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# CRITICAL SUCCESS FACTORS OF INTERNET OF THINGS APPLICATIONS IN TAIWAN'S INTERNATIONAL COMMERCIAL PORTS

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Key words: critical success factors, international commercial port, internet of things.

## ABSTRACT

Rapid technological developments have led to innovations in international commercial port operations worldwide. Leading ports have effectively applied new technologies to integrate their port resources. These ports have used the new technologies to reduce waste, thereby increasing their global influence and economic value. The Internet of things (IoT) enables vehicles, devices, and other items embedded with sensors and actuators to exchange data across an established network. IoT technology has been extensively applied in commercial ports, including in cruise-assisting transportation systems that simultaneously manage port electricity, water, and energy use. This study suggests that technology development and user trust should receive greater attention in the development of Taiwan's international commercial ports.

## I. INTRODUCTION

The Internet of things (IoT) relies on domain-specific communication protocols and heterogeneous hardware (e.g., sensors, gateways, and actuators). It has been widely used in smart cities, intelligent buildings, supply chains, and other processes and industries. IoT architectures can be divided into three layers: network, sensor, and application. IoT technology has been improved through developments in wireless mobile communication, the sensor layer, and cloud computing, and these improvements have facilitated a greater range of IoT applications. IoT enables the control and remote sensing of objects across a network infrastructure (Miorandi et al., 2012). The emergence and evolution of IoT has facilitated substantial improvements in management efficiency for resource distribution and consumption, thereby benefitting suppliers, operators, and consumers.

IoT technology plays a crucial role in the modern information technology era. IoT objects may exchange information using a sensor apparatus, such as a global position system, radio frequency identification (RFID), or SmartSens, to perform tracking, intelligent recognition, monitoring, and management of other objects (Xu and Qian, 2011). Among the components of the management system, the network layer enables the creation of platforms or networks, including cloud computing platforms, Internet, and private networks. To create opportunities for increasing direct integration and economic benefits of the physical world based on the computer system, crucial technical support for the integration of the IoT with the physical world and all economically beneficial applications therein. The main function of the sensor layer is similar to that of the nerve endings in a human body: information recognition and collection. The sensor layer mainly comprises various sensor gateways, such as those for humidity, density, and temperature. The application layer of the IoT involves flexible connections between the management system and users with various requirements at different levels of hybrid industries.

Numerous governments worldwide have increased their attention to IoT systems because of the systems' market prospects. IoT systems represent the third wave of information technology, following the Internet and mobile communication networks. More than two billion people worldwide use the Internet to send and receive emails, play online games, share local information, engage with social networking applications, access multimedia services, and browse websites (Zhu et al., 2011). Data about consumer behavior on the Internet is constantly generated and exchanged. An increasing number of individuals have gained access to new means of communication and to information from around the world. Use of the Internet as a global platform for interactions among smart objects has stimulated innovations in the computing, coordination, and communication functions of machines. These innovations have enabled global connection of "smart" objects, resulting in a cyber-physical infrastructure. This infrastructure, in turn, had led to further innovations in the communication and information technology sectors by embedd-

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ing the electronics into physical objects. IoT also leads to new applications and services to use the connections between the virtual and physical worlds. Thus, the extreme heterogeneity of IoT-based systems and global reach of the IoT have also resulted in challenges to development and practical application.

The IoT relies on the support of various facilities and equipment, such as waterproof cameras for streaming underwater videos and biochip transponders to monitor farm animals. In the realization of IoT-based applications, the IoT concept has evolved and has been used to enhance traditional technologies, such as wireless sensors, automated systems (including building automation and smart family systems), embedded systems, and control systems. IoT applications have become integrated with technology in all aspects of operating productions and people's daily lives. The IoT has also been applied in industrial and social fields (e.g., engineering operations, city management, public security, and marketing).

The IoT can also be used to integrate control, information, and communications processes across various related port management and transportation systems. Innovations in port operations have increased the sophistication and complexity of the production environment, resulting in more efficient processes. These enhancements are interrelated with the diversity of the operators, managers, facilitators, and customers. In general, customer requirements and other factors (e.g., degree to which ports are connected to a specific distribution channel) vary according to the transportation cargo; thus, international commercial ports are a critical part of industrial supply chains and a natural focus for employment and regional development initiatives. The main function of international commercial ports is to serve as convenient stockholding locations and efficiently integrate port resources to respond to individual customers' specific service requirements (Pettit and Beresford, 2009). The world's major commercial ports have begun to revolutionize operations; Taiwan's port operations must also be further developed to maintain and increase the international influence of these ports.

IoT application to the operating management of international commercial ports represents a satisfactory approach, and it extends to all aspects of transportation systems (e.g., drivers, infrastructure, and vehicles) has produced substantial results. For instance, regarding logistics and port equipment management, an IoT platform system can be used to continually monitor equipment, transactions, and location of cargo through wireless sensors, and the system may send alerts to operators when management exceptions occur (e.g., ship delay, cargo damage, and theft). This study explored the critical success factors (CSFs) of IoT applications in Taiwan's international commercial ports to help port operators and managers monitor operations more efficiently.

