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An Analysis of the Importance of Success Factors for Cloud Computing System Adoption in Vessel Traffic Service Systems

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Abstract: This study aims to identify the key success factors for the adoption of a cloud computing system in vessel traffic service (VTS) systems and evaluate the relative importance of each factor. Through a literature review and expert Delphi surveys, 12 success factors were derived across the dimensions of technology, organization, environment, and institution. The results of the analytic hierarchy process (AHP) analysis revealed that stability in the technological dimension was the most important factor. This study provides useful implications for future decision-making in VTS cloud adoption by systematically identifying the key success factors and presenting their priorities through the application of the TOE-I framework to VTS cloud computing.

Keywords: vessel traffic services (VTS); cloud computing; Delphi method; analytic hierarchy process (AHP); technology–organization–environment (TOE) framework; success factors



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1. Introduction

The recent advances in cloud computing technology are accelerating the digital transformation of various industries. The advantages of cloud computing, such as improved efficiency through virtualization and resource sharing, flexible scalability, and enhanced accessibility, are gaining attention as innovative means to overcome the limitations of existing IT infrastructures. In particular, there is growing interest in adopting cloud computing in the field of VTS, which aims to improve the safety and efficiency of ship operations. Cloud computing systems can be distinguished into three different service delivery models based on the scope of services they provide [1]. Infrastructure-as-a-Service (IaaS) enables the utilization of IT infrastructure and eliminates the need for investment in building and managing IT systems [2]. Platform-as-a-Service (PaaS) provides users with an environment that enables the development, testing, and deployment of applications, accelerating application development by simplifying many steps of the process [3]. Software-as-a-Service (SaaS) offers a complete product managed and run by cloud service provider (CSP) [4].

Cloud computing systems can also be broadly classified into public cloud and private cloud based on the cloud provider. Public and private deployment models [5] are commonly used to differentiate one cloud provider from another. The former is made available to the general public on a pay-per-use basis, whereas the latter is operated solely for internal users in organizations [6]. These diverse cloud computing models are meeting the needs of enterprises as well as government agencies and are rapidly spreading across various fields. Recently, The U.S. Department of Defense signed contracts with cloud companies such as AWS, Microsoft, Google Cloud, and Oracle for the Joint Warfighting Cloud Capability (JWCC) project, which aims to integrate distributed IT infrastructure and develop an integrated cloud capable of global operations [7]. This demonstrates that cloud computing systems are being actively adopted even by government agencies that handle critical security information, such as the Department of Defense.

Moreover, in the operation of the VTS system by the national Korea Coast Guard, the necessity of introducing a cloud computing system is being emphasized to realize continuous control through the sharing of control information among nationwide VTS centers, establish a VHF voice system for remote control, and increase the need for linking control information with related agencies due to the diversification of coast guard duties.

Particularly in South Korea, the VTS system initiated the VTS cloud system R&D in 2021 to ultimately improve users' accessibility to control information by converting the maritime traffic information independently managed by nationwide VTS into a centralized cloud-based system environment, opening it not only to the Korea Coast Guard but also to related agencies such as the Navy and maritime industry practitioners. The project aims to integrate information from nationwide VTS centers and link it with the E-navigation system by 2025 [8].

In fact, in the SafeSeaNet (SSN) system operated by the European Maritime Safety Agency (EMSA), which is similar to the VTS system, as the volume of maritime data increased rapidly it became difficult to process the data volume in the self-built on-premises environment, so a cloud environment was established in Microsoft Azure [9]. The transition of the VTS system to a cloud computing system is in its initial stage, so for the successful establishment and operation of the cloud computing system, the success factors must be clearly identified.

However, most of the previous studies analysing major factors following the introduction of a cloud computing system have been conducted through cases in various fields such as hospitals [10], cyber universities [11], higher education institutes [12], and small and medium-sized enterprises [13], but there is a lack of research on the analysis of success factors for the introduction of a cloud computing system in the VTS system.

Given the critical role that VTS systems play in maritime safety and the emerging importance of digital transformation within this sector, our study addresses the specific needs and challenges associated with adopting cloud computing in VTS systems, which directly impact the safety, efficiency, and management of maritime traffic.

Therefore, this study aims to identify the key success factors of VTS cloud computing and evaluate the relative importance of each factor. To this end, the TOE framework and institutional dimension were utilized as analytical frameworks, and the opinions of expert groups were gradually converged through the Delphi technique and AHP. The results of this study are expected to provide practical guidelines for strategy formulation by VTS.

Furthermore, it could serve as an opportunity for practitioners and researchers in related fields to contemplate the issues and challenges arising from the spread of cloud computing.

While the adoption of cloud computing in VTS systems holds great potential for enhancing maritime safety and efficiency, its successful implementation requires the consideration of multiple complex factors. Therefore, it is crucial to systematically identify and evaluate the key success factors for VTS cloud computing adoption. This will provide essential guidance for future strategy formulation and decision-making in the digital transformation of VTS systems.

This paper is structured as follows: Section 2 reviews the relevant literature, focusing on the key success factors for cloud computing adoption across various dimensions. Section 3 details the research methodology, including the Delphi surveys and AHP analysis used to identify and prioritize the success factors. Section 4 presents the results of the study, including the analysis of the identified factors. Section 5 discusses the implications of the findings and addresses the limitations of the study. Finally, Section 6 concludes the paper by summarizing the key findings and suggesting directions for future research.

2. Literature Review

This section analyzes previous studies on factors influencing the adoption of cloud computing systems in various fields. The success factors were classified by adding the institutional dimension to the technology–organization–environment (TOE) framework [14]. These four dimensions encompass both the constraints and possibilities for technological

innovation and are considered to influence how organizations identify the need for new technologies, review them, and adopt them.

2.1. Technology Dimension

The technology dimension refers to both internal and external technologies related to the organization, including the technologies used within the organization as well as all technologies available in the market. Yoo and Kim [15] presented a decision-making model for adopting a cloud computing system and derived the priorities of decision factors through the AHP method. In the decision-making hierarchy structure, the technology dimension was classified into related advantage and compatibility.

Related advantage was further divided into cost advantage, efficiency, flexibility, manageability, reliability/continuity, and security concern. Compatibility was subdivided into ease of use, usefulness, integration, and customization. The results showed that usefulness, integration, and ease of use were the most important factors in the technology dimension. However, this model was not specifically tailored to the maritime industry or VTS systems, limiting its direct applicability to our context.

Lian et al. [10] conducted an exploratory study using the AHP method to identify the key factors influencing the adoption of cloud computing in Taiwanese hospitals. The upper layer was classified with reference to the TOE framework and the human–organization–technology fit (HOT-fit) model [16,17]. The results indicated that the relative importance of the technology dimension was the most significant in the upper layer. Among the sub-factors of the technology dimension, data security ranked the highest among the 12 sub-factors, with costs and complexity ranking 3rd and 5th, respectively, showing relatively high rankings compared to other dimensions. While this study provides valuable insights, the healthcare context differs significantly from VTS operations, potentially affecting the relevance of its findings.

