remained unchanged. Levels 4 and 5 were defined based on the HW output levels and categorized as breadboard (low fidelity), brassboard (medium fidelity), and prototype (high fidelity).

SW TRL	Definition	Validation environment	SW output
1	Understanding the basic principles	Paper	-
2	Basic principle coding	Paper, laboratory	Basic principle source code
3	SW component development	Laboratory	SW components
4	SW component integration	Laboratory	SW components
5	Prototype SW demonstration	Laboratory or similar operating environment	Prototype SW
6	Completion of the beta version SW	Similar operating environment	Beta version SW
7	Integration and verification of the SW in the test bed	Similar operating environment	Level of integration into the test bed
8	Integration into the system and validated SW	Operational environment	Level of integration into the target system
9	Proven operations	Operational environment	Level of integration into the target system

FIGURE 9. SWTRLs.

Level 6 represents the level of a completed prototype, level 7 indicates the integration and verification of the HW product at the subsystem level, and level 8 defines the completion of physical system integration at the system level with the completion of testing and evaluation.

2) SWTRL

The SWTRL is an indicator that is used to assess the technological maturity of SW. It was redefined as described in Fig. 9 [21], [22], [23].

Levels 1, 8, and 9 were redefined in terms of SW, as the levels in HWTRL have been in terms of HW. Level 2 represented the stage in which basic principles were coded, level 3 represented the development of the components, level 4 represented the integration of the components, level 5 involved the demonstration of a prototype, and level 6 signified the completion of the beta version with subsequent version management. At level 7, the SW functionality was integrated into a testbed and verified in a similar operating environment.

3) IFTRL

The IFTRL is a metric that is used to assess the maturity of IF technologies. It was redefined as depicted in Fig. 10 [7], [13].

Level 1 corresponded to the identification and definition of IF points based on operational concepts, whereas level 2 was the level at which the IF interactions were defined. Level 3 involved the completion of IF diagrams, including IF points, input/output relationships, and data.

Level 4 represented the detailed design level at which both the data communication and IF verification and management structures were established. Level 5 was the level at which the IF technology was demonstrated and level 6 was the level at which the prototype was demonstrated.

IF TRL	Definition	Validation environment	IF output
1	Interface identification	Paper	-
2	Interface interaction definition	Paper	-
3	Preliminary interface design	Paper	-
4	Detailed interface design	Paper	-
5	Interface technology demonstration	Laboratory	Simulation SW
6	Interface prototype demonstration	Similar operating environment	IF prototype
7	Integration and validation of the IF in the test bed	Similar operating environment	Level of integration into the test bed
8	Integration into the system and validated IF	Operational environment	Level of integration into the target system
9	Proven operations	Operational environment	Level of integration into the target system

FIGURE 10. IFTRLs.

Levels 7–9 represented subsystem integration and validation, completion of system-level IF development, and mission accomplishment, respectively.

The TRL evaluation team used the redefined HW/SW/IF TRLs to perform a TRA on the final selected CTE and report the results.

IV. CASE STUDY

A case study was conducted on three SoS using the proposed TRA framework. A technical WBS was developed, and CTE identification and TRA evaluation were performed using this framework.

The results of the case study of the target surveillance system (TSS) are presented in this section. The case study outcomes for the airfield damage assessment and recovery management system (ADARMS) and naval tactical data system (NTDS) are presented in the appendix.

A. OVERVIEW OF TSS

The TSS is a system that supports the rapid assessment and analysis of enemy movements using electro-optical/infrared (EO/IR) imagery.

It collects near real-time data from installed EO and IR sensors and promptly transmits them to the personnel overseeing the designated area.

Notably, the collected EO imagery supports automatic target detection based on artificial intelligence (AI). The system displays the collected EO and IR images on a digital map and provides the personnel with the capability to analyze them.

The key quantitative objective is to achieve a 5-s (assumption) timeframe for EO imagery collection and updates. The process diagram of the TSS in the case study is presented in Fig. 11.

The processes related to the key quantitative objectives involved target detection from EO sensors, data processing and manipulation, and displaying the targets on a map for user interpretation, each of which is marked separately.

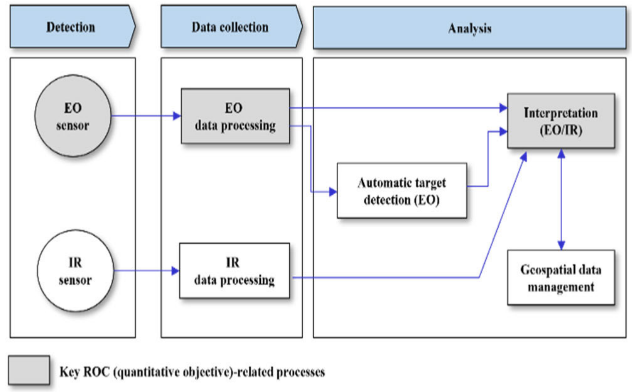

FIGURE 11. Processes in the working of the TSS.

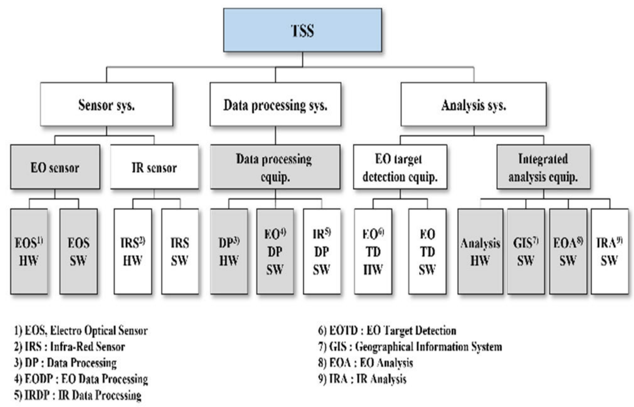

FIGURE 12. Technical WBS for TSS.

B. CONSTRUCTION OF TECHNICAL WBS AND DERIVATION OF TEs

The technical WBS for the TSS is depicted in Fig. 12.

In this study, the TSS was structured into sensor, data processing, and analysis systems. Each subsystem was further divided into components and HW/SW.

To derive the TE, the HWTE and SWTE required for developing the HW and SW items based on the technical WBS were identified.

Fifteen HWTEs/SWTEs, including the EO detector fabrication technology, were identified. Overall, the TEs included three EO sensors, three IR sensors, three pieces of data-processing equipment, two pieces of data target-detection equipment, and four pieces of integrated analysis equipment.

According to the system operational concept, we identified components (gray area) that are related to the key ROC quantitative objectives.

The obtained results are presented in the TE definition document in Fig. 13.

To identify the IFTE, the requirements were analyzed and the interrelationships between TSS components were

TBS		TE		
Level 2	Level 3	TE ID	Technology name	Technology definition
Sensor sys.	EO sensor	HWTE 1	EO detector	High-resolution EO detector fabrication technology
		HWTE 2	EO optical system	High-resolution EO optical system fabrication technology
		SWTE 1	EO image processing firmware	EO image processing firmware technology
	IR sensor	HWTE 3	IR detector	High-resolution IR detector fabrication technology
		HWTE 4	IR optical system	High-resolution IR optical system fabrication technology
		SWTE 2	IR image processing firmware	IR image processing firmware technology
Data processing sys.	Data processing equip.	HWTE 5	CPU-based hardware production	High-performance CPU-based hardware production technology
		SWTE 3	EO image collection	EO metadata and image processing technology
		SWTE 4	IR image collection	IR metadata and image processing technology
Analysis sys.	EO target detection equip.	HWTE 6	GPU-based hardware	High-performance GPU-based hardware production technology
		SWTE 5	AI-based image processing	AI-based automatic target detection technology
	Integrated analysis equip.	HWTE 7	CPU-based parallel processing	High-performance CPU-based parallel processing technology
		SWTE 6	GIS technology	Location-based image mapping technology
		SWTE 7	EO image analysis	EO image analysis and editing technology
		SWTE 8	IR image analysis	IR image analysis and editing technology

FIGURE 13. Definitions of HWTEs/SWTEs.

Technical WBS		EO sensor		IR sensor		Data processing equip.			EO target detection equip.		Integrated analysis equip.			
Level 3	Level 4	EOS HW	EOS SW	IRS HW	IRS SW	DP HW	EODP SW	IRDP SW	EOTD HW	EOTD SW	Anaysis HW	GIS SW	EOA SW	IRA SW
EO sensor	EOS HW		IFTE 1			IFTE 2								
	EOS SW	IFTE 1					IFTE 3							
IR sensor	IRS HW				IFTE 4	IFTE 5								
	IRS SW			IFTE 4				IFTE 6						
Data processing equip.	DP HW	IFTE 2		IFTE 5			IFTE 7	IFTE 8	IFTE 9		IFTE 11			
	EODP SW		IFTE 3			IFTE 7				IFTE 10			IFTE 12	
	IRDP SW				IFTE 6	IFTE 8								IFTE 13
EO target detection equip.	EOTD HW					IFTE 9				IFTE 14	IFTE 15			
	EOTD SW						IFTE 10		IFTE 14				IFTE 16	
Integrated analysis equip.	Analysis HW					IFTE 11			IFTE 15			IFTE 17	IFTE 18	IFTE 19
	GIS SW										IFTE 17			
	EDA SW									IFTE 16	IFTE 18			
	IRA SW							IFTE 13			IFTE 19			

FIGURE 14. Identification results of IFTEs.

determined to identify the interfaces between each HW and SW item, as shown in Fig. 14. Overall, 19 IFTEs were identified as TSS components.

The identified IFTEs were documented and managed using the IFTE definition document for each IF segment, as shown in Fig. 15.

