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Research Article

An Uncertain QFD Approach for the Strategic Management of Logistics Services

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Due to customers' growing concern about logistics performances related to products, logistics service increasingly contributes to the core competence of an enterprise or product, which calls an appropriate tool to develop effective strategic actions to improve logistics performances and gain customer satisfaction. Therefore, an uncertain quality function deployment (QFD) approach for selecting the most effective strategic actions in terms of efficiency to meet the customer requirements is developed in this paper, which integrates uncertainty theory into the traditional QFD methodology in order to rationally deal with imprecise information inherently involved in the QFD process. The framework and systematic procedures of the approach are presented in the context of logistics services. Specifically, the calculations for the prioritization of strategic actions are discussed in detail, in which uncertain variables are used to capture the linguistic judgements given by customers and experts. Applications of the proposed approach are presented as well for illustration.

1. Introduction

Since technology diffusion makes the features of products tend to be same [1], customers become more and more concerned about logistics performances related to the products. Nowadays, it is increasingly vital for the enterprises that their products can be delivered to customers via an efficient logistics system, which has been treated as a core strength in the business competition.

Due to the growing concern about logistics performances, it is of great significance to provide logistics services with good-quality to meet customers' requirements and remain as a persistent concern on how to improve their satisfaction effectively. In order to gain and improve customer satisfaction, decision makers should figure out the service requirements (SRs) desired by customers first and then implement related strategic actions (SAs), since customer satisfaction is attained only when the provided services meet or even exceed their requirements [2]. Consequently, a core issue arisen in the strategic management of logistics services is how to develop effective strategic actions to meet the customer requirements. Furthermore, this issue usually should be considered with limited resources. Therefore, an appropriate approach to evaluate these strategic actions in terms of efficiency to meet the customer requirements is needed.

Although service requirements and strategic actions for logistics services have been extensively studied in the literature, a guideline for evaluating the association between SRs and SAs was rarely discussed. In 2006, Bottani and Rizzi [3] initially attempted to develop a suitable tool to evaluate strategic actions in the logistics context by introducing the quality function deployment (QFD) approach into the logistics strategic management. QFD is a well known customer-driven product design methodology, which can be used in not only manufacturing but also service industry [4, 5]. It provides an effective tool to convert the customer requirements (CRs) into appropriate engineering characteristics (ECs). On the basis of QFD methodology, Bottani and Rizzi built a connection between the SRs and SAs for logistics services. In other words, the gap between logistics strategic management and customer requirements is effectively bridged.

However, in practical logistics management as well as many other applications of the QFD approach, the utilizing of this methodology cannot be handled in a deterministic and precise framework [6, 7]. For example, it is unrealistic to expect that customers can determine the importance of their requirements accurately. Instead of detailed figures, some language judgement, such as very important, medium, and unimportant, is often used. Similarly, when the related experts are asked to evaluate the relationships between the SRs and SAs, they may also give some linguistic assessments such as strong, medium, and weak. Due to the linguistic ambiguity and vagueness inherently involved in the QFD process, it is difficult to prioritize the strategic actions. In order to solve this problem, various methods have been proposed in last decades. For instance, Birdogan et al. [8] integrated the SEVQUAL and Kanos model into QFD for logistics services. Lin and Pekkarinen [9] developed a new methodology which integrates the house of quality (HoQ) and modular logic for logistics service design. In addition, Ho et al. [10] integrated QFD and fuzzy analytic hierarchy process (AHP) approach to select an ideal third-party logistics provider. Noori et al. [11] presented a fuzzy approach that focuses on the customer needs and designed a logistics system to meet these needs. Furthermore, Lai et al. [12] used fuzzy mathematics to capture the importance of SRs. Liao and Kao [13] integrated QFD, fuzzy extended AHP, and multisegment goal programming to evaluate logistics service management.