The remainder of this paper is organized as follows: Section II briefly reviews the literature on IoT applications and related CSFs. An interval-valued fuzzy number measurement method is introduced in Section II, and the research process comprising an expert questionnaire, data collection and analysis, and evaluation of results are summarized in Section IV. Based on our findings, Section V offers conclusions regarding the development of Taiwan's international commercial ports.

## II. LITERATURE REVIEW

### 1. IoT Applications

In the twentieth century, Carnegie Mellon University was the first institution to propose the concept of the IoT, and a Coke machine was modified to become the first Internet-connected appliance. Subsequently, scholars began focusing on IoT-related science and technology. Nabati and Taheri (2016) indicated that the concept of an IoT system was first introduced by Kevin (1999) at an international conference. Nabati and Taheri (2016) also indicated that IoT applications would revolutionize wireless communications and become the dominant technological platform in this field. Yan et al. (2008) discussed the critical role of IoT applications for RFID improvement and indicated that any object, from a tire to a toothbrush, could become connected to the IoT. He further argued that this pervasive technology would lead to new levels of global interconnection based on smart object networks. Atzori et al. (2010) indicated that the main reason for use of the IoT in complex scenarios is the potential integration of communications solutions and technological developments. Tracking technologies, communication protocols, wired and wireless sensors, and distributed intelligence systems may be integrated using the IoT, thus enhancing the usability of related objects. Xu and Qian (2011) suggested that crop growth models could be embedded in an IoT-based system to increase the models' intelligence and adaptiveness. They reported practical experience in initial study of this concept and proposed engineering challenges to address in further deployment of the system.

Researchers have explored various platforms for IoT applications. Haller et al. (2008) studied the relationship between the IoT and the future of the Internet in general with regard to business value. Findings of this and related studies suggest that enterprises must invest in research on IoT applications. Moreover, real-world awareness and business process decomposition are the two major paradigms supporting the future business value of IoT. Qian and Wang (2012) proposed an IoT application architecture on the basis of two basic IoT concepts; their proposed model includes the key technologies for convergence gateway access, network protocol layers for the underlayer network distribution, a network control platform for interconnected network integration, and an application terminal platform for terminal user applications. Vogler et al. (2015) introduced the DIANE framework for dynamic generation of optimized deployment topologies for IoT applications. Chen et al. (2017) developed a technique based on distributed collaborative filtering to select feedback using a similarity rating of users' social contacts, friendships, and communities; based on the results, an adaptive filtering technique was proposed to enhance IoT applications.

### 2. Critical Success Factors

CSFs determine an organization's performance outcomes

(Digman, 1986; Guynes et al., 1996). They are commonly assessed in research methods that are used to examine purchase decisions and other consumer behaviors. Nijkamp and Yim (2001) summarized the research concept of CSFs as "operationalizations of our independent variable."

International cargo trade has increased substantially; thus, international commercial ports have become economic lifelines for some countries. CSFs for ordinary port operations have been explored and reported in the literature. Keceli et al. (2007) indicated that although operators of Turkish ports heavily invested in management and technology infrastructure, they delayed the implementation of information technology, limiting the efficiency of port operations. The researchers then investigated the CSFs for operation efficiency in Turkish international commercial ports. Mutua (2014) employed descriptive quantitative and qualitative analysis methods to evaluate the CSFs of public-private partnership project designs for the Luma port in Kenya; the data were collected through questionnaires, and statistical analysis was performed using SPSS.

New roles are being ascribed to some international commercial ports within supply chain logistics, and contrasting patterns and development paths among ports have been observed. For example, operators of the Associated British Ports in the United Kingdom aim to offer logistical services with smart features to fulfill the individual customer requirements. The IoT has been used to integrate dynamic interactions among crucial components of port transportation systems, including with regard to smart traffic control, fleet management in ports, intervehicular and intravehicular communication systems, and port assistance. However, few studies have examined IoT applications related to port operations. The current study explored the CSFs of IoT application in the operation of Taiwan's international commercial ports according to port development status and basic national conditions.