The segments needed to be non-overlapping and the IF specifications needed to be documented according to the type of IF: HW-HW IF, HW-SW IF, and SW-SW IF.

C. SELECTION OF CTEs IN TSS

The HWTEs, SWTEs, and IFTEs that were identified in the previous step were considered as candidates for CTE selection.

Following the improved TRA framework, the TEs related to the primary ROC quantitative objectives were first identified. A process diagram was generated based on the system's operational concept and the core processes related to the key ROC quantitative objectives were identified. Using the

Interface section		IFTE	
		TE ID	Technology definition
EO sensor	EO sensor	IFTE 1	EO data bus technology
	Data processing equip.	IFTE 2	Gigabit optical communication technology (EO)
		IFTE 3	EO MTF technology
IR sensor	IR sensor	IFTE 4	IR data bus technology
	Data processing equip.	IFTE 5	Optical communication technology (IR)
		IFTE 6	IR MTF (Message Text Format) technology
Data processing equip.	Data processing equip.	IFTE 7	DP-EO API (Application Programming Interface) technology
		IFTE 8	DP-IR API technology
	EO target detection equip.	IFTE 9	Gigabit optical communication technology (EO/IR)
		IFTE 10	EODP-EOTD API technology
DP HW	Analysis HW	IFTE 11	Gigabit optical communication technology (EO/IR)
EODP SW	EOA SW	IFTE 12	Rest API (EODP-EDA)
IRDP SW	IRA SW	IFTE 13	Rest API (IRDP-IRA)
EOTD HW	EOTD SW	IFTE 14	Web-based middleware technology
	Analysis HW	IFTE 15	Gigabit optical communication technology (EO)
EOTD SW	EOA SW	IFTE 16	Rest API (EOTD-EDA)
Analysis HW	GIS SW	IFTE 17	GIS API
	EOA SW	IFTE 18	IAE-EDA API
	IRA SW	IFTE 19	IAE-IRA API

FIGURE 15. Definitions of IFTEs. MTF: message text format; API: application programming interface; DP–EO: data processing-electro optical; DP–IR: data processing–infrared; EODP–EOTD: electro-optical data processing–electro-optical target detection.

Identification results related to the key ROCs (Quantitative objective)			Difficulty level	Application of COTS
TE ID	Technology definition	Key ROC related items		
HWTE 1	High-resolution EO detector fabrication technology	●	N/A	●
HWTE 2	High-resolution EO optical system fabrication technology	●	N/A	×
HWTE 3	High-resolution IR detector fabrication technology	×	4	●
HWTE 5	High-performance CPU-based hardware production technology	●	N/A	●
HWTE 6	High-performance GPU-based hardware production technology	×	5	●
HWTE 7	High-performance CPU-based parallel processing technology	●	N/A	●
SWTE 1	EO image processing firmware technology	●	N/A	×
SWTE 3	EO metadata and image processing technology	●	N/A	×
SWTE 5	AI-based automatic target detection technology	×	4	×
SWTE 6	Location-based image mapping technology	●	N/A	×
SWTE 7	EO image analysis and editing technology	●	N/A	×
IFTE 1	EO data bus technology	●	N/A	●
IFTE 2	Gigabit optical communication technology (EO)	●	N/A	●
IFTE 3	EO MTF technology	●	N/A	×
IFTE 4	IR data bus technology	×	4	●
IFTE 7	DP-EO API (Application Programming Interface) technology	●	N/A	×
IFTE 11	Gigabit optical communication technology (EO/IR)	●	N/A	●
IFTE 12	Rest API (EODP-EDA)	●	N/A	●
IFTE 17	GIS API	●	N/A	●
IFTE 18	IAE-EDA API	●	N/A	×

FIGURE 16. Filtered results for CTE selection.

TABLE 1. Technical work breakdown structure (WBS) for airfield damage assessment and recovery management system (ADARMS).

Level 1	Level 2	Level 3	Level 4	Key ROC allocation
ADARMS	Damage information collection system	UAV platform	AP HW	
			AV HW	
			FC SW	
			NV SW	
			PS HW	
			CM HW	●
			CM SW	●
		Payload equipment	EO HW	●
			EO SW	●
			IR HW	
			IR SW	●
		Ground control equipment	DL HW	●
			DL SW	●
			GC HW	
			GC SW	
	Damage assessment system	Image processing equipment	IP HW	●
			GW SW	●
			2D_EO IP SW	●
			2D_IR IP SW	●
			3D_IP SW	
		Damage assessment equipment	DA HW	●
			DA SW	●
			MS SW	
	Damage recovery management system	DRM equipment	DRM HW	
			DRM SW	

AP: Airframe and propulsion system; AV: Avionics; FC: Flight control; NV: Navigation; PS: Platform sensor; CM: Communication; EO: Electro-optical; IR: Infrared; DL: Data link; GC: Ground control; IP: Image processing; GW: Gateway; DA: Damage assessment; MS: Minimum operate stripe selection; DRM: Damage recovery management.

CTE			Results of TRA
CTE ID	Name	TRL	Reference
HWCTE 1	High-resolution EO optical system fabrication technology	6	EOTS project for ships (experience in EO optical system design and prototype production)
SWCTE 1	EO image processing firmware technology	6	EOTS project for ships (experience in EO optical system design and prototype production)
SWCTE 2	EO metadata and image processing technology	6	EOTS project for ships (experience in EO optical system design and prototype production)
SWCTE 3	AI-based automatic target detection technology	5	Critical technology research and development project of automatic target detection using EO images
SWCTE 4	Location-based image mapping technology	7	O-class UAV project (experience in image mapping technology)
SWCTE 5	EO image analysis and editing technology	7	O-class UAV project (experience in image analysis and editing technology)
IFCTE 1	EO MTF technology	8	M-project (experience in processing EO images with MTF)
IFCTE 2	DP-EO API technology	7	O-class UAV project (experience in image analysis and editing technology)
IFCTE 3	IAE-EOA API technology	7	O-class UAV project (experience in image analysis and editing technology)

FIGURE 17. Results of TRA. EOTS: electro-optical tracking system; UAV: unmanned aerial vehicle; IAE–EOA: integrated analysis equipment–electro-optical analysis.

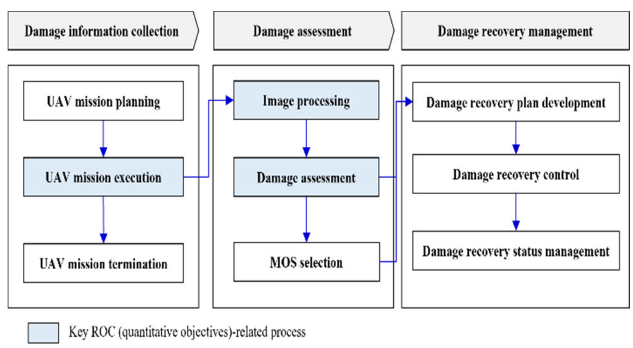

FIGURE 18. Processes in the working of a ADARMS.

WBS, we identified the HW and SW configuration items relevant to these core processes. The identified items and the corresponding mapped TEs represent TEs related to the key ROC quantitative objectives. Additionally, by utilizing the interface matrix, we identified the interrelationships associated with the core processes. These TEs included HWTEs (four items), SWTEs (four items), and IFTEs (eight items).

Thereafter, a difficulty evaluation was conducted among the TEs that were unrelated to the primary ROC quantitative objectives. Four TEs, including high-resolution IR detector fabrication technology, with difficulty levels of four or higher were identified.

Finally, 11 technologies that could be obtained through COTS technologies, such as high-performance CPU-based HW production technology, were excluded from the list of CTEs.

TABLE 2. Definitions of ADARMS HWTEs and SWTEs.

TBS		TE		
Level 2	**Level 3**	**TE ID**	**Technology name**	**Technology definition**
Damage information collection system	UAV platform	HWTE 1	Airframe and propulsion HW	Airframe and propulsion system design and manufacturing technology (fuselage, wings, rotors, etc.)
		HWTE 2	Avionics HW	Avionics HW design and manufacturing technology
		SWTE 1	Flight control SW	Flight control SW technology
		SWTE 2	Navigation SW	Navigation SW technology
		HWTE 3	Platform sensors	Platform sensor design and integration technology (GPS, IMU, altitude sensor, etc.)
		HWTE 4	Communication HW	Communication HW technology (data link, bus, etc.)
		SWTE 3	Communication SW	Communication SW technology
	Payload equipment	HWTE 5	EO camera	EO camera design and integration technology
		SWTE 4	EO image processing SW	EO image processing SW technology
		HWTE 6	IR camera	IR camera design and integration technology
		SWTE 5	IR image processing SW	IR image processing SW technology
	Ground control equipment	HWTE 7	Data link HW (GCS)	Communication module design and manufacturing technology
		SWTE 6	Data link SW (GCS)	Data link SW technology
		HWTE 8	Remote control HW	Remote control HW technology for GCS
		SWTE 7	Mission planning SW	Mission planning SW technology
		SWTE 8	Diagnostics and monitoring SW	UAV diagnostics and monitoring SW technology
Damage assessment system	Image processing equipment	HWTE 9	IP HW	High-performance GPU-based HW production technology
		SWTE 9	Gateway SW	Gateway SW technology
		SWTE 10	2D_EO IP SW (SYS)	2D EO image processing SW technology (image mapping, etc.)
		SWTE 11	2D_IR IP SW	2D IR image processing SW technology (image mapping, etc.)
		SWTE 12	3D_IP SW	3D IR image processing SW technology (DSM, point cloud, etc.)
	Damage assessment equipment	HWTE 10	DA HW	High-performance CPU-based HW production technology
		SWTE 13	Damage detection	AI-based damage detection SW technology
		SWTE 14	Damage recognition	AI-based damage recognition SW technology
		SWTE 15	Calculate damage scale	Automatic damage calculation SW technology
		SWTE 16	MOS selection SW	Automatic MOS candidate recommendation SW technology
Damage recovery management system	Damage recovery management equipment	HWTE 11	DRM HW	High-performance CPU-based HW production technology
		SWTE 17	Resource management SW	Resource management SW technology
		SWTE 18	Decision support SW	Decision support SW technology
		SWTE 19	Communication and coordination SW	Real-time communication and coordination SW technology
		SWTE 20	Situation monitoring SW	Situation monitoring SW technology (GIS integration)