It can be found that most of the linguistic inputs are treated as either crisp or fuzzy numbers in the above literature. Although these methods have provided some appropriate frameworks to assess SAs (or ECs) with imprecise information, they are far from enough to rationally deal with the uncertain phenomenon encountered in the QFD process, since there still exist many imprecise quantities, particularly those involving linguistic ambiguity and subjective estimation, behaving neither like randomness nor like fuzziness [14, 15]. On the other hand, the uncertainty theory founded by Liu [16], which has become a branch of axiomatic mathematics for manipulating human uncertainty [17–19], provides an alternative effective tool to deal with this imprecise information. Therefore, on the basis of uncertainty theory, an uncertain QFD approach is developed for the strategic management of logistics services in this paper.

The contribution of the present work is threefold. Firstly, the work contributes to the methodology of quality function deployment by integrating uncertainty theory into the traditional QFD methodology. The uncertain QFD approach as well as the framework and systematic procedures of this approach is proposed, in which uncertain variables are used to capture the imprecise information (linguistic judgements) inherently involved in the QFD process. Through converting linguistic judgements into uncertain variables, the imprecise information can be rationally handled in the framework of uncertainty theory. Secondly, along with the first contribution, techniques concerning the calculations for the prioritization of strategic actions (engineering characteristics) are presented as well. Lastly, the proposed approach is discussed in the context of the strategic management of logistics services. Obviously, not only does it provide an appropriate tool to develop effective strategic actions to meet customer requirements for logistics services, but also it can be applied to the strategic management of other service industries.

The rest of this paper is organized as follows. In Section 2, some basic concepts in the uncertainty theory are introduced. In Section 3, an overview of the proposed uncertain QFD approach is presented. Subsequently, the identification of SRs and SAs in the context of logistics services is given in Section 4, and the prioritization of SAs is presented in Section 5. Finally, applications of the approach are given in Section 6 for illustration.

2. Preliminaries

Uncertainty theory, founded by Liu [16], is an efficient tool to deal with nondeterministic information, especially expert data and subjective estimations. In this section, some basic concepts in the uncertainty theory are introduced, which will be used to model the uncertain factors encountered in the strategic management of logistics services.

Definition 1 (see [16]). Let Γ be a nonempty set and $\mathscr{L}$ a σ-algebra over Γ. The set function $\mathscr{M} : \mathscr{L} \to [0, 1]$ is called an uncertain measure if it satisfies the following:

(i) $\mathscr{M}\{\Gamma\} = 1$ for the universal set Γ.

(ii) $\mathscr{M}\{\Lambda\} + \mathscr{M}\{\Lambda^c\} = 1$ for any event Λ.

(iii) For every countable sequence of events $\Lambda_1, \Lambda_2, \ldots$, we have

$$\mathscr{M}\left\{\bigcup_{i=1}^{\infty}\Lambda_i\right\} \le \sum_{i=1}^{\infty}\mathscr{M}\{\Lambda_i\}. \quad (1)$$

Moreover, for a series of uncertainty spaces $(\Gamma_k, \mathscr{L}_k, \mathscr{M}_k)$, $k = 1, 2, \ldots$, the product uncertain measure is defined as

$$\mathscr{M}\left\{\prod_{k=1}^{\infty}\Lambda_k\right\} = \bigwedge_{k=1}^{\infty}\mathscr{M}_k\{\Lambda_k\}, \quad (2)$$

where Λ_k are arbitrarily chosen events from $\mathscr{L}_k$ for $k = 1, 2, \ldots$, respectively.

Based on the concept of uncertain measure, a formal definition of an uncertain variable is given as follows.

Definition 2 (see [16]). An uncertain variable is a measurable function ξ from an uncertainty space $(\Gamma, \mathscr{L}, \mathscr{M})$ to the set of real numbers; that is, for any Borel set B of real numbers, the set

$$\{\xi \in B\} = \{\gamma \in \Gamma \mid \xi(\gamma) \in B\} \quad (3)$$

is an event.