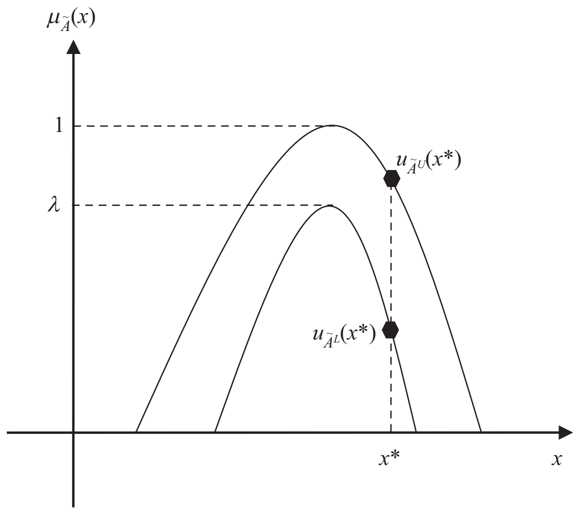


**Fig. 1. Interval-valued fuzzy set $\tilde{A}$ .**

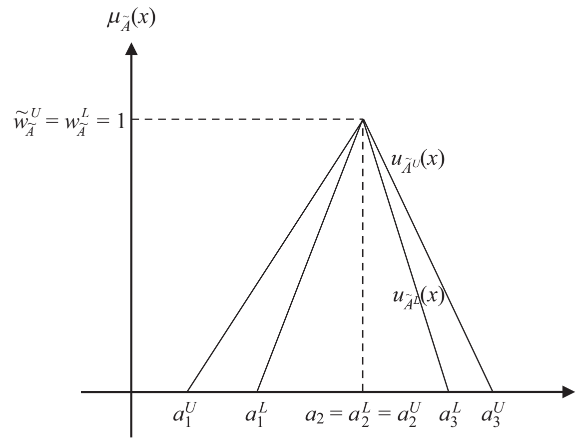


**Fig. 2. Normal triangular interval-valued fuzzy number *A***

## III. METHODOLOGY

In this study, an expert questionnaire was used to evaluate the CSFs. Accurate quantification of factor values by individual experts in this context is impossible, and differences in the surveyed individuals' subjective evaluations may lead to biased results. Therefore, a semantic evaluation was performed to reduce the effects of human error, and the importance of each factor is reflected in an interval-valued fuzzy number. The study methods were based on the interval-valued fuzzy number approach for supplier selection proposed by Lee et al. (2016).

Based on the research of Gorzalczany (1987), the interval-valued fuzzy numbers are defined as follows:

$$\tilde{A} = \{x, [\mu_{\tilde{A}^L}(x), \mu_{\tilde{A}^U}(x)]\}, x \in (-\infty, \infty), \mu_{\tilde{A}^L},$$

$$\mu_{\tilde{A}^U} : (-\infty, \infty) \to [0, 1],$$

$$\mu_{\tilde{A}^L} \le \mu_{\tilde{A}^U}, \forall x \in (-\infty, \infty),$$

$$\mu_{\tilde{A}}(x) = [\mu_{\tilde{A}^L}(x), \mu_{\tilde{A}^U}(x)], x \in (-\infty, \infty),$$

where $\mu_{\tilde{A}^U}(x)$ denotes the upper limit of the degree of membership and $\mu_{\tilde{A}^L}(x)$ denotes the lower limit. An interval-valued fuzzy number is presented in Fig. 1, which illustrates that the degree of membership at $x^*$ is in the interval $[\mu_{\tilde{A}^L}(x^*), \mu_{\tilde{A}^U}(x^*)]$.

Notably, the current study focuses on the normal triangular interval-valued fuzzy number defined by Lee et al. (2016), under a specific situation for the triangular interval-valued fuzzy number proposed by Yao and Lin (2002). The normal triangular interval-valued fuzzy number $A$ is a triangular interval-valued fuzzy number occurring in $a_2^L = a_2^U$ and $\tilde{w}_{\tilde{A}}^L = \tilde{w}_{\tilde{A}}^U = 1$. Let $a_2 = a_2^L = a_2^U$ . Then, $A = (A^L, A^U) = ((a_1^L, a_2^L, a_3^L), (a_1^U, a_2^U, a_3^U)) = (a_1^U, a_1^L, a_2, a_3^L, a_3^U)$ denotes the normal triangular interval-valued fuzzy number $A$, as presented in Fig. 2.

According to Chen (1997), Hong and Lee (2002), and Chen and Chen (2008), supposing that two normal triangular interval-valued fuzzy numbers are given by $A$ and $B$; then, arithmetic operations of $A$ and $B$ can be described as follows:

(1) Addition of two normal triangular interval-valued fuzzy numbers:

$$A \oplus B = (a_1^U, a_1^L, a_2, a_3^L, a_3^U) \oplus (b_1^U, b_1^L, b_2, b_3^L, b_3^U)$$
$$= (a_1^U + b_1^U, a_1^L + b_1^L, a_2 + b_2, a_3^L + b_3^L, a_3^U + b_3^U)$$

(2) Subtraction of two normal triangular interval-valued fuzzy numbers:

$$A \Theta B = (a_1^U, a_1^L, a_2, a_3^L, a_3^U) \Theta (b_1^U, b_1^L, b_2, b_3^L, b_3^U)$$
$$= (a_1^U - b_3^U, a_1^L - b_3^L, a_2 - b_2, a_3^L - b_1^L, a_3^U - b_1^U)$$

(3) Multiplication of two normal triangular interval-valued fuzzy numbers:

$$A \otimes B = (a_1^U, a_1^L, a_2, a_3^L, a_3^U) \otimes (b_1^U, b_1^L, b_2, b_3^L, b_3^U)$$
$$= (a_1^U \times b_1^U, a_1^L \times b_1^L, a_2 \times b_2, a_3^L \times b_3^L, a_3^U \times b_3^U)$$

(4) Division of two normal triangular interval-valued fuzzy numbers:

$$A \phi B = (a_1^U, a_1^L, a_2, a_3^L, a_3^U) \phi (b_1^U, b_1^L, b_2, b_3^L, b_3^U)$$
$$= (a_1^U / b_3^U, a_1^L / b_3^L, a_2 / b_2, a_3^L / b_1^L, a_3^U / b_1^U)$$