Kang [18] derived and evaluated the priorities for important factors that companies should consider before adopting cloud computing services. The analysis results showed that the order of importance was security, reliability, and economic efficiency. Among the sub-factors of security, the top priority was the controllability of access rights, and the second was safety from external threats. This study, however, focused on general business considerations and did not address the unique security and operational requirements of VTS systems.

Gui et al. [19] mentioned that vendor lock-in plays a crucial role among the key factors influencing the adoption of cloud computing by micro, small, and medium-sized enterprises (MSMEs) in Indonesia. Although vendor lock-in is a valid concern, its importance may vary in the context of government-operated VTS systems, which was not explored in this study. Vendor lock-in refers to a situation where an organization finds it difficult to switch to another cloud provider and lacks mobility and interoperability. In other words, when an organization adopts a specific cloud solution, it becomes challenging and costly to switch to another provider. Additionally, cloud software providers lock in customers in various ways, such as designing systems that are incompatible with software developed by other companies, using proprietary standards or closed architectures without interoperability, or licensing software under exclusive terms. These issues can make organizations hesitant to adopt cloud technologies [20].

Sharma et al. [21] applied the fuzzy AHP approach to identify and rank the factors influencing the adoption of cloud computing in Indian higher education institutions. Through a literature review and expert interviews, a total of 13 factors and 22 sub-factors were derived from the technological, organizational, and economic dimensions. In the technological dimension, the relative advantage, compatibility, complexity, security, and time to cater to IT demand were identified as key factors. While this study offers a comprehensive analysis, the educational sector's priorities may not align with those of maritime traffic management, a gap our study aims to address.

In particular, time to cater to IT demand emerged as the most important factor, as cloud computing adoption enables rapid access to software/hardware resources and commencement of operations. The next most important factors were security and relative advantage. In terms of security, vulnerability to external attacks may increase in the cloud environment, making it essential to secure cybersecurity capabilities.

Regarding the relative advantage, on-demand availability and scalability were found to play important roles in cloud adoption. On the other hand, integration complexity, a sub-factor of compatibility, was found to be more important than implementation complexity. This suggests that the difficulty of integrating existing systems with cloud services can act as a barrier to cloud adoption. In summary, the above contents indicate that when adopting cloud computing in Indian higher education institutions, technological factors, especially rapid accessibility and scalability of IT resources and security assurance, should be considered the most important. The studies also confirm that compatibility and ease of integration with existing systems are major considerations. Waqar et al. [22] analyzed the key success factors for adopting cloud computing in small construction projects in Malaysia. They identified 12 success factors across the dimensions of technology, organization, environment, and institution. Their analysis revealed that stability in the technological dimension was the most important factor. This study emphasizes the critical role of technological factors, particularly system stability, in the successful adoption of cloud computing, which is especially crucial in critical systems like VTS. These findings align with those of Sharma et al. [21], reaffirming the importance of considering technological factors when adopting cloud computing.

2.2. Organization Dimension

The organizational dimension refers to the characteristics and resources of the organization, such as its size and management structure. Amini and Bakri [23] mentioned that among the decisive factors influencing the adoption of cloud computing systems in small and medium-sized enterprises (SMEs) with limited budget and personnel, 'top manager support' plays a crucial role in the consideration of various aspects such as resource allocation, service integration, and process redesign for cloud computing system adoption. They also stated that if top managers do not properly understand the benefits of the cloud computing system, they tend to oppose its adoption. However, this study did not consider the hierarchical decision-making structure often present in government agencies overseeing VTS operations.

Alshamaila et al. [24] stated that factors such as the size of the organization, the support of top management, and prior experience all play a role in SMEs' adoption of cloud services. In particular, organizational size is considered to be a significant positive factor in the adoption of cloud computing; compared to larger firms, small firms adapt quickly to the changes in their environment [25]. While these factors are relevant, the study did not account for the unique organizational characteristics of maritime safety agencies, which our research aims to address.

Gangwar et al. [26] analyzed the factors influencing the implementation of cloud computing systems using the TAM-TOE model and mentioned that 'organization readiness' is an important element among the factors. They also explained 'organization readiness' in two dimensions: financial readiness (financial resources for continuous costs during the implementation and use cloud computing) and technical readiness (infrastructure and personnel for the use and management cloud computing) [27,28]. This study, however, did not explore the specific readiness requirements for critical infrastructure systems like VTS, a gap our research intends to fill.

Ahmed [29] proposed a three-layer hierarchical framework based on the technology-oriented environmental (TOE) framework, which was established through a systematic literature review. By considering the TOE model for cloud computing adoption, the study identified the key factors that influence the use of cloud services in Bangladeshi SMEs. Among the key factors, ‘vision for long term’, ‘commitment of resources’, and ‘establishing goal’ were mentioned as sub-factors of ‘organization’. First, a clear vision for the long term is important in the adoption of cloud technologies. Organizations need to define their long-term goals as well as how cloud computing aligns with their strategic vision. While this framework provides a solid foundation, it lacks specific considerations for the maritime industry and VTS operations, which our study aims to incorporate.

Cho et al. [30] utilized the TOE framework and AHP analysis to examine the key success factors for Samsung Electro-Mechanics’ overseas market expansion strategy. They identified 12 success factors across the dimensions of technology, organization, and environment. Their analysis revealed that the technology dimension was the most important factor. Specifically, within the technology factor, ‘R&D availability’ and ‘production availability’ were analyzed as the most critical influencing factors. This study suggests that global electronic component companies can achieve successful results when they pursue overseas market expansion strategies by prioritizing technology development and focusing on growth strategies suited to the market environment. These findings align with those of Ahmed [29], reaffirming the importance of a long-term vision and resource investment for the organization.

This involves understanding the potential benefits of cloud adoption and how it can contribute to the organization’s growth and success in the future. Cloud adoption requires the commitment of various resources, including financial, human, and technological resources. Organizations need to allocate the necessary budget, invest in the training and skill development of employees, and ensure the availability of the required infrastructure and technologies to support cloud adoption. Without adequate resource commitment, the adoption process may face obstacles and challenges. It is crucial for organizations to establish clear goals and objectives for their cloud adoption initiatives. This includes identifying specific outcomes and targets they aim to achieve through the adoption of cloud technologies. Setting goals helps organizations stay focused, measure their progress, and evaluate the success of their cloud adoption efforts. Clear goals also facilitate decision-making and resource allocation throughout the adoption process.

2.3. Environment Dimension

The environmental dimension refers to aspects including the structure and size of the organization, related institutions, and economic factors.

Kang and Kim [11] analyzed the importance of success factors for “establishing a cloud computing system in domestic cyber universities” by considering the dimensions of the organization and the individual, taking into account the characteristics and size of the work, and derived the priority of importance. Through a survey of experts with knowledge related to cloud computing, 14 important factors were derived from previous studies and models, and the AHP method was used to analyze the differences in the success factors of cloud computing system construction. The results showed that among the 14 sub-factors, the factor with the highest relative importance was ‘maintenance cost’ in the economic aspects. However, this study focused on the educational environment, limiting its consideration of the unique operational environment of maritime safety systems like VTS.