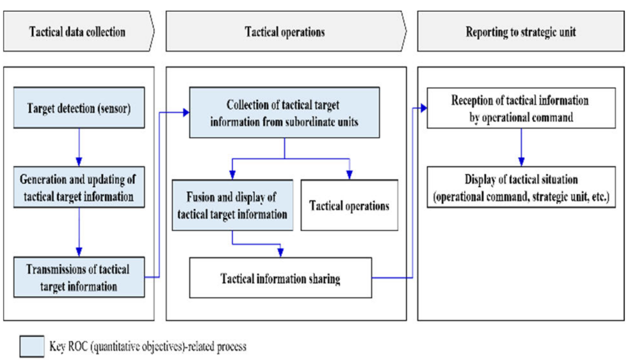

FIGURE 19. Processes in the working of a NTDS.

The filtered results for the CTEs based on the identified TEs are summarized in Fig. 16. Finally, nine CTEs were selected, including the high-resolution EO optical system fabrication technology.

D. ASSESSMENT OF TRLS FOR TSS

The TRA was performed based on the redefined HWTRL, SWTRL, and IFTRL in the improved TRA framework. The results are presented in Fig. 17. The system-level TRL of the TSS was 5.

V. CONCLUSION

This study has proposed a framework that solves the limitations of TRA from an SE perspective. Although maximizing the utilization of the existing research results was one of the objectives, the focus was on methodological improvements.

TABLE 3. Identification Results of ADARMS IFTEs.

TBS		UAV platform							Payload equipment				Ground control equipment			
Level 3	**Level 4**	**AP HW**	**AV HW**	**FC SW**	**NV SW**	**PS HW**	**CM HW**	**CM SW**	**EO HW**	**EO SW**	**IR HW**	**IR SW**	**DL HW**	**DL SW**	**GC HW**	**GC SW**
UAV platform	AP HW		IFTE 1													
	AV HW	IFTE 1		IFTE 2	IFTE 3		IFTE 4									
	FC SW		IFTE 2		IFTE 5			IFTE 6								
	NV SW		IFTE 3	IFTE 5				IFTE 7								
	PS HW						IFTE 8									
	CM HW		IFTE 4			IFTE 8		IFTE 9	IFTE 10		IFTE 11		IFTE 12			
	CM SW			IFTE 6	IFTE 7		IFTE 9			IFTE 13		IFTE 14		IFTE 15		
Payload equipment	EO HW						IFTE 10			IFTE 14						
	EO SW							IFTE 13	IFTE 14							
	IR HW						IFTE 11					IFTE 16				
	IR SW							IFTE 14			IFTE 16					
Ground control equipment	DL HW						IFTE 12							IFTE 17	IFTE 18	
	DL SW							IFTE 15					IFTE 17			IFTE 20
	GC HW												IFTE 18			IFTE 22
	GC SW													IFTE 20	IFTE 22	
Image processing equipment	IP HW												IFTE 19			
	GW SW													IFTE 21		
	2D_EO IP SW															
	2D_IR IP SW															
	3D_IP SW															
Damage assessment equipment	DA HW															
	DA SW															
	MS SW															
Damage recovery management equipment	DRM HW															
	DRM SW															

TBS		Image processing equipment					Damage assessment equipment			Damage recovery management equipment	
Level 3	**Level4**	IP HW	GW SW	2D_EO IP SW	2D_IR IP SW	3D_IP SW	DA HW	DA SW	MS SW	DRM HW	DRM SW
UAV platform	AP HW										
	AV HW										
	FC SW										
	NV SW										
	PS HW										
	CM HW										
	CM SW										
Payload equipment	EO HW										
	EO SW										
	IR HW										
	IR SW										
Ground control equipment	DL HW	IFTE 19									
	DL SW		IFTE 21								
	GC HW										
	GC SW										
Image processing equipment	IP HW		IFTE 23	IFTE 24	IFTE 25	IFTE 26	IFTE 27			IFTE 28	
	GW SW	IFTE 23		IFTE 29	IFTE 30	IFTE 31		IFTE 32	IFTE 33		IFTE 34
	2D_EO IP SW	IFTE 24	IFTE 29								
	2D_IR IP SW	IFTE 25	IFTE 30								
	3D_IP SW	IFTE 26	IFTE 31								
	DA HW	IFTE 27						IFTE 35	IFTE 36	IFTE 37	

TABLE 3. *(Continued.)* **Identification Results of ADARMS IFTEs.**

TBS		Image processing equipment					Damage assessment equipment			Damage recovery management equipment	
Level 3	Level4	IP HW	GW SW	2D_EO IP SW	2D_IR IP SW	3D_IP SW	DA HW	DA SW	MS SW	DRM HW	DRM SW
Damage assessment equipment	DA SW		IFTE 32				IFTE 35		IFTE 38		
	MS SW		IFTE 33				IFTE 36	IFTE 38			
Damage recovery management equipment	DRM HW	IFTE 28					IFTE 37				IFTE 39
	DRM SW		IFTE 34							IFTE 39	

TABLE 4. **Definitions of ADARM IFTEs.**

Interface section (TBS level 4)		IFTE	
		TE ID	Technology definition
AP HW	AV HW	IFTE 1	Control system design and integration technology
AV HW	FC SW	IFTE 2	FC data bus technology
	NV SW	IFTE 3	NV data bus technology
	CM HW	IFTE 4	AV-CM standard interface technology
FC SW	NV SW	IFTE 5	FC-NV API technology
	CM SW	IFTE 6	FC-CM API technology
NV SW	CM SW	IFTE 7	NV-CM API technology
PS HW	CM HW	IFTE 8	PS-CM standard interface technology
CM HW	CM SW	IFTE 9	Communication firmware technology
	EO HW	IFTE 10	CM-EO standard interface technology
	IR HW	IFTE 11	CM-IR standard interface technology
	DL HW	IFTE 12	Standard data link construction technology
CM SW	EO SW	IFTE 13	CM-EO API technology
	IR SW	IFTE 14	CM-IR API technology
	DL SW	IFTE 15	CM-DL API technology
IR HW	IR SW	IFTE 16	IR firmware technology
DL HW	DL SW	IFTE 17	DL standard firmware technology
	GC HW	IFTE 18	DL-GC standard interface technology
	IP HW	IFTE 19	Standard data link construction technology
DL SW	GC SW	IFTE 20	DL-GC API technology
	GW SW	IFTE 21	DL standard protocol technology
GC HW	GC SW	IFTE 22	GC firmware technology
IP HW	GW SW	IFTE 23	Web based middleware technology
	2D_EO IP SW	IFTE 24	Web based middleware technology
	2D_IR IP SW	IFTE 25	Web based middleware technology
	3D_IP SW	IFTE 26	Web based middleware technology
	DA HW	IFTE 27	Gigabit optical communication technology
	DRM HW	IFTE 28	Gigabit optical communication technology
GW SW	2D_EO IP SW	IFTE 29	Rest API technology
	2D_IR IP SW	IFTE 30	Rest API technology
	3D_IP SW	IFTE 31	Rest API technology
	DA SW	IFTE 32	Rest API technology
	MS SW	IFTE 33	Rest API technology
	DRM SW	IFTE 34	Rest API technology
DA HW	DA SW	IFTE 35	Web-based middleware technology
	MS SW	IFTE 36	Web-based middleware technology
	DRM HW	IFTE 37	Gigabit optical communication technology
DA SW	MS SW	IFTE 38	API and DBMS technology
DRM HW	DRM SW	IFTE 39	Web-based middleware technology

The proposed framework provides detailed procedures and deliverables for system-integration-oriented TRA.

The effectiveness of this framework was confirmed through a case study using three SoS (TSS, ADARMS, and NTDS). Experts with experience in SE-based defense R&D can easily understand and apply this framework. It enables systematic and comprehensive identification of TEs as it first determines the HWTEs and SWTEs from the technical WBS and then the IFTEs through the IF relationships of the system components.

TABLE 5. Key ROC quantitative objective-related HWTEs/SWTEs.