Based on these arithmetic operations, Lee et al. (2016) introduced a ranking algorithm using the normal triangular interval-valued fuzzy numbers for supplier selection. Suppose $m$ suppliers are evaluated according to $n$ criteria. The normal triangular interval-valued fuzzy number $A_{ij}$ denotes the rating of the $i$th supplier under the $j$th criterion, and the normal triangular interval-valued fuzzy number $W_j$ denotes the weight of the $j$th criterion. Therefore, the preference intensity function of one normal triangular interval-valued number $A$ over another number $B$ can be described as $Q(A, B) = \max\{\mu_R(A, B), 0\}$, where the extended fuzzy preference relation $\mu_R(A, B) = \int_0^1 ((A\Theta B)_{m\alpha}^L + (A\Theta B)_{m\alpha}^U) / 2d\alpha$ is true for any normal triangular interval-valued numbers denoted by $A$ and $B$.

Let $J$ be the set of benefit criteria and $J'$ be the set of the cost criteria where

$$J = \{1 \le j \le n \text{ and } j \text{ belongs to the benefit criteria}\},$$

$$J' = \{1 \le j \le n \text{ and } j \text{ belongs to the cost criteria}\},$$

and $JUJ' = \{1, \ldots, n\}$.

Larger values for benefit criteria indicate better suppliers, whereas larger values for cost criteria indicate worse suppliers. The advantage of the $i$th supplier under the $j$th criterion is given by

$$a_{ij} = \begin{cases} \sum_{k \ne i} Q(W_j A_{ij}, W_j A_{kj}) \text{ if } j \in J \\ \sum_{k \ne i} Q(W_j A_{kj}, W_j A_{ij}) \text{ if } j \in J' \end{cases} \quad (1)$$

Similarly, the disadvantage of $i$th supplier under the $j$th criterion is given by

$$d_{ij} = \begin{cases} \sum_{k \ne i} Q(W_j A_{kj}, W_j A_{ij}) \text{ if } j \in J \\ \sum_{k \ne i} Q(W_j A_{ij}, W_j A_{kj}) \text{ if } j \in J' \end{cases} \quad (2)$$

Notably, both $a_{ij}$ and $d_{ij}$ are crisp numbers. The superiority of the $i$th supplier is given by

$$S_i = \sum_{j=1}^{n} a_{ij} \quad (3)$$

The inferiority of the $i$th supplier is given by

$$I_i = \sum_{j=1}^{n} d_{ij} \quad (4)$$

The composite index for the $i$th supplier is given by

$$C_i = \frac{S_i}{S_i + I_i} \quad (5)$$

According to the aforementioned introduction, the entire evaluation process in the ranking algorithm for the normal triangular interval-valued fuzzy number can be summarized as follows:

Step 1. Identify the corresponding evaluation weight of expert $W_j$, $j = 1, \ldots, n$.

Step 2. Construct a matrix of the original data with the significances of 4 categories and 15 factors, as provided by each expert.

Step 3. Construct the importance matrix $[A_{ij}]_{m\times n}$, where $A_{ij}$ is a normal triangular interval-valued fuzzy number denoting the rating of the $i$th factor under the $j$th expert.

Step 4. Calculate the advantage matrix $[a_{ij}]_{m\times n}$, where $a_{ij}$ is a scalar $h$ that denotes the advantage of the $i$th factor under the $j$th expert and is determined using (1).

Step 5. Calculate the disadvantage matrix $[d_{ij}]_{m\times n}$, where $d_{ij}$ denotes the disadvantage of the $i$ th factor under the $j$th expert and is determined according to (2).

Step 6. Use (3) to obtain the superiority index $S_i$ for the $i$th factor.

**Table 1. Profiles of the interviewed experts.**

| Characteristics of experts | Industry-related | | Manager | | Academic | |
|---|---|---|---|---|---|---|
| | Frequency | % | Frequency | % | Frequency | % |
| *Sex* | | | | | | |
| Male | 4 | 26.67 | 4 | 26.67 | 4 | 26.67 |
| Female | 2 | 13.33 | N/A | N/A | 1 | 0.07 |
| *Age* | | | | | | |
| Less than 40 years old | 2 | 13.33 | 1 | 6.67 | 1 | 0.07 |
| 41-50 years old | 2 | 13.33 | 1 | 6.67 | 3 | 20.00 |
| More than 50 years old | 2 | 13.33 | 2 | 13.33 | 1 | 0.07 |
| **Seniority** | | | | | | |
| Less than 10 years | 1 | 6.67 | N/A | N/A | 1 | 0.07 |
| 11-20 years | 4 | 26.67 | 1 | 6.67 | 3 | 20.00 |
| More than 20 years | 1 | 6.67 | 3 | 20.00 | 1 | 0.07 |

Step 7. Use (4) to obtain the inferiority index $I_i$ for the $i$th factor.

Step 8. Obtain the composite index $C_i$ for each factor using (5), and rank all factors according to the composite indices obtained.

## IV. EMPIRICAL EXAMPLE

### 1. Questionnaire Survey

This study explored a new framework related to the key factors of the daily operation of Taiwan's international commercial ports to determine potential applications of the IoT. Fifteen experts were invited to be interviewed. The experts were broadly divided into three types based on their backgrounds: IoT-industry-related enterprise representatives, port operation managers, and academic scholars.