Ahmed [29] mentioned ‘access to the vendor’, ‘suitable user and technical assistance’, and ‘provider relationship’ as sub-factors of ‘environment’ among the key factors influencing the implementation of cloud computing systems. First, establishing effective communication and access to the cloud service provider is crucial. Organizations should establish communication channels with the vendor and ensure accessibility for issue resolution and technical support. Swift and efficient contact with the vendor plays a vital role

in cloud adoption and operations. Secondly, successful adoption of cloud services requires appropriate user training and technical support. Users need to possess the necessary technical skills and knowledge to effectively utilize cloud services. Additionally, having a dedicated technical support team is essential for problem-solving and providing technical assistance. Lastly, the relationship with the cloud service provider holds significant importance. Collaborating closely and building a trusted partnership with a reliable provider can offer benefits in terms of cloud adoption and operations. Organizations should actively manage the relationship with the provider, aiming to foster a cooperative environment that enhances service quality and support. However, this study dealt with general business environments, so it did not fully reflect the operational characteristics and requirements of VTS systems.

Al-Ramahi et al. [31] proposed the TOEQCC framework for sustainable adoption of cloud computing in higher education institutions in Jordan. They identified and analyzed various factors in the technology, organization, environment, and quality dimensions. The study found that government support, trust in cloud service providers, and security and privacy concerns were key factors. Notably, they emphasized that trust in cloud service providers, as an environmental factor, plays a crucial role in accelerating the adoption of cloud computing.

2.4. Institutional Dimension

The institutional perspective refers to relevant policies and laws; the importance of government support and policies is very high, especially for government agencies, when introducing new technology-based systems.

Tashkandi and Al-Jabri [32] analyzed the factors influencing the implementation of cloud computing systems in Saudi Arabian higher education institutions using the TOE framework and mentioned that 'regulatory policies' and 'government pressure' are important elements among the factors. Regulatory policies refer to the policies implemented by the government to regulate the cloud computing market, and government pressure is defined as promoting the adoption of cloud computing through government efforts and encouragement. However, this study focused on educational institutions, and did not consider the stricter security regulations applied to national critical infrastructure like VTS.

Amini and Bakri [23] mentioned that among the factors influencing the implementation of cloud computing systems in SMEs in Malaysia, 'regulatory support' is an important element in the institutional dimension. Regulatory support refers to the support provided by government authorities to promote IT innovation in enterprises [33,34]. Prevailing government regulations can either promote or hinder the adoption of cloud computing by enterprises [35]. However, this study targeted private companies and did not fully address the government policies that affect cloud adoption in public services like VTS.

Naveed et al. [36] used AHP-GDM and FAHP methodologies to analyze and prioritize the key success factors for cloud-based mobile learning (CBML). They identified 'organizations' management readiness' as one of the four main factors, which includes sub-factors such as service support, increased productivity, organizational culture, and commitment towards M-learning. Their study emphasized that organizational preparation and support is the most crucial factor for a successful implementation of CBML in higher education institutions. This aligns with the findings of Tashkandi and Al-Jabri [29], who highlighted the importance of government support and regulatory policies, reaffirming that institutional-level readiness and support play a decisive role in the success of CBML adoption.

In order to provide a comprehensive overview of the existing literature reviewed, we have summarized the key studies across the four dimensions in Table 1. This table categorizes the studies according to their focus areas and the sectors they addressed, illustrating the breadth and depth of our literature review.

Table 1. Overview of reviewed studies.

Dimension	Study	Sector	Key Success Factors
Technology	Yoo and Kim [15], “A Decision-Making Model for Cloud Computing Adoption”	IT	Performance improvement, cost reduction
	Lian et al. [10], “Critical Factors Influencing Cloud Computing Adoption in Hospitals”	Healthcare	Security, system integration, maintenance
	Kang [18], “Priorities of Cloud Computing Adoption Factors in Business”	Business	Cost reduction, performance improvement, data management
	Gui et al. [19], “Vendor Lock-In and Interoperability Challenges in Cloud Adoption for SMEs”	SMEs	Interoperability, data portability
	Sharma et al. [21], “Technological Factors in Cloud Adoption for Higher Education”	Education	Accessibility, scalability, user-friendliness
	Waqar et al. [22], “Key Success Factors for Cloud Computing Adoption in Construction Projects”	Construction	Project management, resource optimization, cost reduction
Organization	Amini and Bakri [23], “Top Management Support in Cloud Adoption for SMEs”	SMEs	Leadership, strategic vision, resource allocation
	Alshamaila et al. [24], “Organizational Factors Affecting Cloud Adoption in SMEs”	SMEs	Organizational culture, employee training, change management
	Gangwar et al. [26], “Readiness for Cloud Adoption in Critical Infrastructure Systems”	General	Technical readiness, resource availability, security
	Ahmed [29], “Long-Term Vision and Resource Commitment in Cloud Adoption for SMEs”	SMEs	Long-term goal setting, resource allocation, sustainability
	Cho et al. [30], “Success Factors for Overseas Market Expansion in Large Enterprises Using Cloud”	Large-scale enterprise	Executive support, global strategy, resource allocation
Environment	Kang and Kim [11], “Environmental Factors Influencing Cloud Adoption in Cyber Universities”	Education	Internet infrastructure, policy support, technology acceptance
	Ahmed [29], “General Environmental Factors for Cloud Adoption”	General	Regulatory compliance, market demand, competitive pressure
	Al-Ramahi et al. [31], “Sustainable Cloud Adoption in Higher Education Institutions”	Higher education	Sustainability, cost efficiency, energy saving
Institutional	Tashkandi and Al-Jabri [32], “Regulatory Policies for Cloud Adoption in Educational Institutions”	Education	Data security regulations, accessibility policies, standards compliance
	Amini and Bakri [23], “Government Support for Cloud Adoption in SMEs”	SMEs	Government grants, policy support, infrastructure investment
	Naveed et al. [36], “Institutional Factors for Cloud-Based Mobile Learning”	Education	Institutional support, technical infrastructure, educational policy
-	Shin et al. [Current Study], “Key Success Factors for Cloud Computing Adoption in VTS Systems”	VTS	System stability, security, scalability, real-time data processing, operational efficiency, etc.

3. Methodology

In this study, to derive the key factors for the success of VTS system cloud computing system adoption, we first analyzed the existing relevant literature and previous studies on the adoption of cloud computing systems in other fields to derive the success factors. Among the derived success factors, we gathered opinions from experts and practitioners, conducted Delphi surveys three times, and finally derived the key success factors. The final success factors were used in the AHP technique for hierarchical analysis to evaluate the relative importance of the success factors.

3.1. Delphi Method

The Delphi technique is a research method aimed at structuring group opinions and discussions [33]. Dalkey, N and Helmer [34] stated that it is a research method suitable for any problem and subsequent policymaking, requiring expert judgment as an essential input. The Delphi method typically possesses the following characteristics. Firstly, it ensures anonymity, allowing participants to express their individual opinions openly. Secondly, through multiple rounds of questions and discussions, it gradually converges and adjusts participants' opinions. Thirdly, it synthesizes the opinions of expert groups and derives a consensus, ultimately leading to a final conclusion.