TBS		TE		Key ROC-related items
Level 2	Level 3	TE ID	Technology definition	
Damage information collection system	UAV platform	HWTE 1	Airframe and propulsion system design and manufacturing technology (fuselage, wings, rotors, etc.)	×
		HWTE 2	Avionics HW design and manufacturing technology	×
		SWTE 1	Flight control SW technology	×
		SWTE 2	Navigation SW technology	×
		HWTE 3	Platform sensor design and integration technology (GPS, IMU, altitude sensor, etc.)	×
		HWTE 4	Communication HW technology (data link, bus, etc.)	●
		SWTE 3	Communication SW technology	●
	Payload equipment	HWTE 5	EO camera design and integration technology	●
		SWTE 4	EO image processing SW technology	●
		HWTE 6	IR camera design and integration technology	●
		SWTE 5	IR image processing SW technology	●
	Ground control equipment	HWTE 7	Communication module design and manufacturing technology	●
		SWTE 6	Data link SW technology	●
		HWTE 8	Remote control HW technology for GCS	×
		SWTE 7	Mission planning SW technology	×
		SWTE 8	UAV diagnostics and monitoring SW technology	×
Damage assessment system	Image processing equipment	HWTE 9	High-performance GPU-based HW production technology	●
		SWTE 9	Gateway SW technology	●
		SWTE 10	2D EO image processing SW technology (2D EO mapping, etc.)	●
		SWTE 11	2D IR image processing SW technology (2D IR mapping, etc.)	●
		SWTE 12	3D IR image processing SW technology (DSM, point cloud, etc.)	×
	Damage assessment equipment	HWTE10	High-performance CPU-based HW production technology	●
		SWTE 13	AI-based damage detection SW technology	●
		SWTE 14	AI-based damage recognition SW technology	●
		SWTE 15	Automatic damage calculation SW technology	×
		SWTE 16	Automatic MOS candidate recommendation SW technology	×
Damage recovery management system	Damage recovery management equipment	HWTE 11	High-performance CPU-based HW production technology	×
		SWTE 17	Resource management SW technology	×
		SWTE 18	Decision support SW technology	×
		SWTE 19	Real time communication and coordination SW technology	×
		SWTE 20	Situation monitoring SW technology (GIS integration)	×

In terms of CTE selection, the intuitive process of identifying TEs relating to the key ROC quantitative objectives is highly practical. These elements can be easily identified by analyzing the data flow according to operational concepts and assigning key ROC quantitative objectives to the system components. Furthermore, the clear differences between levels make it easier to assess the technical difficulty. The decision regarding the application of COTS technology can

TABLE 6. Key ROC quantitative objective-related IFTEs.

Interface section (TBS level 4)		IFTE		Key ROC-related items
		TE ID	Technology definition	
AP HW	AV HW	IFTE 1	Control system design and integration technology	×
AV HW	FC SW	IFTE 2	FC data bus technology	×
	NV SW	IFTE 3	NV data bus technology	×
	CM HW	IFTE 4	AV-CM Standard interface technology	×
FC SW	NV SW	IFTE 5	FC-NV API technology	×
	CM SW	IFTE 6	FC-CM API technology	×
NV SW	CM SW	IFTE 7	NV-CM API technology	×
PS HW	CM HW	IFTE 8	PS-CM Standard interface technology	×
CM HW	CM SW	IFTE 9	Communication firmware technology	●
	EO HW	IFTE 10	CM-EO Standard interface technology	●
	IR HW	IFTE 11	CM-IR Standard interface technology	●
	DL HW	IFTE 12	CM-DL Standard interface technology	●
CM SW	EO SW	IFTE 13	CM-EO API technology	●
	IR SW	IFTE 14	CM-IR API technology	●
	DL SW	IFTE 15	CM-DL API technology	●
IR HW	IR SW	IFTE 16	IR firmware technology	●
DL HW	DL SW	IFTE 17	DL standard firmware technology	●
	GC HW	IFTE 18	DL-GC standard interface technology	×
	IP HW	IFTE 19	Standard data link construction technology	●
DL SW	GC SW	IFTE 20	DL-GC API technology	
	GW SW	IFTE 21	DL standard protocol technology	●
GC HW	GC SW	IFTE 22	GC firmware technology	
IP HW	GW SW	IFTE 23	Web-based middleware technology	●
	2D_EO IP SW	IFTE 24	Web-based middleware technology	●
	2D_IR IP SW	IFTE 25	Web-based middleware technology	●
	3D_IP SW	IFTE 26	Web-based middleware technology	×
	DA HW	IFTE 27	Gigabit optical communication technology	×
	DRM HW	IFTE 28	Gigabit optical communication technology	×
GW SW	2D_EO IP SW	IFTE 29	Rest API technology	×
	2D_IR IP SW	IFTE 30	Rest API technology	×
	3D_IP SW	IFTE 31	Rest API technology	×
	DA SW	IFTE 32	Rest API technology	×
	MS SW	IFTE 33	Rest API technology	×
	DRM SW	IFTE 34	Rest API technology	×
DA HW	DA SW	IFTE 35	Web-based middleware technology	×
	MS SW	IFTE 36	Web-based middleware technology	×
	DRM HW	IFTE 37	Gigabit optical communication technology	×
DA SW	MS SW	IFTE 38	API & DBMS technology	×
DRM HW	DRM SW	IFTE 39	Web-based middleware technology	×

be easily determined by confirming the evidence for its sale and operation. Applying COTS technology not only reduces the cost of acquiring weapon systems but is also advantageous in terms of future system expandability and maintenance.

The proposed framework adopts the system-integration perspective for the evaluation and examined the TRA targets from the HW, SW, and IF perspectives. The implementation of TRLs that are redefined from these three perspectives does not pose significant difficulties in practical applications compared with the conventional approach.

The redefinition of the TRL in terms of HW, SW, and IF along with the provision of output formats as supplementary indicators of the TRL help to determine the maturity level of the corresponding technologies in the TRL.

Overall, the TRL is a useful communication tool for technological maturity. Technology evaluation is ultimately performed by experts; therefore, if the TRL is straightforward and the boundaries of each stage are clear, TRA will become significantly more seamless and intuitive, thereby minimizing potential disagreements regarding the results. This study should contribute to future research on the evaluation criteria and procedures for TRA from a system-integration perspective.

In the future, we aim to enhance the completeness of the proposed framework by incorporating diverse perspectives from relevant experts on the methodological level. Our subsequent goal is to institutionalize this framework within the ROK military weapons system-acquisition process. This will involve developing a software tool that allows TRA evaluators to conduct assessments easily and intuitively and manage the results. Thus, we would streamline the integration of the framework into defense-acquisition procedures. This

TABLE 7. Difficulty evaluation results for HWTEs and SWTEs.

TBS		TE		Key ROC-related items	Difficulty level	Reference project
Level 2	Level 3	TE ID	Technology definition			
Damage information collection system	UAV platform	HWTE 1	Airframe and propulsion system design and manufacturing technology (fuselage, wings, rotors, etc.)	×	2	H-UAV, M-UAV project
		HWTE 2	Avionics HW design and manufacturing technology	×	2	H-UAV, M-UAV project
		SWTE 1	Flight control SW technology	×	2	H-UAV, M-UAV project
		SWTE 2	Navigation SW technology	×	2	H-UAV, M-UAV project
		HWTE 3	Platform sensor design and integration technology (GPS, IMU, altitude sensor, etc.)	×	2	H-UAV, M-UAV project
	Ground control equipment	HWTE 8	Remote control HW technology for GCS	×	2	H-UAV, M-UAV project
		SWTE 7	Mission planning SW technology	×	2	H-UAV, M-UAV project
		SWTE 8	UAV diagnostics and monitoring SW technology	×	2	H-UAV, M-UAV project
Damage assessment system	Image processing equipment	SWTE 12	3D IR image processing SW technology (DSM, point cloud, etc.)	×	3	M-project, A-R&D project
	Damage assessment equipment	SWTE 15	Automatic damage calculation SW technology	×	4	A-R&D project
		SWTE 16	Automatic MOS candidate recommendation SW technology	×	4	A-R&D project
Damage recovery management system	Damage recovery management equipment	HWTE 11	High-performance CPU-based HW production technology	×	5	M-project
		SWTE 17	Resource management SW technology	×	3	A-C4I project
		SWTE 18	Decision support SW technology	×	3	A-C4I project
		SWTE 19	Real-time communication and coordination SW technology	×	2	A-C4I project
		SWTE 20	Situation monitoring SW technology (GIS integration)	×	2	A-C4I project

software tool will be designed to facilitate TRA execution, ensuring that the process aligns with the proposed framework. Moreover, it will enable effective results management, thereby improving the overall efficiency and effectiveness of the TRA process in terms of weapons-system acquisition.

APPENDIX
CASE STUDY RESULTS

The following case study was conducted to validate the effectiveness of the technology readiness assessment (TRA) framework for complex weapon systems from a systems-integration perspective. We selected systems that met the following two criteria as the subjects of the case study. First, the targeted systems should be a system of systems (SoS). They should not exist independently but should be a complex system (SoS) that interfaces to a higher-level command-and-control system such as the C4I system. Second, the research team must have a substantial understanding of the targeted systems as it has direct involvement in research and development (R&D), or system development projects related to those weapons systems. We ultimately selected the airfield damage assessment and recovery management system (ADARMS) and naval tactical data system (NTDS) as systems that met both criteria. Subsequently, we conducted the case study according to the proposed framework and present the results in this document. Through these case studies, we confirmed the practicability and substantial practical value of this framework. The case studies were focused on the core aspects of the system, excluding any information related to military security.

TABLE 8. Difficulty evaluation results for IFTEs.