The interviewees' characteristics, summarized in Table 1, indicate that most experts were men, with female respondents accounting for only 13.40%. Age distribution was relatively balanced; most interviewees were aged 41-50 years (41.00%), followed by those aged older than 50 years (26.73%) and younger than 40 years (21.07%). Seniority may be considered an indicator of the extent of work experience; more than 90% of the interviewees had worked for more than 10 years, and more than 50% had worked in related fields for 11-20 years.

### 2. Framework

This study constructed an initial questionnaire with 16 criteria based on the work experience of the invited experts and a literature review. After discussion and duplication, the final framework of the questionnaire was established (Fig. 3).

### 3. Evaluation Process and Data Analysis

Fig. 3 illustrates the decision-making items based on four main criterion layers: technology development (TD), social value, government support, and user trust (UT). Layers based on subcriterion were also evaluated. To reduce the influence of the interviewed experts' subjectivity, linguistic variables were used to supplement the responses of each expert. The linguistic variables and corresponding fuzzy numbers employed in this study are defined in Table 2.

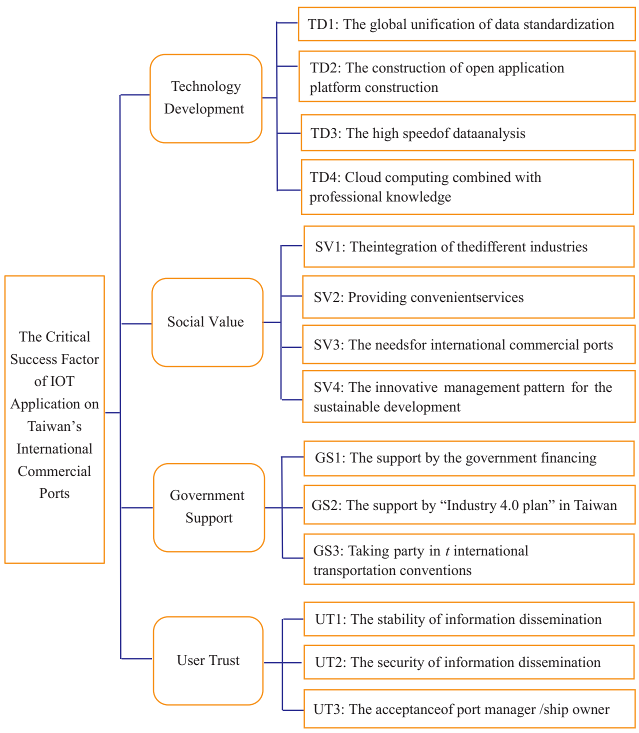


**Fig. 3. Framework of the CSFs of IoT applications in Taiwan's international commercial ports.**

In the first step of the ranking algorithm, $n = 15$ because 15 experts from different fields were invited to be interviewed. Each expert's work experience was substantial; therefore, the ex-

**Table 2. Linguistic variables and corresponding normal triangular interval-valued fuzzy numbers.**

| Linguistic variables | Normal triangular interval-valued fuzzy number |
|---|---|
| Very Important (VI) | (9,9.5,10,10,10) |
| Important (I) | (7,8,9,9.5,10) |
| Medium Important (MI) | (5,6,7,8,9) |
| Fair (F) | (3,4,5,6,7) |
| Medium Unimportant (MU) | (1,2,3,4,5) |
| Unimportant (U) | (0,0.5,1,2,3) |
| Very Unimportant (VU) | (0,0,0,0.5,1) |

**Table 3. Evaluation data of criterion layers and subcriterion layers by linguistic variables.**

| | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 | E12 | E13 | E14 | E15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TD | VI | VI | MI | F | I | VI | I | VI | I | VI | I | VI | I | VI | MI |
| SV | VI | I | I | MI | MI | I | I | F | I | VI | MU | I | I | F | I |
| GS | VI | VI | I | MU | VI | VI | I | MI | MI | VI | I | VI | VI | I | MI |
| UT | VI | VI | F | F | I | I | I | MI | I | VI | F | VI | VI | VI | I |
| | | | | | | | | | | | | | | | |
| TD 1 | VI | VI | I | F | VI | VI | I | F | I | VI | MU | I | I | F | I |
| TD 2 | VI | VI | MI | MU | I | VI | I | MI | MI | VI | I | VI | VI | I | MI |
| TD 3 | VI | VI | MI | MU | I | I | I | MI | I | VI | F | VI | VI | VI | I |
| TD 4 | VI | I | I | F | I | VI | I | I | I | I | MI | VI | I | MI | F |
| SV 1 | VI | VI | I | MI | I | I | I | MI | I | I | I | I | MI | I | I |
| SV 2 | MI | I | MI | F | MI | I | I | I | F | MI | MU | I | F | MI | I |
| SV 3 | VI | I | MI | MI | F | I | I | MI | MI | I | MI | I | I | MI | MI |
| SV 4 | VI | VI | MI | MI | MI | I | I | VI | I | VI | F | VI | I | VI | MI |
| GS 1 | VI | VI | MI | MI | F | VI | I | VI | MI | VI | MI | VI | MI | MI | F |
| GS 2 | VI | VI | MI | MI | F | VI | I | MI | F | MI | I | I | I | I | MI |
| GS 3 | VI | I | MI | I | F | I | MI | I | MI | MI | I | I | I | I | F |
| UT 1 | VI | VI | MI | F | I | VI | I | MI | I | VI | I | VI | VI | I | F |
| UT 2 | VI | I | MI | F | MI | VI | MI | MI | I | VI | I | VI | VI | I | MI |
| UT 3 | VI | VI | I | F | F | I | I | VI | I | I | MI | VI | I | I | I |