In this study, three rounds of Delphi surveys were conducted to derive the success factors for VTS cloud computing adoption. The process began with a comprehensive literature review covering Sections 2.1–2.4, which led to the identification of 40 initial factors. These factors encompassed various aspects affecting cloud computing adoption across technological, organizational, environmental, and institutional dimensions.

The first survey involved presenting these 40 factors to the expert panel, resulting in the selection of 30 factors. In the second survey, these 30 factors were evaluated using a 7-point Likert scale, leading to further refinement down to 20 factors. The third and final survey confirmed 12 key success factors. Figure 1 illustrates the step-by-step procedure of the Delphi surveys. The Delphi technique was chosen for this study due to its ability to systematically combine expert opinions and reach a consensus on complex issues. The three-round approach was adopted to allow for iterative refinement of ideas while preventing survey fatigue. Each round had a specific purpose:

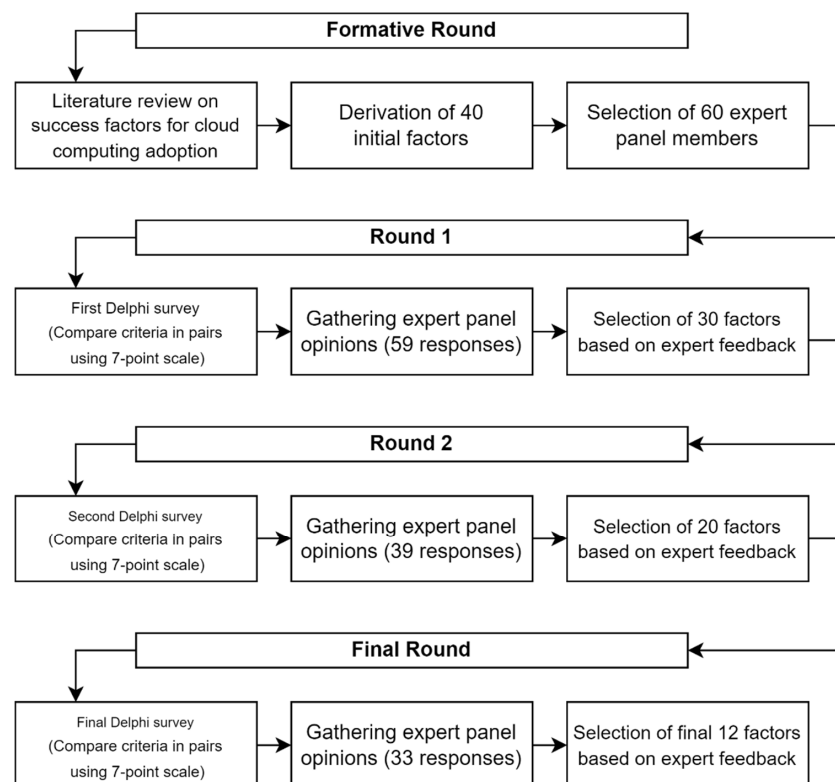


Figure 1. Flowchart of the Delphi method.

Round 1: to gather a comprehensive list of potential success factors from experts, based on the initial 40 factors derived from literature;

Round 2: to evaluate the importance of these factors using a quantitative scale;

Final Round: to achieve a final consensus on the most critical factors.

This step-by-step approach ensured that we captured a wide range of expert opinions while systematically narrowing down the most crucial factors for VTS cloud adoption.

Through this iterative process of feedback and opinion gathering, a consensus among the Delphi panelists was reached and the success factors of VTS cloud computing were objectified. This approach ensured that insights from all the relevant literature were reflected in the survey process, while being validated and refined by expert opinions in the context of VTS systems.

3.2. Analytic Hierarchy Process (AHP) Method

In this study, we utilized the AHP, one of the multi-criteria decision-making (MCDM) techniques, to evaluate the relative importance of success factors for the adoption of cloud computing in VTS systems. AHP is a technique developed by Saaty [35,36] that decomposes a decision-making problem into a hierarchical structure of goals, criteria, and alternatives, and derives the relative importance of the criteria and alternatives through pairwise comparisons. AHP can combine qualitative judgments with quantitative evaluations and is useful for selecting an optimal alternative by simultaneously considering multiple attributes [37]. The AHP method was selected to complement the Delphi technique for several reasons:

1. It provides a structured approach to quantify expert judgments;
2. It allows for the calculation of consistency ratios, ensuring the reliability of the pairwise comparisons;
3. It enables the derivation of relative weights for each factor, providing a clear priority ranking.

By combining the Delphi method with AHP, we were able to identify key success factors and establish their relative importance in the context of VTS cloud adoption. The AHP methodology includes the following steps [36,38] (Figure 2):

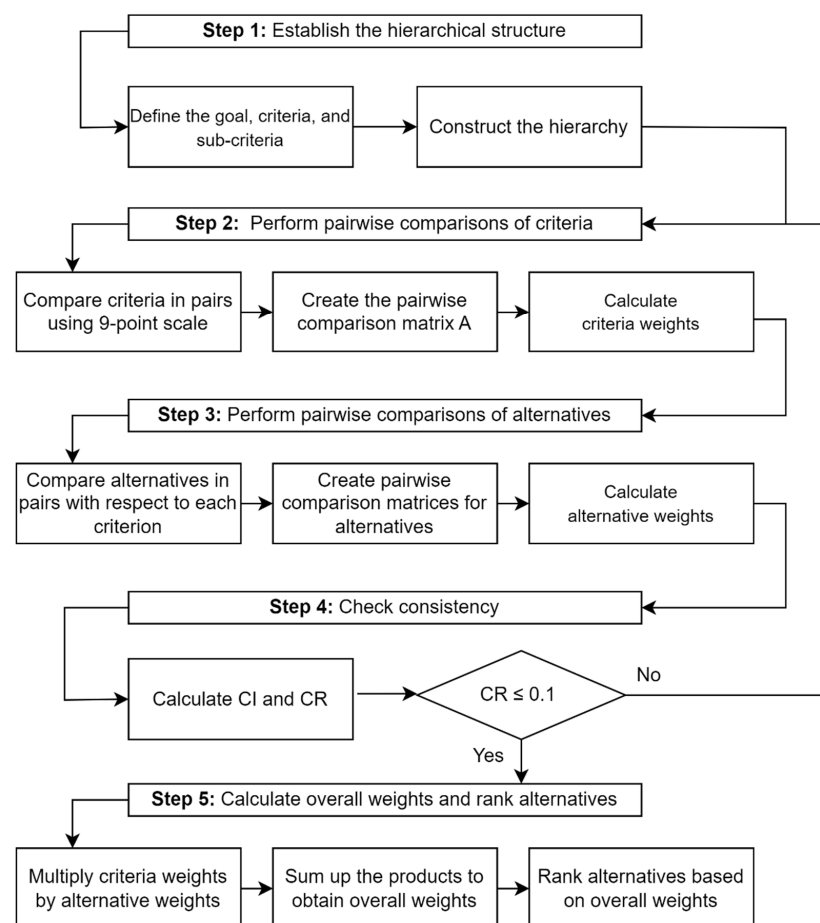


Figure 2. Flowchart of the AHP method.