In order to describe uncertain variables, the uncertainty distribution of an uncertain variable ξ is defined as

$$\Phi(x) = \mathscr{M}\{\xi \le x\} \quad (4)$$

for any real number x.

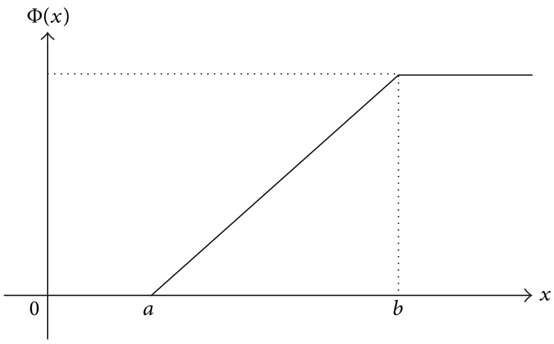

Figure 1: Linear uncertainty distribution.

Definition 3 (see [16]). An uncertain variable ξ is called linear if it has a linear uncertainty distribution (see Figure 1)

$$\Phi(x) = \begin{cases} 0, & \text{if } x \le a \\ \dfrac{(x-a)}{(b-a)}, & \text{if } a \le x \le b \\ 1, & \text{if } x \ge b \end{cases} \quad (5)$$

denoted by $\mathscr{L}(a,b)$, where a and b are real numbers with $a < b$.

Definition 4 (see [20]). An uncertainty distribution Φ is said to be regular if its inverse function $\Phi^{-1}(\alpha)$ exists and is unique for each $\alpha \in (0,1)$.

It is clear that the linear uncertainty distribution is regular. The inverse uncertainty distribution of a linear uncertain variable $\xi \sim \mathscr{L}(a,b)$ is

$$\Phi^{-1}(\alpha) = (1-\alpha)a + \alpha b. \quad (6)$$

Definition 5 (see [21]). The uncertain variables $\xi_1, \xi_2, \ldots, \xi_n$ are said to be independent if

$$\mathscr{M}\left\{\bigcap_{i=1}^{n}\{\xi_i \in B_i\}\right\} = \bigwedge_{i=1}^{n}\mathscr{M}\{\xi_i \in B_i\} \quad (7)$$

for any Borel sets $B_1, B_2, \ldots, B_n$ of real numbers.

Theorem 6 (see [20]). *Let $\xi_1, \xi_2, \ldots, \xi_n$ be independent uncertain variables with regular uncertainty distributions $\Phi_1, \Phi_2, \ldots, \Phi_n$, respectively, and $f : \mathfrak{R}^n \to \mathfrak{R}$ a continuous and strictly increasing function. Then the uncertain variable $\xi = f(\xi_1, \xi_2, \ldots, \xi_n)$ has an inverse uncertainty distribution*

$$\Psi^{-1}(\alpha) = f\left(\Phi_1^{-1}(\alpha), \Phi_2^{-1}(\alpha), \ldots, \Phi_n^{-1}(\alpha)\right). \quad (8)$$

It can be deduced easily from Theorem 6 that the addition operation is close overall independent linear uncertain variables, which can be represented as the following theorem.

Theorem 7 (see [21]). *Assume that ξ_1, ξ_2 are independent linear uncertain variables $\mathscr{L}_1(a_1,b_1)$ and $\mathscr{L}_2(a_2,b_2)$, respectively. Then the sum $\xi_1 + \xi_2$ is also a linear uncertain variable $\mathscr{L}(a_1+a_2, b_1+b_2)$; that is,*

$$\mathscr{L}_1(a_1,b_1) + \mathscr{L}_2(a_2,b_2) = \mathscr{L}(a_1+a_2, b_1+b_2). \quad (9)$$

The product of a linear uncertain variable $\mathscr{L}(a,b)$ and a scalar number $k > 0$ is also a linear variable $\mathscr{L}(ka,kb)$; that is,

$$k \cdot \mathscr{L}(a,b) = \mathscr{L}(ka,kb). \quad (10)$$

The expected value of an uncertain variable is the average value in the sense of uncertain measure and can be represented by the inverse uncertainty distribution as follows.