**Table 4. Importance matrix for each evaluated factor.**

| | E1 | E2 | E3 ··· E13 | E14 | E15 |
|---|---|---|---|---|---|
| TD 1 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (405,541.500,700,800,900) | (135,228,350,480,630) |
| TD 2 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (567,722,900,950,1000) | (225,342,490,640,810) |
| TD 3 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (729,857.375,1000,1000,1000) | (225,342,490,640,810) |
| TD 4 | (729,857.375,1000,1000,1000) | (567,722,900,950,1000) | ...... | (729,857.375,1000,1000,1000) | (315,456,630,760,900) |
| SV 1 | (729,857.375,1000,1000,1000) | (567,722,900,950,1000) | ...... | (189,304,450,570,700) | (441,608,810,902.500,1000) |
| SV 2 | (405,541.500,700,800,900) | (441,608,810,902.5,1000) | ...... | (135,228,350,480,630) | (441,608,810,902.500,1000) |
| SV 3 | (729,857.375,1000,1000,1000) | (441,608,810,902.5,1000) | ...... | (135,228,350,480,630) | (315,456,630,760,900) |
| SV 4 | (729,857.375,1000,1000,1000) | (567,722,900,950,1000) | ...... | (243,361,500,600,700) | (315,456,630,760,900) |
| GS 1 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (315,456,630,760,900) | (135,228,350,480,630) |
| GS 2 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (441,608,810,902.500,1000) | (225,342,490,640,810) |
| GS 3 | (729,857.375,1000,1000,1000) | (567,722,900,950,1000) | ...... | (441,608,810,902.500,1000) | (135,228,350,480,630) |
| UT 1 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (567,722,900,950,1000) | (189,304,450,570,700) |
| UT 2 | (729,857.375,1000,1000,1000) | (567,722,900,950,1000) | ...... | (567,722,900,950,1000) | (315,456,630,760,900) |
| UT 3 | (729,857.375,1000,1000,1000) | (729,857.375,1000,1000,1000) | ...... | (567,722,900,950,1000) | (441,608,810,902.500,1000) |

**Table 5. Advantage matrix for each evaluated factor.**

| | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 | E12 | E13 | E14 | E15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TD 1 | 267.48 | 815.83 | 936.50 | 276.00 | 3517.13 | 1245.48 | 310.13 | 3425.25 | 2499.56 | 696.25 | 2325.50 | 896.77 | 576.75 | 1133.56 | 0.00 |
| TD 2 | 267.48 | 815.83 | 327.75 | 0.00 | 2464.94 | 1245.48 | 310.13 | 4452.89 | 1119.75 | 0.00 | 3876.13 | 242.81 | 576.75 | 2339.81 | 465.75 |
| TD 3 | 267.48 | 815.83 | 327.75 | 0.00 | 2464.94 | 404.69 | 310.13 | 4452.89 | 1245.75 | 1537.05 | 2325.50 | 896.77 | 576.75 | 3460.88 | 465.75 |
| TD 4 | 267.48 | 161.88 | 2797.25 | 276.00 | 2464.94 | 1245.48 | 310.13 | 4452.89 | 38.25 | 696.25 | 3876.13 | 896.77 | 576.75 | 3460.88 | 1318.00 |
| SV 1 | 267.48 | 161.88 | 2797.25 | 2770.00 | 1069.38 | 0.00 | 310.13 | 0.00 | 38.25 | 696.25 | 285.75 | 0.00 | 173.50 | 172.50 | 3023.69 |
| SV 2 | 0.00 | 0.00 | 936.50 | 1252.00 | 217.13 | 0.00 | 310.13 | 172.50 | 182.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3023.69 |
| SV 3 | 267.48 | 0.00 | 936.50 | 2770.00 | 0.00 | 0.00 | 310.13 | 0.00 | 1119.75 | 696.25 | 178.50 | 0.00 | 576.75 | 0.00 | 1318.00 |
| SV 4 | 267.48 | 161.88 | 936.50 | 2770.00 | 217.13 | 0.00 | 310.13 | 300.38 | 2499.56 | 1537.05 | 59.50 | 242.81 | 576.75 | 300.38 | 1318.00 |
| GS 1 | 238.94 | 647.88 | 752.13 | 74.25 | 107.00 | 1015.13 | 233.38 | 1400.63 | 258.25 | 1311.38 | 2094.63 | 722.88 | 229.50 | 687.13 | 0.00 |
| GS 2 | 267.48 | 815.83 | 936.50 | 119.00 | 171.50 | 1245.48 | 310.13 | 336.88 | 0.00 | 0.00 | 3876.13 | 242.81 | 1305.19 | 1692.31 | 465.75 |
| GS 3 | 267.48 | 161.88 | 936.50 | 379.50 | 171.50 | 404.69 | 0.00 | 1189.13 | 389.25 | 0.00 | 3876.13 | 242.81 | 1305.19 | 1692.31 | 0.00 |
| UT 1 | 267.48 | 815.83 | 0.00 | 276.00 | 2464.94 | 404.69 | 310.13 | 336.88 | 2499.56 | 1537.05 | 1111.00 | 896.77 | 2426.25 | 2339.81 | 258.75 |
| UT 2 | 267.48 | 161.88 | 0.00 | 276.00 | 1069.38 | 404.69 | 0.00 | 336.88 | 2499.56 | 1537.05 | 1111.00 | 896.77 | 2426.25 | 2339.81 | 1318.00 |
| UT 3 | 267.48 | 815.83 | 172.50 | 276.00 | 86.25 | 0.00 | 310.13 | 1684.63 | 2499.56 | 696.25 | 679.75 | 896.77 | 1305.19 | 2339.81 | 3023.69 |