Step 1: establishing the hierarchical structure of the decision-making problem.

The decision-making problem is decomposed into a hierarchical structure consisting of a goal, criteria, and sub-criteria. The top level represents the goal of decision-making, the middle level consists of the evaluation criteria and sub-criteria for achieving the goal, and the lowest level is composed of the alternatives being evaluated. In this study, successful adoption of VTS cloud computing was set as the top-level goal, the four main dimensions (technology, organization, environment, institution) as the evaluation criteria, and 12 sub-factors as the sub-criteria.

Step 2: pairwise comparison of evaluation criteria and derivation of weights.

Pairwise comparisons were performed to evaluate the relative importance of elements at each level of the hierarchy. This is the process of taking two elements as a pair and evaluating how much more important one element is compared to the other. The 9-point scale proposed by Saaty is commonly used for pairwise comparisons. This scale consists of odd values of 1 (equal importance), 3 (moderately important), 5 (important), 7 (very important), 9 (extremely important), and even values (2, 4, 6, 8) in between, with reciprocal values used for inverse comparisons. The results of the pairwise comparisons are expressed as an $n \times n$ matrix A , where the element a_{ij} represents the relative importance of element i over element j . The diagonal elements a_{ii} of the matrix are always 1, and the reciprocal elements $a_{ji} = \frac{1}{a_{ij}}$ hold. The pairwise comparison matrix A is expressed as follows:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \quad (1)$$

Step 3: pairwise comparison of alternatives with respect to evaluation criteria and derivation of weights.

The relative weights of each element, i.e., the priority vector, are derived from the pairwise comparison matrix. The priority vector can be obtained as the eigenvector corresponding to the principal eigenvalue of the matrix.

The weight vector $W = [w_1, w_2, \dots, w_n]$ of the evaluation criteria $C_1, C_2, \dots, C_n$ is the eigenvector of matrix A , satisfying the following equation:

$$AW = \lambda_{max}W \quad (2)$$

where λ_{max} is the maximum eigenvalue of matrix A . Therefore, the weight vector w can be obtained by solving the above equation and represents the relative weights of the evaluation criteria. The weight vector is generally normalized so that the sum equals 1.

Step 4: consistency check and final ranking.

To assess the consistency of the pairwise comparison matrix, the consistency index (CI) and consistency ratio (CR) are calculated. The consistency index is a measure of the degree of logical contradiction in pairwise comparisons and is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where n is the number of elements being compared. The CR is the value of the CI divided by the random index (RI), where RI is the average CI of randomly generated pairwise comparison matrices. The CR is calculated as follows:

$$CR = \frac{CI}{RI} \quad (4)$$

The RI is given according to the number of elements being compared, as shown in Table 2. For example, when comparing four elements, the RI value is 0.90. As the number of

elements being compared increases, the *RI* value tends to increase gradually. This suggests that it becomes more difficult to maintain consistency in pairwise comparisons as the number of elements being compared increases.

Table 2. Random index (*RI*) values.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Generally, if the *CR* value is 0.1 or less, the pairwise comparison is considered to have reasonable consistency. If the *CR* value is greater than 0.2, the consistency is considered insufficient and the pairwise comparison needs to be performed again.

Step 5: calculation of overall weights and final ranking.

The overall weights of the evaluation criteria and sub-criteria are then calculated. This can be obtained by multiplying the weights of the upper-level elements by the weights of the lower-level elements. The overall weight G_i of sub-criterion i is calculated as follows:

$$G_i = \sum_{j=1}^m w_j l_{ij} \quad (5)$$

where w_j is the weight of evaluation criterion j and l_{ij} is the weight of sub-criterion i with respect to evaluation criterion j , m is the number of evaluation criteria. The overall weights allow us to understand the overall importance of each sub-criterion and identify the factors that should be considered as priorities when adopting VTS cloud computing.

4. Analytical Results

4.1. Delphi Method

The Delphi survey group sizes appear to be very different in the literature. However, it is often recommended to have a group between 9 and 18 participants in order to draw some relevant conclusions and avoid the difficulty in reaching a consensus among experts [39]. However, in this study, to more objectively derive the success factors for “VTS system cloud computing system adoption”, the surveys were conducted three times with a total of 60 experts who had knowledge related to VTS and cloud computing.

The expert panel to whom the questionnaire was sent for the Delphi survey is shown in Table 3.

Table 3. Delphi survey participants demographics.

Division		Frequency	Rate [%]
Age	20–29	3	5.00
	30–39	35	58.33
	40–49	15	25.00
	50–59	6	10.00
	60–69	1	1.67
Careers (years)	3–4	7	11.67
	5–6	14	23.33
	7–8	10	16.67
	9–	29	48.33
Employment	University/educational institution	15	25.00
	Government department	40	66.67
	IT company	4	6.67
	Other	1	1.67
Major filed	VTS operation	35	58.33
	VTS facility	6	10.00
	Maritime industry	16	26.67
	IT	2	3.33
	Other	1	1.67

All survey participants consisted of panels with at least three years of practical experience in VTS, the maritime industry, or the maritime IT field. In addition, their position and project participation history in the relevant field were comprehensively considered, and experts from various backgrounds such as academia, research institutes, industry, and government agencies were included. This was to identify the success factors of VTS cloud computing from an unbiased perspective. The selection of experts for our survey was based on several criteria to ensure a comprehensive and unbiased perspective:

1. Minimum of three years of practical experience in VTS, maritime industry, or maritime IT;
2. Diverse representation from academia, research institutes, industry, and government agencies;
3. Inclusion of experts with various roles and responsibilities within the VTS ecosystem.

This diverse expert panel was crucial to validating the theoretical factors derived from the literature and ensuring their relevance to real-world VTS operations. The diverse backgrounds of the survey participants (academia, research institutes, industry, government agencies) helped evaluate and validate the wide range of factors derived from the literature review in the context of actual VTS environments. This allowed us to confirm the suitability and importance of theoretical factors when applied to real VTS operational environments. In terms of their careers, the proportion of experts with more than nine years of experience was the highest at approximately 48.33%. In terms of employment, the proportion working in government departments was the highest at 66.67%, and most of them worked in VTS. The experts' major fields showed that the proportion in VTS operation was the highest at 58.33%, and most of them were experts working as VTSOs. First, among the three Delphi surveys, the primary survey distributed questionnaires to 60 experts and collected 59 questionnaires. The primary survey presented 40 factors derived from the analysis of previous studies. From the primary survey, 30 factors were re-derived from the 40 factors, as shown in Table 4.

Table 4. Primary Delphi survey result.

Main Dimension	Sub-Dimension (30)
Technology dimension	Stability, convenience, efficiency, integration, compatibility, manageability, customization, flexibility, security
Organization dimension	Resource investment, long-term vision for the organization, prior experience, final objectives, internal human resources
Environment dimension	Cloud computing maintenance costs, data communication speed, regulations and policies on cybersecurity, cloud computing adoption costs, technical support from cloud computing providers, expertise of cloud computing providers, education, high-performance computer resources, openness, adequate testing before cloud computing adoption
Institutional dimension	Government support, government research and development (R&D) support, cloud computing technology standards and validation, government policies, legal liability and insurance, establishment of company guidelines

In the second survey, questionnaires were distributed to 60 experts and 39 questionnaires were collected. Using a 7-point Likert scale, 20 success factors were derived in order of the highest scores from the 30 success factors derived from the first survey, as shown in Table 5.