Interface section (TBS level 4)		IFTE		Difficulty level	Reference project
		TE ID	Technology definition		
AP HW	AV HW	IFTE 1	Control system design and integration technology	2	H-UAV, M-UAV project
AV HW	FC SW	IFTE 2	FC data bus technology	2	H-UAV, M-UAV project
	NV SW	IFTE 3	NV data bus technology	2	H-UAV, M-UAV project
	CM HW	IFTE 4	AV-CM standard interface technology	2	H-UAV, M-UAV project
FC SW	NV SW	IFTE 5	FC-NV API technology	2	H-UAV, M-UAV project
	CM SW	IFTE 6	FC-CM API technology	2	H-UAV, M-UAV project
NV SW	CM SW	IFTE 7	NV-CM API technology	2	H-UAV, M-UAV project
PS HW	CM HW	IFTE 8	PS-CM standard interface technology	2	H-UAV, M-UAV project
DL HW	GC HW	IFTE 18	DL-GC standard interface technology	1	H-UAV, M-UAV project
DL SW	GC SW	IFTE 20	DL-GC API technology	2	H-UAV, M-UAV project
GC HW	GC SW	IFTE 22	GC firmware technology	2	H-UAV, M-UAV project
IP HW	3D_IP SW	IFTE 26	Web-based middleware technology	2	M-project, A-C4I project
	DA HW	IFTE 27	Gigabit optical communication technology	1	M-project, A-C4I project
	DRM HW	IFTE 28	Gigabit optical communication technology	1	M-project, A-C4I project
GW SW	2D_EO IP SW	IFTE 29	Rest API technology	2	M-project
	2D_IR IP SW	IFTE 30	Rest API technology	2	M-project
	3D_IP SW	IFTE 31	Rest API technology	2	M-project
	DA SW	IFTE 32	Rest API technology	2	M-project
	MS SW	IFTE 33	Rest API technology	2	M-project
	DRM SW	IFTE 34	Rest API technology	2	M-project
DA HW	DA SW	IFTE 35	Web-based middleware technology	2	M-project, A-C4I project
	MS SW	IFTE 36	Web-based middleware technology	2	M-project, A-C4I project
	DRM HW	IFTE 37	Gigabit optical communication technology	1	M-project, A-C4I project
DA SW	MS SW	IFTE 38	API and DBMS technology	2	M-project, A-C4I project
DRM HW	DRM SW	IFTE 39	Web-based middleware technology	2	M-project, A-C4I project

VI. ADARMS

A. OVERVIEW OF ADARMS

The ADARMS aims to ensure the continuity of aviation operations by providing a management system for rapid damage recovery in runways at airfields during both peacetime and wartime. The core operational concept of the system is illustrated in Fig. 18.

The damage assessment team operated unmanned aerial vehicles (UAVs) equipped with electro-optical/infrared (EO/IR) sensors to capture images of damage on a runway at an airfield. Subsequently, this imagery was transmitted to a central control center via a wireless communication network. The system utilized the EO/IR imagery collected via a wireless communication system to automatically classify the damage types and determine the locations and extent of damage. The commander utilized the damage analysis results to review the minimum operate stripe (MOS) recommended by the system and ultimately selected the MOS. Subsequently, they swiftly established a recovery plan and shared it with the troubleshoot team. The commander utilized the system to communicate with the recovery team members on site, controlling the runway damage repair and managing the progress status.

The key required operational capability (ROC) quantitative objective was to automatically recognize and classify the types of airfield damage (such as cracks, depressions, etc.) within 20 min (assumption) by collecting and analyzing imagery captured by UAVs.

B. DEVELOPMENT OF TECHNICAL WORK BREAKDOWN STRUCTURE

The results of the technical work breakdown structure (WBS) for the ADARMS are presented in Table 1.

The system was broken down into damage information collection, assessment, and recovery management systems. The damage assessment system consisted of a platform, payload, and ground control equipment for operating UAVs.

The damage assessment system was divided into image processing equipment, which performs 2D/3D mapping using imagery captured by UAVs, and damage assessment equipment, which automatically classifies damage types, calculates damage extents, and recommends the MOS. The

TABLE 9. Selection of CTE candidates (first).

TE		Key ROC-related items	Difficulty level
TE ID	Technology definition		
HWTE 4	Communication HW technology (data link, bus, etc.)	●	
HWTE 5	EO camera design and integration technology	●	
HWTE 6	IR camera design and integration technology	●	
HWTE 7	Communication module design and manufacturing technology	●	
HWTE 9	High-performance GPU-based HW production technology	●	
HWTE 10	High-performance CPU-based HW production technology	●	
HWTE 11	High-performance CPU-based HW production technology	×	5
SWTE 3	Communication SW technology	●	
SWTE 4	EO image processing SW technology	●	
SWTE 5	IR image processing SW technology	●	
SWTE 6	Data link SW technology	●	
SWTE 9	Gateway SW technology	●	
SWTE 10	2D EO image processing SW technology (2D EO mapping, etc.)	●	
SWTE 11	2D IR image processing SW technology (2D IR mapping, etc.)	●	
SWTE 13	AI-based damage detection SW technology	●	
SWTE 14	AI-based damage recognition SW technology	●	
SWTE 15	Automatic damage calculation SW technology	×	4
SWTE 16	Automatic MOS candidate recommendation SW technology	×	4
IFTE 9	Communication firmware technology	●	
IFTE 10	CM-EO standard interface technology	●	
IFTE 11	CM-IR standard interface technology	●	
IFTE 12	CM-DL standard interface technology	●	
IFTE 13	CM-EO API technology	●	
IFTE 14	CM-IR API technology	●	
IFTE 15	CM-DL API technology	●	
IFTE 16	IR firmware technology	●	
IFTE 17	DL standard firmware technology	●	
IFTE 19	Standard data link construction technology	●	
IFTE 21	DL standard protocol technology	●	
IFTE 22	GC firmware technology		
IFTE 23	Web-based middleware technology	●	
IFTE 24	Web-based middleware technology	●	
IFTE 25	Web-based middleware technology	●	

damage recovery-management system is responsible for establishing and controlling the damage recovery plan.

According to the system operational concept, we identified components related to the key ROC quantitative objectives. Configuration items related to sharing images captured by UAVs using EO/IR sensors and conducting two-dimensional (2D) mapping were identified. Additionally, hardware (HW) and software (SW) configuration items related to automatically detecting and classifying damage types from collected imagery were identified.

C. SELECTION OF CTEs

1) IDENTIFICATION OF TECHNICAL ELEMENTS (TEs)

a: IDENTIFICATION OF HWTEs and SWTEs

The HWTEs and SWTEs identified based on the WBS of the ADARMS are summarized in Table 2.

TEs were identified and defined as the TEs necessary for developing HW and SW items corresponding to WBS Level 4.

For HWTE, eight elements were identified for the damage information collection system, two elements for the damage assessment system, and one element for the damage recovery management system. For SWTE, eight elements were identified for the damage information collection system, eight elements for the damage assessment system, and four elements for the damage recovery management system.

b: IDENTIFICATION OF IFTEs

According to the operational concept of the ADARMS, 39 interface TEs (IFTEs) were identified, which are summarized in Table 3.

TABLE 10. List of CTE candidates (first).

CTE candidate ID	CTE candidate (1st)	TE ID
C-HWCTE 1	Communication HW technology (data link, bus, etc.)	HWTE 4
C-HWCTE 2	EO camera design and integration technology	HWTE 5
C-HWCTE 3	IR camera design and integration technology	HWTE 6
C-HWCTE 4	Communication module design and manufacturing technology	HWTE 7
C-HWCTE 5	High-performance GPU-based HW production technology	HWTE 9
C-HWCTE 6	High-performance CPU-based HW production technology	HWTE 10
C-HWCTE 7	High-performance CPU-based HW production technology	HWTE 11
C-SWCTE 1	Communication SW technology	SWTE 3
C-SWCTE 2	EO image processing SW technology	SWTE 4
C-SWCTE 3	IR image processing SW technology	SWTE 5
C-SWCTE 4	Data link SW technology	SWTE 6
C-SWCTE 5	Gateway SW technology	SWTE 9
C-SWCTE 6	2D EO image processing SW technology (2D EO mapping, etc.)	SWTE 10
C-SWCTE 7	2D IR image processing SW technology (2D IR mapping, etc.)	SWTE 11
C-SWCTE 8	AI-based damage detection SW technology	SWTE 13
C-SWCTE 9	AI-based damage recognition SW technology	SWTE 14
C-SWCTE 10	Automatic damage calculation SW technology	SWTE 15
C-SWCTE 11	Automatic MOS candidate recommendation SW technology	SWTE 16
C-IFCTE 1	Communication firmware technology	IFTE 9
C-IFCTE 2	CM-EO standard interface technology	IFTE 10
C-IFCTE 3	CM-IR standard interface technology	IFTE 11
C-IFCTE 4	CM-DL standard interface technology	IFTE 12
C-IFCTE 5	CM-EO API technology	IFTE 13
C-IFCTE 6	CM-IR API technology	IFTE 14
C-IFCTE 7	CM-DL API technology	IFTE 15
C-IFCTE 8	IR firmware technology	IFTE 16
C-IFCTE 9	DL standard firmware technology	IFTE 17
C-IFCTE 10	Standard data link construction technology	IFTE 19
C-IFCTE 11	DL standard protocol technology	IFTE 21
C-IFCTE 12	GC firmware technology	IFTE 22
C-IFCTE 13	Web-based middleware technology	IFTE 23
C-IFCTE 14	Web-based middleware technology	IFTE 24
C-IFCTE 15	Web-based middleware technology	IFTE 25

By tracking the data flow in the operational concept, we identified the interrelationships between HW and SW configuration items.

Table 4 summarizes the definitions of the identified IFTEs. It defines the necessary technology for IFs between the HW and SW configuration items.

2) SELECTION OF CTE CANDIDATES (FIRST)

a: IDENTIFICATION OF TEs RELATED TO KEY ROC QUANTITATIVE OBJECTIVES

The HWTEs and SWTEs related to the key ROC quantitative objectives were identified (Table 5).

The method to identify the TEs related to the key ROC quantitative objectives was as follows: a process diagram was generated based on the system's operational concept and the core processes related to the key ROC quantitative objectives were identified.

The WBS was used to identify the HW and SW configuration items involved in handling the identified core processes. TheTEs mapped to these items were related to the key ROC quantitative objectives.

Fig. 18 illustrates the operational concept of the ADARMS represented with a high-level process diagram. According to the mission plan, UAVs utilized the onboard EO/IR to capture images of damaged areas and transmit them to the control center.

TABLE 11. Determination of COTS technology application.