**Table 6. The disadvantage matrix for each evaluated factor.**

| | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 | E12 | E13 | E14 | E15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TD 1 | 0.00 | 0.00 | 310.13 | 820.50 | 0.00 | 0.00 | 0.00 | 280.27 | 0.00 | 467.11 | 620.25 | 0.00 | 591.53 | 1417.47 | 2783.69 |
| TD 2 | 0.00 | 0.00 | 1405.88 | 1927.00 | 80.94 | 0.00 | 0.00 | 0.00 | 791.06 | 2207.73 | 0.00 | 653.95 | 591.53 | 186.84 | 1317.44 |
| TD 3 | 0.00 | 0.00 | 1405.88 | 1927.00 | 80.94 | 467.11 | 0.00 | 0.00 | 696.56 | 0.00 | 620.25 | 0.00 | 591.53 | 0.00 | 1317.44 |
| TD 4 | 0.00 | 653.95 | 0.00 | 820.50 | 80.94 | 0.00 | 0.00 | 0.00 | 2810.56 | 467.11 | 0.00 | 0.00 | 591.53 | 0.00 | 465.19 |
| SV 1 | 0.00 | 653.95 | 0.00 | 0.00 | 856.25 | 1195.55 | 0.00 | 3795.52 | 2810.56 | 467.11 | 3573.50 | 1544.27 | 2359.16 | 3752.53 | 0.00 |
| SV 2 | 3477.30 | 1625.20 | 310.13 | 414.00 | 1708.50 | 1195.55 | 0.00 | 2760.52 | 2282.56 | 2207.73 | 5599.25 | 1544.27 | 4614.66 | 4787.53 | 0.00 |
| SV 3 | 0.00 | 1625.20 | 310.13 | 0.00 | 3423.38 | 1195.55 | 0.00 | 3795.52 | 791.06 | 467.11 | 4041.75 | 1544.27 | 591.53 | 4787.53 | 465.19 |
| SV 4 | 0.00 | 653.95 | 310.13 | 0.00 | 1708.50 | 1195.55 | 0.00 | 2291.64 | 0.00 | 0.00 | 4755.75 | 653.95 | 591.53 | 3283.66 | 465.19 |
| GS 1 | 0.00 | 0.00 | 310.13 | 1213.00 | 1790.63 | 0.00 | 0.00 | 976.52 | 1765.06 | 0.00 | 620.25 | 0.00 | 1615.91 | 1974.91 | 2783.69 |
| GS 2 | 0.00 | 0.00 | 310.13 | 1213.00 | 1790.63 | 0.00 | 0.00 | 2200.39 | 3307.81 | 2207.73 | 0.00 | 653.95 | 186.84 | 672.47 | 1317.44 |
| GS 3 | 0.00 | 653.95 | 310.13 | 763.00 | 1790.63 | 467.11 | 1860.75 | 1348.14 | 1765.06 | 2207.73 | 0.00 | 653.95 | 186.84 | 672.47 | 2783.69 |
| UT 1 | 0.00 | 0.00 | 3010.13 | 820.50 | 80.94 | 467.11 | 0.00 | 2200.39 | 0.00 | 0.00 | 1834.75 | 0.00 | 0.00 | 186.84 | 1834.94 |
| UT 2 | 0.00 | 653.95 | 3010.13 | 820.50 | 856.25 | 467.11 | 1860.75 | 2200.39 | 0.00 | 0.00 | 1834.75 | 0.00 | 0.00 | 186.84 | 465.19 |
| UT 3 | 0.00 | 0.00 | 1975.13 | 820.50 | 2302.13 | 1195.55 | 0.00 | 976.52 | 0.00 | 467.11 | 2611.00 | 0.00 | 186.84 | 186.84 | 0.00 |

perts' responses were assigned equal importance weights, which were defined according to the normal triangular interval-valued fuzzy number $w_j = (9, 9.5, 10, 10, 10)$.