Theorem 8 (see [20]). *Let ξ be an uncertain variable with a regular uncertainty distribution. Then*

$$E[\xi] = \int_0^1 \Phi^{-1}(\alpha)\,d\alpha, \quad (11)$$

where Φ and Φ^{-1} are the uncertainty distribution and the inverse uncertainty distribution of ξ, respectively.

It is easy to verify that the expected value of a linear uncertain variable $\xi \sim \mathscr{L}(a,b)$ is

$$E[\xi] = \frac{a+b}{2}. \quad (12)$$

3. Overview of the Uncertain QFD Approach

In this section, we briefly recall the traditional QFD methodology first, following from which a HoQ-based framework for the strategic management of logistics services is developed subsequently. Due to uncertain factors involved in the logistics strategic management, uncertainty theory is further integrated into the approach to handle the imprecise information.

3.1. The Traditional QFD Methodology. Quality function deployment is a well known customer-driven product (or service) development approach originated in Japan in 1972 [22], which provides a systematic method to transform customer requirements (namely, "what" customer needs) into appropriate engineering characteristics (namely, "how" the product has to be made) in order to achieve high customer satisfaction.

Generally, a complete QFD process is composed of four successive phases, that is, product planning, part deployment, process planning, and production planning [23]. The overall process of QFD is based on its core matrix framework, called the house of quality (HoQ). In this paper, we only focus on the first phase to develop the HoQ-based framework for the strategic management of logistics services.

The HoQ in the first phase, also called the customer requirements planning matrix, consists of two main parts, related to customer requirements and engineering characteristics, respectively. By assessing how each EC impacts on each CR in the framework of HoQ, the QFD approach makes it possible to rank ECs in terms of efficiency to reach the customer's requirements [3]. Roughly speaking, this process contains the following steps:

(1) Identify customer requirements (CRs) as well as their relative importance.

(2) Develop engineering characteristics (ECs).

(3) Evaluate the relationship between CRs and ECs as well as the relationships (interactions) among ECs.

(4) Calculate the importance of ECs.

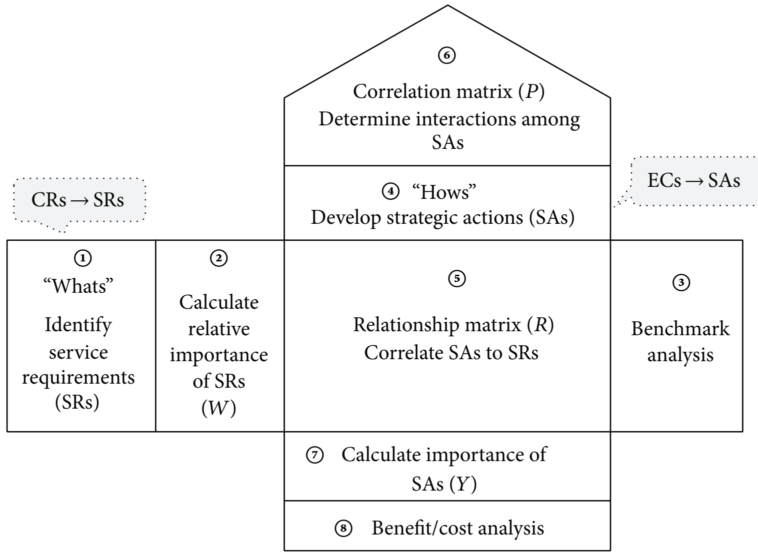

Figure 2: The house of quality for strategic management of logistics services.

It can be found that the issue of providing logistics services to meet customer's requirements may be handled in a similar manner with the above steps. Therefore, a similar HoQ-based framework for the strategic management of logistics services can be developed.