Table 5. Second Delphi survey result.

Main Dimension	Sub-Dimension (20)
Technology dimension	Stability, convenience, efficiency, integration, compatibility, manageability, security
Organization dimension	Resource investment, long-term vision for the organization, internal human resources
Environment dimension	Data communication speed, regulations and policies on cybersecurity, technical support from cloud computing providers, expertise of cloud computing providers, adequate testing before cloud computing adoption, high-performance computing resources
Institutional dimension	Government support for cloud computing personnel recruitment, government R&D support, cloud computing technology standards and validation, legal liability and insurance

In the third and final survey, questionnaires were distributed to 60 experts and 33 questionnaires were collected. Using a 7-point Likert scale, 12 success factors were derived in order of the highest scores from the 20 success factors derived from the first survey, as shown in Table 6.

Table 6. Final Delphi survey result.

Main Dimension	Sub-Dimension	Definition
Technology dimension	Stability	The ability of the cloud computing system in VTS to provide consistent and uninterrupted services
	Security	The cyber-security capabilities used to protect systems, applications, and data in the cloud environment from external attacks
	Integration	The ability to effectively combine and manage the systems, applications, and data of nationwide VTS
Organization dimension	Resource investment	The financial support from an organizational dimension for cloud computing technology, implementation, and operation
	Internal human resources	The support of human resources within the organization necessary to effectively manage and maintain the cloud infrastructure
	Long-term vision for the organization	Setting the long-term goals and direction that the organization pursues for the adoption of a ‘cloud computing-based VTS system’
Environment dimension	Data communication speed	The speed of data transmission and processing between servers (RADAR, AIS, VHF, etc.)
	Adequate testing before cloud computing adoption	Conducting sufficient testing before deploying the cloud computing system in a real environment
	High-performance computing resources	The hardware resources with high-performance processing capabilities. It typically refers to servers, storage, and network equipment
Institutional dimension	Human resources support from the government	The government’s support of human resources for cloud management and operation
	Government R&D support	The government’s financial and policy support for the R&D of a ‘cloud computing-based VTS system’
	Cloud computing technology standards and validation	The process of verifying whether the cloud-related infrastructure and services meet the organization’s internal requirements and security standards, and standardizing and validating them if necessary

4.2. Analytic Hierarchy Process (AHP) Method

To calculate the weights of the 12 evaluation items derived from the final Delphi survey, the priority of importance was derived and analyzed using AHP. For the AHP analysis, a questionnaire survey was conducted first. The content of the questionnaire survey was largely composed of three parts. The first part included survey items on the type of respondents. The second part consisted of explanations of how to respond to the survey for respondents who were not familiar with the AHP technique, thereby reducing errors and missing values in the response results. The third part arranged the 12 evaluation items into pairwise comparison questions. The items were prepared using the ‘9-point Likert scale’, which is commonly used to express the relative importance of each factor. In other words, the minimum level of the scale was 1 and the maximum was 9. The general characteristics of the AHP survey respondents are shown in Table 7. Among the respondents, 57.63% were in their 30s, and those with more than nine years of experience accounted for the largest proportion at 49.15%. Government agencies accounted for more than half of the workplaces at 66.10%, and VTS operation (57.63%) was the most common major field.

Table 7. The general characteristics of the AHP survey respondents.

Division		Frequency	Rate [%]
Age	20–29	3	5.08
	30–39	34	57.63
	40–49	15	25.42
	50–59	6	10.17
	60–69	1	1.69
Careers (years)	3–4	7	11.86
	5–6	13	22.03
	7–8	10	16.95
	9–	29	49.15
Employment	University/educational institution	15	25.42
	Government department	39	66.10
	IT company	4	6.78
	Other	1	1.69
Major filed	VTS operation	34	57.63
	VTS facility	6	10.17
	Maritime industry	16	27.12
	IT	2	3.39
	Other	1	1.68

As a result of the AHP survey, 42 out of a total of 60 respondents met the CR 0.1 or lower criterion and were used for the final analysis. According to the AHP analysis results, the technological dimension (0.3342) showed the highest importance in the main dimension, followed by the institutional dimension (0.2387), environmental dimension (0.2135), and organizational dimension (0.2137) (Table 8).

Table 8. The relative importance of main dimensions.

Main Dimension	Weight	Priority
Technology dimension	0.3342	1
Institutional dimension	0.2387	2
Environment dimension	0.2135	3
Organization dimension	0.2137	4

Table 9 shows the local weight, local priority, global weight, and global priority of each sub-factor. Local weight represents the relative weight of sub-factors within each

upper dimension, and local priority refers to the priority within the corresponding upper dimension. For example, in the technological dimension, the local weight and local priority were highest in the order of stability (0.4989), security (0.2805), and integration (0.2206). On the other hand, global weight represents the overall weight of each sub-factor in the entire hierarchical structure and is calculated by multiplying the local weight of the corresponding sub-factor by the weight of the upper dimension. Global priority refers to the priority of all factors based on the global weight.

Table 9. The relative importance and ranking of sub-factors.

Main Dimension	Sub-Factor	Local Weight	Local Priority	Global Weight	Global Priority
Technology dimension	Stability	0.4989	1	0.1667	1
	Security	0.2805	2	0.0937	3
	Integration	0.2206	3	0.0737	5
Institutional dimension	Human resources support from the government	0.3592	1	0.0857	2
	Government R&D support	0.3264	2	0.0779	4
	Cloud computing technology standards and validation	0.3144	3	0.0750	6
Environment dimension	Adequate testing before cloud computing adoption	0.3873	1	0.0827	7
	Data communication speed	0.3185	2	0.0680	9
	High-performance computing resources	0.2942	3	0.0628	10
Organization dimension	Resource investment	0.3612	1	0.0772	8
	Internal human resources	0.3467	2	0.0741	11
	Long-term vision for the organization	0.2922	3	0.0624	12

In the case of stability, the local weight is 0.4989, which has the highest weight within the technological dimension, and the local priority is ranked first. Additionally, the global weight is calculated as 0.1667 ($= 0.3342 \times 0.4989$), showing the highest value among all factors, and the global priority also ranked first. This suggests that stability is the most important factor for the successful adoption of VTS cloud computing. Human resource support from the government ranked first with a local weight of 0.3592 and a local priority of 1 in the institutional dimension, and its global weight of 0.0857 ranked it as the second highest importance among all factors. Security was the second most important factor in the technological dimension (local weight 0.2805, local priority 2), but overall it showed the third highest importance with a global weight of 0.0937.