The evaluation results of each main criterion layer based on the linguistic variables are listed in rows 2-5 of Table 3. The other rows denote the evaluation results of the corresponding sub-criterion layers.

After creating a matrix comprising the original evaluation data of the four main criterion layers and 14 subcriterion layers provided by the experts, the importance matrix $[A_{ij}]_{m\times n}$ was obtained and combined with the importance weight of each expert. The results are summarized in Table 4.

In the fourth step, the advantages of each factor were computed based on the importance matrix. The advantage evaluation results for each expert are presented in Table 5. For example, factor TD 2 exhibited an advantage of 4452.89 according to expert 8 but 0.00 according to expert 4.

In the fifth step, the disadvantages of each factor were computed based on the importance matrix. The disadvantage evaluation results for each expert are presented in Table 6. For example, factor TD 1 exhibited a disadvantage of 310.13 according to expert 3 but 0.00 according to expert 1.

The superiority index $S_i$ of each evaluated factor was obtained using (3), and the results are presented in Table 7.

Similarly to the previous step, the inferiority index $I_i$ for each evaluated factor was computed using (4), and the results are presented in Table 8.

## 4. Results Analysis

Finally, the composite performance index $C_i$ for each evaluated factor was obtained using (5). Table 9 displays the final ranking of all the evaluated factors based on the composite indices.

**Table 7. Superiority indices for each evaluated factor.**

| Factors | Superiority indices |
|---|---|
| TD 1 | 18922.19 |
| TD 2 | 18505.50 |
| TD 3 | 19552.14 |
| TD 4 | 22839.06 |
| SV 1 | 11766.05 |
| SV 2 | 6094.19 |
| SV 3 | 8173.36 |
| SV 4 | 11497.53 |
| GS 1 | 9773.06 |
| GS 2 | 11784.98 |
| GS 3 | 11016.36 |
| UT 1 | 15945.13 |
| UT 2 | 14644.73 |
| UT 3 | 15053.83 |

**Table 8. Inferiority indices for each evaluated factor.**

| Factors | Inferiority indices |
|---|---|
| TD 1 | 2498.25 |
| TD 2 | 9162.38 |
| TD 3 | 7106.70 |
| TD 4 | 5889.78 |
| SV 1 | 21008.39 |
| SV 2 | 32527.18 |
| SV 3 | 23038.20 |
| SV 4 | 15909.84 |
| GS 1 | 13050.08 |
| GS 2 | 13860.39 |
| GS 3 | 15463.45 |
| UT 1 | 10435.59 |
| UT 2 | 12355.86 |
| UT 3 | 10721.61 |

As indicated in Table 9, TD 1 ranked first with the composite significance index of 0.8834; that is, "technology development" should be prioritized for the criterion layer "the global unification of data standardization." The top four CSFs were derived from the first criterion layer, indicating that the development of certain critical technologies may play a vital role in IoT applications in Taiwan's international commercial ports according to the experts' evaluations. In addition, three subcriteria in the fourth criterion layer, UT, received relatively high importance evaluation results, with satisfactory results also presented in the corresponding composite significance indices. Among these subcriteria, "the stability of information dissemination" received the highest importance score.

**Table 9. Final composite significance indices for each evaluated factor.**

| Factors | Composite significance indices | Rank |
|---|---|---|
| TD 1 | 0.8834 | 1 |
| TD 2 | 0.6688 | 4 |
| TD 3 | 0.7334 | 3 |
| TD 4 | 0.7950 | 2 |
| SV 1 | 0.3590 | 12 |
| SV 2 | 0.1578 | 14 |
| SV 3 | 0.2619 | 13 |
| SV 4 | 0.4195 | 9 |
| GS 1 | 0.4282 | 11 |
| GS 2 | 0.4595 | 8 |
| GS 3 | 0.4160 | 10 |
| UT 1 | 0.6044 | 5 |
| UT 2 | 0.5424 | 7 |
| UT 3 | 0.5840 | 6 |

## V. CONCLUSIONS

The IoT may facilitate the automatic connection of digital and physical objects through information and communication technologies to create a new class of applications and services (Miorandi et al., 2012). The Internet is a fabric of traditionally networked objects that offers a convenient technological foundation for the development of smart production processes and lifestyle-related technologies. Academic and industrial efforts have been devoted to developing IoT applications for the integration of complex resources. IoT-based device integration and the development of specific IoT applications in various fields have contributed to proprietary application runtime environments with nonstandardized service management processes (Li et al., 2013). In sum, IoT applications may be used to increase lifestyle comfort, enhance environment systems, and smarter, safer and more efficient working conditions.

In this study, a framework was presented for the analysis of the CSFs in the context of IoT applications in Taiwan's international commercial ports. The results of a ranking algorithm involving the normal triangular interval-valued fuzzy numbers proposed by Lee et al. (2016) suggested that the criterion layer TD is the most crucial factor, and warrants further investigation. In particular, "the global unification of data standardization" (TD 1) and "cloud computing combined with professional knowledge" (TD 4) should be improved to enhance Taiwan's port operations. In addition, according to the experts' evaluations, stable information dissemination may also ensure successful application of IoT technology to Taiwan's international commercial port operations.

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