3.2. The HoQ-Based Framework for Logistics Strategic Management. In the strategic management of logistics services, the core issue is to design strategic actions to meet customer's requirements. Following from the QFD methodology, a HoQ-based framework for this purpose is proposed as shown in Figure 2. This modified HoQ for logistics strategic management is composed of two main parts, related to the service requirements (SRs) and strategic actions (SAs), respectively. It is clear that the SRs and SAs are analogous to the customer requirements (CRs) and engineering characteristics (ECs) in the traditional QFD approach, respectively.

On the basis of this HoQ-based framework, the strategic actions can be prioritized in terms of efficiency to meet the service requirements as follows.

Step 1 (identify service requirements). The strategic management of logistics services starts from listening and understanding the voice of the customer. In other words, "what" the customers need (or expect) from the company should be identified at the beginning of the process. They are placed on the left side of the HoQ. The service requirements concerning logistics are usually expressed by some logistics service indexes [24], which can be obtained through market surveys, interview, or expert assessment. Detailed discussion concerning the logistics service requirements is presented in Section 4.1.

Step 2 (calculate relative importance of SRs). Different service requirements may be of different importance for customers. In order to express their relative importance, SRs are weighted. The weights of SRs are denoted by the vector W, which is also added in a column on the left side of the HoQ. Detailed discussion on the calculation of relative importance of SRs is given in Section 5.1.

Step 3 (benchmark analysis). Based on the service requirements identified in Step 1, benchmark analysis of the logistics services provided by the company as well as those of other competitors is conducted and placed on the right side of the HoQ.

Step 4 (develop strategic actions). In order to meet the service requirements, corresponding strategic actions that affect these SRs are developed. In other words, possible solutions to the issue that "how" the company has to do (or the service to be improved) are picked out in this step. The SAs are listed in a row on the upside of the HoQ. Detailed discussion concerning the strategic actions is presented in Section 4.2.

Step 5 (correlate SAs with SRs). How and to what extent each strategic action impacts on each service requirement are assessed. The relationship between these SAs and SRs is denoted by a relationship matrix R, which is the core of the HoQ. Usually, the strength of the relationship between SA and SR is expressed by linguistic judgements (e.g., weak, medium, and strong), and thus imprecise information is involved in this approach, which calls uncertainty theory to be integrated to model these uncertain factors. The uncertainty issues encountered in this approach (including those in other steps) are further discussed in Section 3.3.

Step 6 (determine interactions among SAs). The interactions among SAs are expressed by a correlation matrix P and placed on the top of the HoQ, which indicates how the strategic actions affect each other. Similarly to the relationship matrix, the correlation matrix may be expressed by linguistic judgements as well.

Step 7 (calculate importance of SAs). In order to prioritize the strategic actions, the importance of each SA in terms of efficiency to meet the service requirements should be calculated. On the basis of relative importance of SRs (W), relationship matrix (R), and correlation matrix (P), the importance of SAs can be derived as follows [25]:

$$Y = \left(W^T R P\right)^T. \tag{13}$$

Moreover, normalization of the importance of SAs can be further conducted in this step. Detailed discussion on the calculation of importance of SAs, in which imprecise information is involved to be handled, is given in Section 5.2.

Step 8 (benefit/cost analysis). The importance of SAs indicates the relative significance of each strategic action to the improving of customer satisfaction. The higher importance implies that more attention should be concentrated on that strategic action. However, the implementation of strategic actions may be constrained by the limited resources. Therefore, benefit/cost analysis is put forward to get a trade-off between the importance and costs of SAs, which is further discussed in Section 5.3.

Through the above procedures, the strategic actions are finally prioritized, which is of great significance to the strategic planning for improving logistics services. Based on the importance and rankings of strategic actions, a company can make the services more attractive to customers and thus gains more competitive advantages.