CTE candidate ID	CTE candidate (1st)	Application of COTS
C-HWCTE 1	Communication HW technology (data link, bus, etc.)	●
C-HWCTE 2	EO camera design and integration technology	●
C-HWCTE 3	IR camera design and integration technology	●
C-HWCTE 4	Communication module design and manufacturing technology	●
C-HWCTE 5	High-performance GPU-based HW production technology	●
C-HWCTE 6	High-performance CPU-based HW production technology	●
C-HWCTE 7	High-performance CPU-based HW production technology	●
C-SWCTE 1	Communication SW technology	●
C-SWCTE 2	EO image processing SW technology	●
C-SWCTE 3	IR image processing SW technology	●
C-SWCTE 4	Data link SW technology	●
C-SWCTE 5	Gateway SW technology	●
C-SWCTE 6	2D EO image processing SW technology (2D EO mapping, etc.)	×
C-SWCTE 7	2D IR image processing SW technology (2D IR mapping, etc.)	×
C-SWCTE 8	AI-based damage detection SW technology	×
C-SWCTE 9	AI-based damage recognition SW technology	×
C-SWCTE 10	Automatic damage calculation SW technology	×
C-SWCTE 11	Automatic MOS candidate recommendation SW technology	×
C-IFCTE 1	Communication firmware technology	●
C-IFCTE 2	CM-EO standard interface technology	●
C-IFCTE 3	CM-IR standard interface technology	●
C-IFCTE 4	CM-DL standard interface technology	●
C-IFCTE 5	CM-EO API technology	●
C-IFCTE 6	CM-IR API technology	●
C-IFCTE 7	CM-DL API technology	●
C-IFCTE 8	IR firmware technology	●
C-IFCTE 9	DL standard firmware technology	●
C-IFCTE 10	Standard data link construction technology	●
C-IFCTE 11	DL standard protocol technology	●
C-IFCTE 12	GC firmware technology	●
C-IFCTE 13	Web-based middleware technology	●
C-IFCTE 14	Web-based middleware technology	●
C-IFCTE 15	Web-based middleware technology	●

The core processes related to the key ROC quantitative objectives started from the moment the EO/IR sensors mounted on the UAVs captured the damage imagery.

It involved transmitting the captured images through a data link to and processing them at the control center.

The system automatically detected and classified types of damages after image processing.

Using the WBS, we identified the HW and SW configuration items relevant to these core processes.

The identified items and the corresponding mapped TEs represent TEs related to the key ROC quantitative objectives.

Additionally, by utilizing the interface matrix, we identified the interrelationships associated with the core processes.

TABLE 12. Final CTEs for ADARMS.

CTE ID	CTE name	CTE candidate ID
SWCTE 1	2D EO image processing SW technology (2D EO mapping, etc.)	C-SWCTE 6
SWCTE 2	2D IR image processing SW technology (2D IR mapping, etc.)	C-SWCTE 7
SWCTE 3	AI-based damage detection SW technology	C-SWCTE 8
SWCTE 4	AI-based damage recognition SW technology	C-SWCTE 9
SWCTE 5	Automatic damage calculation SW technology	C-SWCTE 10
SWCTE 6	Automatic MOS candidate recommendation SW technology	C-SWCTE 11

TABLE 13. Results of TRA for ADARMS.

CTE ID	CTE name	Results of TRA	
		TRL	Reference
SWCTE 1	2D EO image processing SW technology (2D EO mapping, etc.)	6	A-R&D project
SWCTE 2	2D IR image processing SW technology (2D IR mapping, etc.)	6	A-R&D project
SWCTE 3	AI-based damage detection SW technology	6	M-project, A-R&D project
SWCTE 4	AI-based damage recognition SW technology	6	M-project, A-R&D project
SWCTE 5	Automatic damage calculation SW technology	6	A-R&D project
SWCTE 6	Automatic MOS candidate recommendation SW technology	6	A-R&D project

TABLE 14. Technical WBS for NTDS.

Level 1	Level 2	Level 3	Level 4	Key ROC allocation
NTDS	Tactical data processing system	DLP equipment	DLP HW	●
			DLP SW	●
	Tactical operation system	TDP equipment	TDP HW	●
			TDP SW	●
		RDBP equipment	RDBP HW	●
			RDBP SW	●
		TCC equipment	TCC HW	×
			TCC SW	×
	Tactical situational display system	TSD equipment	TSD HW	●
			TSD SW	●

DLP: Data link processing; TDP: Tactical data processing; RDBP: RDB processing; TCC: Tactical coordination console; TSD: Tactical situational display

Subsequently, we identified the IFTEs related to the key ROC quantitative objectives (Table 6).

b: DIFFICULTY EVALUATION

The results of evaluation of the technical difficulty for 16 HWTE and SWTE items unrelated to the key ROC objectives are summarized in Table 7.

SWTE15, SWTE16, and HWTE11 were evaluated with a difficulty level of 4 or higher as new technologies.

The remaining HWTEs and SWTEs can be sufficiently developed by modifying the technology acquired through projects such as H-UAV, M-UAV, A-C4I, or by leveraging existing technologies.

The technical difficulty evaluation was conducted for 25 IFTEs unrelated to the key ROC quantitative objectives, and the results are presented in Table 8.

All necessary TEs were already secured via the H-UAV, M-UAV, and A-C4I projects, so all technical difficulty levels of the IFTEs were evaluated as 2 or less.

c: SELECTION OF CTE CANDIDATES (FIRST)

Thirty-three CTE candidates (first) were selected by combining the ones related to the key ROC quantitative objectives and those with a technical-difficulty evaluation result of 4 or higher (Table 9).

Identifiers were allocated to the selected CTE candidates (first) and are presented in Table 10.

3) DETERMINATION OF COMMERCIAL OFF-THE-SHELF TECHNOLOGY APPLICATION

The assessment results for applying commercial off-the-shelf technology (COTS) to CTE candidates (first) are presented in Table 11.

TABLE 15. Definitions of NTDS HWTEs and SWTEs.

TBS		TE		
Level 2	**Level 3**	**TE ID**	**Technology name**	**Technology definition**
Tactical data processing system	DLP equipment	HWTE 1	Embedded HW	Embedded HW design and development technology
		SWTE 1	Real-time data link processing SW	Standard RT data link processing SW technology (link-11, 14, etc.)
		SWTE 2	External interface SW	Standard external interface SW technology (Sensor to NTDS, NTDS to external sys.)
Tactical operation system	TDP equipment	HWTE 2	High-performance HW	High-performance CPU-based HW production technology
		SWTE 3	Tactical track collection SW	Tactical track collection SW technology using standard data link protocol
		SWTE 4	Tactical track data display SW	Tactical track data display SW technology
		SWTE 5	Risk assessment support SW	Risk assessment support SW technology
		SWTE 6	Weapon control SW	Weapon control SW technology
	RDBP equipment	HWTE 3	High-performance HW	High-performance CPU-based HW production technology
		SWTE 7	DBMS SW	Real-time DBMS technology
	TCC equipment	HWTE 4	Embedded HW	Embedded HW design and development technology
		SWTE 8	Display firmware	Display firmware technology
Tactical situational display system	TSD equipment	HWTE 5	High-performance HW	High-performance CPU-based HW production technology
		SWTE 9	Tactical situation display SW	GIS-based tactical situation display SW technology

TABLE 16. Identification Results of NTDS IFTEs.

TBS		DLP equipment		TDP equipment		RDBP equipment		TCC equipment		TSD equipment	
Level 3	**Level 4**	**DLP HW**	**DLP SW**	**TDP HW**	**TDP SW**	**RDBP HW**	**RDBP SW**	**TCC HW**	**TCC SW**	**TSD HW**	**TSD SW**
DLP equipment	DLP HW		IFTE 1	IFTE 2							
	DLP SW	IFTE 1			IFTE 3						
TDP equipment	TDP HW	IFTE 2				IFTE 4		IFTE 5		IFTE 6	
	TDP SW		IFTE 3	IFTE 7			IFTE 8		IFTE 9		IFTE 10
RDBP equipment	RDBP HW			IFTE 4			IFTE 11				
	RDBP SW				IFTE 8	IFTE 11					
TCC equipment	TCC HW			IFTE 5					IFTE 12		
	TCC SW				IFTE 9			IFTE 12			
TSD equipment	TSD HW			IFTE 6							IFTE 13
	TSD SW				IFTE 10					IFTE 13	

Feasibility of COTS technology application means that the TE can be implemented using COTS products or technology. The final decision regarding the application of COTS technology is determined by confirming evidence for its sale and operation within an actual system.

4) FINAL SELECTION OF CTES

Excluding the technologies obtainable through COTS from CTE candidates (first), six TEs were finally selected as CTEs for the ADARMS.

TABLE 17. Definitions of NTDS IFTEs.

Interface section (TBS level 4)		IFTE	
		TE ID	Technology definition
DLP HW	DLP SW	IFTE 1	Standard bus interface technology
	TDP HW	IFTE 2	Standard data link construction technology
DLP SW	TDP SW	IFTE 3	Standard data link API
TDP HW	RDBP HW	IFTE 4	Optical communication technology
	TCC HW	IFTE 5	Optical communication technology
	TSD HW	IFTE 6	Optical communication technology
TDP SW	TDP HW	IFTE 7	Middleware technology
	RDBP SW	IFTE 8	Middleware technology
	TCC SW	IFTE 9	TDP-TCC API technology
	TSD SW	IFTE 10	TDP-TSD API technology
RDBP SW	RDBP HW	IFTE 11	Real-time DBMS technology
TCC HW	TCC SW	IFTE 12	TCC driver technology
TSD HW	TSD SW	IFTE 13	GIS-based integration technology

TABLE 18. Key ROC quantitative objective-related HWTEs/SWTEs.