5. Discussion

5.1. Technological Dimension

The analysis results showed that the technological dimension is the most important for the successful adoption of VTS cloud computing. This is consistent with the findings of several previous studies on the adoption of cloud computing [10,15,21]. Within the technological dimension, stability ranked first. This was judged to be because system interruptions or errors are directly related to maritime safety due to the nature of VTS operations. In fact, given the characteristics of vessel traffic control, which operates 24 h a day 365 days a year, stable system operation is essential. To ensure this stability, delay issues caused by cloud server OS and software problems should be minimized. Wen et al. [40] stated that situations may occur where service access becomes impossible due to hardware defects, software bugs, or network interruptions on the CSP side. For systems like VTS, where system availability is critical, such issues can pose an even more serious risk. Therefore, when adopting VTS cloud computing, it is necessary to thoroughly analyze potential problems and proactively respond to them, along with securing technical stability. This requires multifaceted efforts such as thorough requirements analysis, securing sufficient capacity, and establishing backup and recovery systems. In addition, ensuring service

levels through service level agreements (SLAs) and continuous operational management, including periodic monitoring and performance tuning, should be carried out in parallel.

Security ranked second. As the vulnerability to external attacks may increase in the cloud environment, securing cybersecurity capabilities becomes an essential requirement [11]. The VTS system is currently operated as a closed network with no external communication, which limits the convenience of information sharing due to the disconnection of external communication transmission and reception, but it also offers relatively high security. However, if a public cloud with an external CSP is used, the risk of security vulnerabilities increases, making security issues a critical concern. In other words, as some security control authority shifts from the internal organization to the external CSP, concerns may arise regarding data confidentiality and integrity. In particular, since the VTS system handles sensitive security information, serious damage is anticipated in the case of external leakage. Therefore, to enhance the security of VTS information, it is necessary to establish a multi-layered security system, including sophisticated access control design, encryption of transmitted and stored data, and isolation between virtual machines [41]. Additionally, it is essential to derive VTS cloud-specific security requirements, reflect them in SLAs, and clearly define the responsibilities and obligations of CSPs. In the long term, security capabilities should be continuously strengthened by adopting new paradigms such as the zero-trust security model [42].

Integration ranked third. The current VTS system is extremely limited in its connection to external systems due to security reasons. However, VTS operators are now required to collect and process various maritime information, deliver it to vessels, and handle data using multiple information access systems. Therefore, seamless integration and linkage between individual VTS systems are also emerging as major objectives of cloud computing adoption [43]. By integrating the current individual systems into a single platform, operational efficiency should be improved, such as real-time sharing of vessel information between adjacent VTS centers and joint responses to maritime accidents. Particularly in maritime traffic, cloud computing facilitates decentralized documentation, enhancing the transparency and effectiveness of incident resolution [44]. In the long term, it could evolve into a part of next-generation e-navigation through data linkage with other organizations such as port logistics, shipping companies, and related agencies. However, integration of legacy systems and the cloud and linkage between heterogeneous clouds are not easy tasks. Compatibility issues may arise due to different interfaces, APIs, and data formats [45]. Therefore, it is important to ensure interoperability by applying open standard protocols and common data models from the design stage of the cloud integration architecture. To ensure the stable and secure operation of a VTS cloud, openness, standardization, and flexibility are necessary, requiring changes in governance and organization as well as close cooperation with stakeholders.

5.2. Institutional Dimension

In the institutional dimension, human resource support from the government was evaluated as the most important factor, ranking first. To adopt a VTS cloud, it is essential to secure specialized personnel dedicated to the cloud system, in addition to the workforce managing the existing legacy systems. Considering that VTS handles sensitive security information such as vessel movements and cargo information, it is desirable to secure cloud experts as internal personnel within the organization. Furthermore, as VTS in South Korea plan to analyze big data using the cloud platform, the demand for internal experts with cloud-based big data processing capabilities is also expected to increase. Additionally, when adopting a private cloud, it is necessary to ensure the procurement of infrastructure management personnel and security experts to operate its own data center. Therefore, the establishment and supply of a systematic cloud workforce development roadmap at the national level is urgently needed.

Government R&D support is a crucial factor for the technological advancement and innovation of VTS cloud systems. Government R&D support is essential for the development

of cloud technology, and it plays a significant role particularly in the technological progress and innovation of VTS clouds [46]. Such support can significantly accelerate R&D activity in cloud-based technologies, thus providing a solid foundation for innovation in VTS cloud systems [47]. Investment at the governmental level is necessary for the development of advanced control technologies integrating cloud-based maritime ICT. Encouraging the participation of small- and medium-sized cloud solution companies in cloud technology development can contribute to the creation of a new industrial ecosystem. Moreover, designing for interoperability and compatibility from the development stage will facilitate subsequent linkage and expansion.

Cloud technology standards and validation ranked third. Standardization plays a crucial role in cloud adoption, particularly for VTS cloud systems which need to transmit, process, and store real-time data collected from various sensors such as radar, AIS, and VHF, so establishing standards in the fields of transmission, communication, and IT is essential. In South Korea, the process of establishing technical standards for building a cloud-based VTS system is currently underway, focusing on three key standardization tasks: radar signal standards, target tracking signal standards, and inter-center signal integration standards. These efforts aim to ensure interoperability between heterogeneous equipment and systems, enhance data compatibility, and resolve vendor lock-in issues. Therefore, the government should proactively establish national standards related to VTS cloud systems by closely monitoring international standardization trends and gathering input from both the VTS community and the industry.

5.3. Environmental Dimension

In the environmental dimension, sufficient testing before actual adoption was identified as the most important factor. Cloud adoption involves large-scale resource investment, making it difficult to change after the decision to adopt. Therefore, it is essential to confirm the system's stability and performance through thorough testing and verification in advance. For example, in 2020, South Korea conducted a project to replace the nationwide VTS system with a new manufacturer's system. The existing system and the new system were operated simultaneously for two years to verify stability. This implies that when transitioning to a large-scale system, it is crucial to discover and resolve problems in advance by going through a sufficient verification period. In a situation where there are no reported cases of cloud adoption in VTS worldwide, rather than rushing into the adoption of a cloud system, the process of demonstrating a system's reliability through long-term testing should precede. To achieve this, the development of test scenarios, the establishment of an anomaly response system, and securing a sufficient pilot operation period are necessary.

The importance of data communication speed was also emphasized. Elif and Selçuk [48] indicated that an enhanced communication environment supported by cloud computing could significantly reduce operational conflicts between systems. Therefore, for the effective operation of a VTS cloud, a high-speed network infrastructure that supports real-time transmission and processing of large-scale data is crucial. According to tests conducted during the VTS cloud R&D process, when remotely monitoring VHF communication from the Busan VTS to Ulsan VTS a delay of 1–2 s occurred. Although this is a short delay, it can be a potential risk factor given the nature of VTS operations which are directly related to vessel safety. Moreover, the VTS system requires considerable bandwidth to collect and process vast amounts of real-time data from sensors such as radar and CCTV. Consequently, when introducing the VTS cloud system, it is necessary to review communication infrastructure improvement measures such as securing sufficient network capacity, introducing edge computing, applying traffic engineering, and ensuring redundancy with high-speed wireless networks.