3.3. Uncertainty Issues in the HoQ-Based Framework. Following from the proposed HoQ-based framework for logistics strategic management, it can be found that there are many uncertain factors to be dealt with in this process. For instance, customer's perception of the importance of SRs, the relationship between SAs and SRs, and the interactions among SAs are all hard to be precisely estimated. Usually, they are subjective judgements given by customers or domain experts and thus are expressed by linguistic variables, such as "very high," "very low," "strong," and "weak."

As mentioned formerly, a main way to deal with these linguistic variables is transforming them to fuzzy numbers, and thus the fuzzy set theory was introduced into the QFD approach [3]. However, it has been shown that it is inappropriate to describe the nondeterministic phenomena as fuzziness in many scenarios, particularly those involving the linguistic ambiguity and subjective estimation [16], whereas the uncertainty theory provides an alternative efficient tool to deal with them. Therefore, uncertainty theory is integrated into the HoQ-based framework, in which uncertain variables are used to capture those linguistic inputs related to the strategic management for logistics services.

For the linguistic judgements related to the degree of importance or correlation, we can convert them into uncertain variables as illustrated in Table 1. Consequently, on the basis of this translation, linguistic judgements involved in the process of prioritizing strategic actions can be easily handled following from uncertain theory. The calculations involving uncertain variables for prioritizing SAs are given detailedly in Section 5.

Table 1: Linguistic judgements and the corresponding uncertain variables.

Linguistic judgements	Uncertain variables
Very high (VH)/very strong (VS)	$\mathscr{L}(0.7, 1)$
High (H)/strong (S)	$\mathscr{L}(0.5, 0.7)$
Low (L)/weak (WA)	$\mathscr{L}(0.3, 0.5)$
Very low (VL)/very weak (VW)	$\mathscr{L}(0, 0.3)$

Table 2: Descriptions of the logistics service requirements.

Service index	Description
Celerity	Capability of delivering orders within due date. Generally, logistics service pursues rapid response to the customer's orders. They should be delivered as soon as possible after being receipted
Reliability	Capability of delivering orders without damage and mistake (e.g., the package stays in a well-condition)
Flexibility	Capability of providing personalized services (e.g., flexible receipt and delivery time) as well as satisfying some particular requirements (e.g., modify orders in terms of due date and quantity)
Accessibility	Capability of providing an easy way for customer to obtain service (e.g., ordering, consulting, complaining, and technical support)
Others	Depending on the particular circumstance

In many practical strategic planning processes, it is usually unrealistic to expect customers to provide much elaborate information timely. Furthermore, the relationship matrix R and the correlation matrix P cannot be precisely determined as well. Therefore, it calls an effective approach to deal with linguistic ambiguity and subjective judgements involved in the strategic planning process. The uncertain QFD approach proposed above provides us with an alternative way to prioritize strategic actions to meet customer requirements based on a large amount of vague information.

4. Identifying Service Requirements and Strategic Actions

The QFD approach for the strategic management of logistics services is aimed at converting the service requirements into strategic actions on the basis of HoQ-based framework. In this section, service requirements and strategic actions are identified in the context of logistics service.

4.1. Identifying Service Requirements. For the logistics services, customer requirements usually focus on the logistics performance, which can be evaluated by a series of logistics service indexes.

According to Franceschini and Rafele [24] as well as some other literatures in the area of logistics and supply chain management (e.g., [26, 27]), the main logistics service indexes include celerity, reliability, flexibility, and accessibility depending on the particular circumstance. The descriptions of these service indexes are presented in Table 2.

Table 2 lists the main logistics service indexes, which indicate the main service requirements perceived by customers. However, it is unreasonable to just adopt all these indexes and ignore the practical situation. For each company, the identification of service requirements depends on their particular circumstances. In other words, a company needs to choose some appropriate related logistics service indexes rather than mechanically adopt these indexes listed in Table 2. Service requirements could be either added or removed according to the practical situation. According to Keller et al. [28], survey is one of the most efficient and effective ways to consider the performance perceived by customer affecting customer satisfaction.