TBS		TE		Key ROC-related items
Level 2	Level 3	TE ID	Technology definition	
Tactical data processing system	DLP equipment	HWTE 1	Embedded HW design and development technology	●
		SWTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	●
		SWTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external sys.)	●
Tactical operation system	TDP equipment	HWTE 2	High-performance CPU-based HW production technology	●
		SWTE 3	Tactical track collection SW technology using standard data link protocol	●
		SWTE 4	Tactical track data display SW technology	●
		SWTE 5	Risk assessment support SW technology	×
		SWTE 6	Weapon control SW technology	×
	RDBP equipment	HWTE 3	High-performance CPU-based HW production technology	●
		SWTE 7	Real-time DBMS technology	●
	TCC equipment	HWTE 4	Embedded HW design and development technology	×
		SWTE 8	Display firmware technology	×
Tactical situational display system	TSD equipment	HWTE 5	High-performance CPU-based HW production technology	●
		SWTE 9	GIS-based tactical situation display SW technology	●

The final CTEs selected by the evaluation team are outlined in Table 12.

D. TRA EXECUTION

Results of the TRA conducted for the final six CTEs are provided in Table 13.

Maturity was evaluated by verifying the evidence from the A-R&D and M-projects. Consequently, the system-level maturity of the ADARMS was rated as 6.

VII. NTDS

A. OVERVIEW OF NTDS

The NTDS operates sensors installed on navy ships and surveillance units to collect tactical target information in near real time and comprehensively share maritime tactical situations with related units.

This system supports rapid decision-making and command control of commanders by sharing the tactical situation of the Korean Peninsula in near real time.

TABLE 19. Key ROC quantitative objective-related IFTEs.

Interface section (TBS level 4)		IFTE		Key ROC-related items
		TE ID	Technology definition	
DLP HW	DLP SW	IFTE 1	Standard bus interface technology	●
	TDP HW	IFTE 2	Standard data link construction technology	●
DLP SW	TDP SW	IFTE 3	Standard data link API	●
TDP HW	RDBP HW	IFTE 4	Optical communication technology	●
	TCC HW	IFTE 5	Optical communication technology	×
	TSD HW	IFTE 6	Optical communication technology	●
TDP SW	TDP HW	IFTE 7	Middleware technology	●
	RDBP SW	IFTE 8	Middleware technology	●
	TCC SW	IFTE 9	TDP-TCC API technology	×
	TSD SW	IFTE 10	TDP-TSD API technology	●
RDBP SW	RDBP HW	IFTE 11	Real-time DBMS technology	●
TCC HW	TCC SW	IFTE 12	TCC driver technology	×
TSD HW	TSD SW	IFTE 13	GIS-based integration technology	●

TABLE 20. Difficulty evaluation results for HWTEs and SWTEs.

WBS		TE		Difficulty level	Reference project
Level 2	Level 3	TE ID	Technology Definition		
Tactical operation system	TDP equipment	SWTE 5	Risk assessment support SW technology	3	N-C4I project
		SWTE 6	Weapons control SW technology	3	N-C4I project
	TCC equipment	HWTE 4	Embedded HW design and development technology	2	Ship combat system project
		SWTE 8	Display firmware technology	2	Ship combat system project

TABLE 21. Difficulty evaluation results for IFTEs.

Interface section (TBS level 4)		IFTE		Difficulty level	Reference project
		TE ID	Technology definition		
TDP HW	TCC HW	IFTE 5	Optical communication technology	2	N-C4I project
TDP SW	TCC SW	IFTE 9	TDP-TCC API technology	3	N-C4I project, ship combat sys. project
TCC HW	TCC SW	IFTE 12	TCC driver technology	2	N-C4I project, ship combat sys. project

The operational concept of the system is illustrated in Fig. 19.

When sensors (such as radars) installed on naval vessels, surveillance units, and similar assets detect maritime targets, the NTDS interface unit receives the target data, updates the tactical targets, and disseminates this information to higher-level units. Each fleet command consolidates the tactical target information from its subordinate units (such as naval vessels, surveillance units, etc.) to utilize it for tactical operations. The aggregated target information is then disseminated to the operational command headquarters. The operational command headquarters receives tactical information from each fleet command and shares this information with joint command and control systems.

The primary ROC quantitative objective is the time (within 2 s; assumption) from the moment a radar system on a naval vessel or surveillance unit detects a target to the rapid transmission of target data via data links, displaying it on the tactical processor at the operational command headquarters.

B. DEVELOPMENT OF TECHNICAL WBS

The technical WBS of the NTDS are summarized in Table 14. The NTDS consists of a tactical data processing, operation,

TABLE 22. Selection of CTE candidates (first).

TE		Key ROC-related items	Difficulty level
TE ID	**Technology definition**		
HWTE 1	Embedded HW design and development technology	●	
HWTE 2	High-performance CPU-based HW production technology	●	
HWTE 3	High-performance CPU-based HW production technology	●	
HWTE 5	High-performance CPU-based HW production technology	●	
SWTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	●	
SWTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external sys.)	●	
SWTE 3	Tactical track collection SW technology using standard data link protocol	●	
SWTE 4	Tactical track data display SW technology	●	
SWTE 7	Real-time DBMS technology	●	
SWTE 9	GIS-based tactical situation display SW technology	●	
IFTE 1	Standard bus interface technology	●	
IFTE 2	Standard data link construction technology	●	
IFTE 3	Standard data link API	●	
IFTE 4	Optical communication technology	●	
IFTE 6	Optical communication technology	●	
IFTE 7	Middleware technology	●	
IFTE 8	Middleware technology	●	
IFTE 10	TDP-TSD API technology	●	
IFTE 11	Real-time DBMS technology	●	
IFTE 13	GIS-based integration technology	●	

TABLE 23. List of CTE candidates (first).

CTE candidate ID	CTE candidate (first)	TE ID
C-HWTE 2	High-performance CPU-based HW production technology	HWTE 2
C-HWTE 3	High-performance CPU-based HW production technology	HWTE 3
C-HWTE 4	High-performance CPU-based HW production technology	HWTE 5
C-SWTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	SWTE 1
C-SWTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external system)	SWTE 2
C-SWTE 3	Tactical track collection SW technology using standard data link protocol	SWTE 3
C-SWTE 4	Tactical track data display SW technology	SWTE 4
C-SWTE 5	Real-time DBMS technology	SWTE 7
C-SWTE 6	GIS-based tactical situation-display SW technology	SWTE 9
C-IFTE 1	Standard bus interface technology	IFTE 1
C-IFTE 2	Standard data link construction technology	IFTE 2
C-IFTE 3	Standard data link API	IFTE 3
C-IFTE 4	Optical communication technology	IFTE 4
C-IFTE 5	Optical communication technology	IFTE 6
C-IFTE 6	Middleware technology	IFTE 7
C-IFTE 7	Middleware technology	IFTE 8
C-IFTE 8	TDP–TSD API technology	IFTE 10
C-IFTE 9	Real-time DBMS technology	IFTE 11
C-IFTE 10	GIS-based integration technology	IFTE 13

and situation-display systems, which comprise five pieces of equipment.

C. SELECTION OF CTEs

1) IDENTIFICATION OF TES

a: IDENTIFICATION OF HWTEs AND SWTEs

The HWTEs and SWTEs identified based on the technical WBS of the NTDS are summarized in Table 15.

We identified the necessary technology elements to develop the HW and SW configuration items corresponding to WBS Level 4. The HWTE consisted of one tactical data-processing system, three tactical operation systems, and two tactical situation-display systems that were identified. The SWTEs comprised two tactical data-processing systems, six tactical operation systems, and one tactical situation-display system that were identified.

TABLE 24. Determination of COTS technology application.

CTE candidate ID	CTE candidate (1^{st})	Application of COTS
C-HWTE 1	Embedded HW design & development technology	●
C-HWTE 2	High-performance CPU-based HW production technology	●
C-HWTE 3	High-performance CPU-based HW production technology	●
C-HWTE 4	High-performance CPU-based HW production technology	●
C-SWTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	×
C-SWTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external sys.)	×
C-SWTE 3	Tactical track collection SW technology using standard data link protocol	×
C-SWTE 4	Tactical track data display SW technology	×
C-SWTE 5	Real-time DBMS technology	●
C-SWTE 6	GIS-based tactical situation display SW technology	×
C-IFTE 1	Standard bus interface technology	●
C-IFTE 2	Standard data link construction technology	●
C-IFTE 3	Standard data link API	×
C-IFTE 4	Optical communication technology	●
C-IFTE 5	Optical communication technology	●
C-IFTE 6	Middleware technology	●
C-IFTE 7	Middleware technology	●
C-IFTE 8	TDP-TSD API technology	×
C-IFTE 9	Real-time DBMS technology	●
C-IFTE 10	GIS-based integration technology	×

TABLE 25. Final CTEs for NTDS.

CTE ID	CTE name	CTE candidate ID
SWCTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	C-SWTE 1
SWCTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external sys.)	C-SWTE 2
SWCTE 3	Tactical track collection SW technology using standard data link protocol	C-SWTE 3
SWCTE 4	Tactical track data display SW technology	C-SWTE 4
SWCTE 5	GIS-based tactical situation display SW technology	C-SWTE 6
IFCTE 1	Standard data link API	C-IFTE 3
IFCTE 2	TDP-TSD API technology	C-IFTE 8
IFCTE 3	GIS-based integration technology	C-IFTE 10

b: IDENTIFICATION OF IFTEs

According to the NTDS operational concept, we identified 13 interfaces among the HW and SW configuration items (Table 16).