Another factor that determines the efficiency of VTS cloud operation is the procurement of high-performance computing resources. High-performance computing typically has three main components: compute, storage, and networking [49]. VTS need to collect and analyze large volumes of data from various sources such as radar and CCTV in real-time, thus high-performance servers and storage capable of rapid processing are essential.

The transition to the cloud overcomes physical limitations and enables flexible resource allocation; however, it also requires an underlying high-performance infrastructure to support it. A recent VTS cloud R&D project confirmed the limitations of processing the rapidly increasing data with general-purpose servers, concluding that significant performance improvement by building a high-performance computing cluster and applying workload distribution and parallelization techniques is needed.

5.4. Organizational Dimension

In the organizational dimension, resource investment was identified as the most crucial factor. Despite the presence of advanced technology and environmental infrastructure, achieving desired outcomes can be challenging without the support of organizational capabilities and investment. The transition to the cloud not only involves technology adoption but also organization-wide changes, necessitating sufficient funding to drive innovation. The current VTS cloud system R&D in South Korea is limited to small-scale budget allocation at the individual VTS center level, which is expected to face difficulties in comprehensive cloud migration. Considering that the adoption of cloud computing in VTS is a public project directly linked to national maritime safety, expanding government-level investment and securing stable financial resources is imperative.

Meanwhile, securing internal specialized personnel and enhancing their capabilities is also essential for the stable operation of a VTS cloud. Cloud technology is rapidly evolving, so continuous learning and expertise development are required to effectively utilize it. Given the nature of the VTS system, which handles security information, rather than simply relying on external personnel, it is necessary to foster cloud experts within the organization and create an environment where they can lead innovation. Most VTS operating agencies in Korea lack specialized ICT personnel, and even the existing personnel are mostly specialized in operating legacy systems, so they face difficulties in cloud adoption. To overcome this, it is necessary to establish and implement a systematic workforce development strategy from a long-term perspective. In conclusion, the transition to a VTS cloud is not a one-time event but a process of continuous innovation, and the key driving force leading this is none other than ‘internal human resources’.

Lastly, establishing a long-term vision for the organization is also an important factor for the successful adoption of a VTS cloud. It is not simply about adopting the latest technology, but clearly establishing the direction and goals that the organization will pursue through it. The set goal should be to enhance VTS operations beyond the cloud adoption and enable real-time monitoring of maritime situations without the constraints of time and space. In fact, Schaefer et al. [50] emphasize that the long-term goal of cloud-based systems should be to support real-time collaboration and monitoring in geographically dispersed environments. To this end, top management should actively communicate with members, share the necessity for change and vision, and present an action plan to achieve it. Furthermore, it is necessary to establish a mid- to long-term roadmap, set phased goals, and seek specific implementation plans.

5.5. Open Challenges

While our study has identified key success factors for VTS cloud adoption, several open challenges remain that warrant further investigation:

1. Data sovereignty and privacy: As VTS systems handle sensitive maritime data, ensuring data sovereignty and privacy in a cloud environment remains a significant challenge. Future research should explore how to balance the benefits of cloud computing with strict data protection requirements;
2. Interoperability between different VTS systems: With various VTS systems potentially adopting different cloud solutions, ensuring seamless interoperability between these systems is crucial. Further studies are needed to develop standardized protocols and interfaces for VTS cloud systems;

3. Cybersecurity in a connected environment: As VTS systems become more connected through cloud adoption, they may become more vulnerable to cyber-attacks. Developing robust cybersecurity measures specifically tailored for cloud-based VTS systems is an ongoing challenge;
4. Performance optimization for real-time operations: VTS operations require real-time data processing and decision-making. Optimizing cloud performance to meet these stringent requirements, especially in areas with limited network infrastructure, remains a challenge;
5. Regulatory compliance in a rapidly evolving technological landscape: As cloud technologies evolve rapidly, ensuring that VTS cloud systems remain compliant with maritime regulations and standards is an ongoing challenge that requires continuous attention.

6. Conclusions

This study aimed to derive the key success factors to consider when adopting cloud computing in VTS systems and evaluate the relative importance of each factor. To achieve this, potential success factors were first identified through a literature review and 12 final success factors were derived through Delphi surveys of expert groups. Then, the relative importance and priority of each factor were analyzed using the AHP technique. The results showed that the priority of sub-factors in the technological dimension was in the order of stability, security, and integration.

This suggests that stable system operation, data security, and seamless information integration between linked systems are essential for VTS' core functions of maritime traffic control and safety assurance. The priority of sub-factors in the institutional dimension was in the order of human resources support from the government, government R&D support, and cloud computing technology standards and validation. This implies that systematic support and management at the government level can determine the success or failure of a VTS cloud, as it is a large-scale project led by government. The priority of sub-factors in the environmental dimension was in the order of adequate testing before cloud computing adoption, data communication speed, and high-performance computing resources.

This suggests that it is important to precede with the process of demonstrating the reliability of the system through long-term testing rather than hastily adopting a VTS cloud, and shows that verified performance and infrastructure construction should be prioritized as a VTS cloud needs to process large-scale data in real-time. Lastly, the priority of sub-factors in the organizational dimension was in the order of resource investment, internal human resources, and long-term vision for the organization. This suggests that a comprehensive approach is required to drive organization-wide changes beyond technology adoption. Theoretically, this study is significant in that it identified the key success factors of VTS cloud computing by combining the TOE framework and institutional perspectives. While existing TOE-based studies have mainly focused on enterprises, this study expanded the scope of application to the public sector, specifically to VTS. It particularly enhanced the practical relevance of the theory through empirical analysis reflecting the opinions of experts in the field. Furthermore, by deriving the priorities among factors using the AHP technique, information that can be practically utilized for decision-making was provided.

The results of this study provide important implications for policymakers and practitioners who are planning to adopt cloud computing in VTS. Above all, it demonstrates the need for a holistic approach encompassing institutional, environmental, and organizational dimensions, not limited to technological changes. Multifaceted efforts are required, such as establishing a mid- to long-term roadmap at the government level, revising laws and regulations, and establishing a governance system. Additionally, it is necessary to proactively identify technical and operational issues through initial pilot projects and seek a phased expansion strategy.

In addition, we identified several open challenges, including data sovereignty, interoperability, cybersecurity, performance optimization, and regulatory compliance, which

warrant further investigation in future studies. The findings of this study provide crucial insights for enhancing maritime safety through the adoption of cloud computing in VTS systems. By prioritizing key success factors such as system stability and real-time data processing, VTS systems can significantly improve their operational efficiency and contribute to safer maritime operations.

Furthermore, efforts should be made to enhance the acceptance of various stakeholders through communication and consensus-building. However, this study has the following limitations. First, caution is needed in generalizing the research results due to the limited representativeness and size of the expert panel. Although experts from various fields were targeted, it is difficult to say whether the perspectives of all stakeholders were comprehensively considered.

Moreover, the inherent limitations of the Delphi and AHP techniques, such as respondent bias and the assumption of independence between the evaluation criteria, should also be considered when interpreting the results. Therefore, in the future, we plan to complement the validity of this study through various methodologies, such as surveys targeting a wider group of experts and case studies.

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