We investigated the data flow according to the operational concept of the NTDS and identified the interfacial relationships among the HW and SW configuration items of the system components. Table 17 summarizes the definitions of the identified IFTEs. It also defines the necessary technologies for IFs among the HW and SW configuration items.

2) SELECTION OF CTE CANDIDATES (FIRST)

a: IDENTIFICATION OF TEs RELATED TO KEY ROC QUANTITATIVE OBJECTIVES

The HWTEs and SWTEs related to the key ROC quantitative objectives were identified (Table 18).

TABLE 26. Results of TRA for NTDS.

CTE ID	CTE name	Results of TRA	
		TRL	Reference project
SWCTE 1	Standard RT data link processing SW technology (link-11, 14, etc.)	7	N-C4I project, MCRC project
SWCTE 2	Standard external interface SW technology (sensor to NTDS, NTDS to external sys.)	7	N-C4I project, ship combat sys. project
SWCTE 3	Tactical track collection SW technology using standard data link protocol	6	N-C4I project, MCRC project
SWCTE 4	Tactical track data display SW technology	7	N-C4I project, ship combat sys. project
SWCTE 5	GIS-based tactical situation display SW technology	7	N-C4I project, ship combat sys. project
IFCTE 1	Standard data link API	7	N-C4I project, MCRC project
IFCTE 2	TDP-TSD API technology	7	N-C4I project, ship combat sys. Project
IFCTE 3	GIS-based integration technology	8	N-C4I project, J-C4I project

The core processes related to the key ROC quantitative objectives were as follows: when sensors operational onboard naval vessels and surveillance units detected a target, the DLP collected and processed the target information through IFs connected to the sensors and subsequently transmitted it to the TDP. The TDP utilized information from the RDBP to fuse data, which were then transmitted to the TSD for display on the situational map.

Based on the NTDS WBS, we identified the HW and SW configuration items involved in handling these core processes. Furthermore, we defined the TEs required for developing each configuration item and mapped it in relation to the key ROC quantitative objectives.

Furthermore, by utilizing the system's operational concept and the IF matrix, we tracked processes related to the key ROC quantitative objectives and identified the associated IFTEs. The identified IFTEs related to key ROC quantitative objectives are listed in Table 19. The IFs with sensors, such as radar, to collect data at the DLP, transmitting them to the TDP via data links, and finally integrating them with the RDBP information for display on the TSD, fall under this category.

b: DIFFICULTY EVALUATION

We conducted a technology-difficulty evaluation for four TEs unrelated to the key ROC objectives (Table 20). The identified HWTEs and SWTEs consisted of TEs secured via the N-C4I project and naval combat system project, which was evaluated at a difficulty level of 3 or lower.

Furthermore, the technological difficulty evaluation results for three IFTE unrelated to key ROC quantitative objectives are presented in Table 21. The identified IFTEs, secured through the N-C4I project and naval combat system project, were evaluated at a difficulty level of 3 or lower, utilizing technology that had already been secured.

c: SELECTION OF CTE CANDIDATES (FIRST)

We selected the CTE candidates (first) by combining the TEs related to the key ROC quantitative objectives and those rated with a technological difficulty of 4 or higher. The results are listed in Table 22.

Regarding the NTDS project, there were no TEs rated with a difficulty of 4 or higher in the technological difficulty evaluation. Therefore, identifiers were allocated to the selected CTE candidates (first) and organized as outlined in Table 23.

3) DETERMINATION OF COTS TECHNOLOGY APPLICATION

The assessment results for applying COTS technology to the CTE candidates (first) are displayed in Table 24. The feasibility of COTS technology application means that the TE can be implemented using COTS or technology. The final decision regarding the application of COTS technology was determined by confirming the evidence for its sale and operation within an actual system.

4) FINAL SELECTION OF CTES

Excluding the technologies obtainable through COTS from the CTE candidates (first), eight TEs were finally selected as CTEs for the NTDS. The final CTEs selected by the evaluation team are outlined in Table 25.

D. TRA EXECUTION

The results of the TRA conducted for the final eight CTEs are presented in Table 26. The maturity was evaluated through evidence verification from the N-C4I project, MCRC project, and naval combat system projects. The system level maturity of the NTDS was rated as 6.

REFERENCES

[1] *Orders for the Development of War Capabilities, Korean Ministry of Defense*, 2020, p. 48.

[2] *Announcement of the Enforcement of the Korean Priority Acquisition System, Defense Acquisition Program Administration (DAPA)*, 2021.

[3] *A Study on the Improvement of Technical Readiness Assessment*, SMI, Secur. Manage. Inst., Seoul, (South) Korea, 2018, p. 54.

[4] *Guidelines for Technology Readiness Assessment, Defense Acquisition Program Administration (DAPA)*, 2019, pp. 3–8.

[5] M. W. Kimmel. (2020). *Technology Readiness Assessment Best Practices Guide*. [Online]. Available: https://ntrs.nasa.gov/citations/20205003605

[6] (2011). *Technology Readiness Assessment (TRA) Guidance, Office of the Assistant Secretary of Defense (Research and Engineering)*. Washington, DC, USA. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA554900

[7] M. T. Persons and M. Mackin. (2020). *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects*. U.S. Government Accountability Office Washington United States. [Online]. Available: https://apps.dtic.mil/sti/citations/ AD1105846

[8] S. R. Sadin, F. P. Povinelli, and R. Rosen, "The NASA technology push towards future space mission systems," *Acta Astronautica*, vol. 20, pp. 73–77, Jan. 1989.

[9] J. C. Mankins, "Technology readiness levels," White Paper, Apr. 1995.

[10] S. L. Cornford and L. Sarsfield, "Quantitative methods for maturing and infusing advanced spacecraft technology," in *Proc. IEEE Aerosp. Conf.*, Mar. 2004, pp. 5–6.

[11] J. C. Mankins, "Approaches to strategic research and technology (R&T) analysis and road mapping," *Acta Astronautica*, vol. 51, nos. 1–9, pp. 3–21, Jul. 2002.

[12] S. Gove, "Defining an integration readiness level for defense acquisition," in *Proc. Int. Symp. Int. Council Syst. Eng. (INCOSE)*, Singapore, 2009, pp. 3–8.

[13] B. Sauser, D. Verma, J. Ramirez-Marquez, and R. Gove, "From TRL to SRL: The concept of systems readiness levels," in *Proc. Conf. Syst. Eng. Res.*, vol. 5. Los Angeles, CA, USA: Stevens Institute of Technology, 2006, pp. 5–7.

[14] J. W. Bilbro, "Using the advancement degree of difficulty (AD2) as an input to risk management," in *Proc. Multi-Dimensional Assessment Technol. Maturity Technol. Maturity Conf.*, Virginia Beach, VA, USA, 2008.

[15] A. Olechowski, S. D. Eppinger, and N. Joglekar, "Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities," in *Proc. Portland Int. Conf. Manag. Eng. Technol. (PICMET)*, Aug. 2015, pp. 2084–2094.

[16] K. Tomaschek, A. Olechowski, S. Eppinger, and N. Joglekar, "A survey of technology readiness level users," in *Proc. INCOSE Int. Symp.*, 2016, vol. 26, no. 1, pp. 2101–2117.

[17] Z. Tompkins, M. Grenn, and B. Roberts, "Improving system maturity assessments by incorporating a design structure matrix," *IEEE Trans. Eng. Manag.*, vol. 67, no. 1, pp. 122–140, Feb. 2020.

[18] D. I. Doukas, "Superconducting transmission systems: Review, classification, and technology readiness assessment," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[19] S. Petrovic and E. Hossain, "Development of a novel technological readiness assessment tool for fuel cell technology," *IEEE Access*, vol. 8, pp. 132237–132252, 2020.

[20] G. T. Jesus and M. F. Chagas Junior, "Using systems architecture views to assess integration readiness levels," *IEEE Trans. Eng. Manag.*, vol. 69, no. 6, pp. 3902–3912, Dec. 2022.

[21] J. Straub, "In search of technology readiness level (TRL) 10," *Aerosp. Sci. Technol.*, vol. 46, pp. 312–320, Oct. 2015.

[22] *Technology Readiness Assessment (TRA) Deskbook*, Office of the Director of Defense Research and Engineering, Washington, DC, USA, 2009.

[23] J. D. Smith, "An alternative to technology readiness levels for non-developmental item (NDI) software," in *Proc. 38th Annu. Hawaii Int. Conf. Syst. Sci.*, Jan. 2005, pp. 29–32.

JI-IN KOO received the B.S. degree in control and instrumentation engineering from Korea Maritime & Ocean University, Pusan, Republic of Korea, in 1994, and the M.S. degree in defense business from Kwangwoon University, Seoul, Republic of Korea, in 2014, where he is currently pursuing the Ph.D. degree in defense business. He was discharged as a Lieutenant of the Korean Navy, in 1997. From 1997 to 2023, he held various positions, including as a Systems Engineer, a Project Manager, and a Research Director, in the defense sector at large Korean enterprises, such as LG, Hanhwa, and LIG Group. His research interests include project risk management, technology maturity assessment of weapon systems, component-based software development, and system interoperability measurements.

SUK-JAE JEONG received the B.S. degree from the Department of Logistics Systems Engineering, Korea Maritime & Ocean University, Republic of Korea, in 2002, and the M.S. and Ph.D. degrees from the Department of Information and Industrial Engineering, Yonsei University, Republic of Korea, in 2004 and 2009, respectively. He has been a Professor of business administration with Kwangwoon University, since 2010. He is currently a Senior Professor with the Department of Defense Acquisition Program, Graduate School, Kwangwoon University. His research interests include supply chain management, smart factories, and defense decision-making.