4.2. Developing Strategic Actions. After the list of service requirements has been obtained, in a similar way, the appropriate strategic actions that affect these SRs can be developed. They are possible actions that can be adopted by a company in order to promote their logistics service performance.

Referring to some logistics and supply chain management literature (e.g., [3, 29, 30]) or expert opinions, a list of possible strategic actions can be obtained. For instance, some typical strategic actions for improving logistics services include distribution with Just-in-Time (JIT) [31] philosophy, developing rapid transportation system, improving information technology, demand forecasting optimization, and customer relationship management (CRM) [32]. Note that here we do not strive to provide an exhaustive list of strategic action options, which has been extensively discussed in the logistics and supply chain management literature. Similarly to the identification of service requirements, the development of strategic actions also depends on the particular circumstance where the company stays in.

5. Prioritizing Strategic Actions under Uncertainty

As discussed in Section 3.3, linguistic ambiguity and subjective judgements are inherently involved in the QFD process for logistics strategic management. By converting linguistic judgements into uncertain variables, the imprecise information can be rationally dealt with by the uncertainty theory founded by Liu [16]. In this section, the prioritization of strategic actions based on a large amount of imprecise information is conducted in a mathematical way. The calculations for the prioritization are discussed in detail.

In the following discussions, it is assumed that there are l customers being surveyed, m service requirements being identified, and n strategic actions being developed in total. Consequently, the relative importance of SRs, W, is a $[m \times 1]$ column vector, and the relationship matrix R and correlation matrix P are $[m \times n]$ and $[n \times n]$ matrices, respectively. The elements W_i, R_{ik}, and P_{kj} ($1 \le i \le m$, $1 \le k \le n$, and $1 \le j \le n$) in W, R, and P denote the relative importance of the ith SR, the relationship between the ith SR and kth SA, and the correlation between the kth and jth SAs, respectively.

5.1. Calculating the Relative Importance of SRs. In the QFD approach for logistics strategic management, obtaining the relative importance of SRs is a crucial step, since it is finally transformed into the importance of SAs and affects the prioritizing of strategic actions.

In practice, a company may provide service for many customers, and these customers may have different perceptions on the importance of SRs. Therefore, different attitudes should be considered to get an aggregate value of the importance of SRs. A natural way is to compute the weighted average value of the importance assigned by customers, and the weights are associated with their contributions to the company's profit.

Let I_x ($x = 1, \ldots, l$) be the weight of xth customer, representing the importance of xth customer's perception on the SRs. I_x is denoted by a crisp number, which can be determined by the percentage of contributions to the company's profit or the share of the company's turnover.

Let $w_{ix} \sim \mathscr{L}(a_{ix}^{w}, b_{ix}^{w})$ ($i = 1, \ldots, m$ and $x = 1, \ldots, l$) represent importance of the ith service requirement given by the xth customer. It is denoted by a linear uncertain variable transformed from the linguistic judgement according to Table 1.

Then, the relative importance of the ith service requirement can be calculated as follows:

$$W_i = \sum_{x=1}^{l} I_x w_{ix}, \quad i = 1, \ldots, m. \tag{14}$$

Since the addition operation is close overall independent linear uncertain variables (see Theorem 7), we have

$$W_i \sim \mathscr{L}\left(\sum_{x=1}^{l} I_x a_{ix}^{w}, \sum_{x=1}^{l} I_x b_{ix}^{w}\right), \quad i = 1, \ldots, m, \tag{15}$$

which implies that the relative importance of the ith SR is also a linear uncertain variable.

5.2. Calculating the Importance of SAs. Since the relative importance of SRs (W), the relationship matrix (R), and the correlation matrix (P) are all composed of uncertain variables, it is clear that the importance of SAs, $Y = (W^T RP)^T$, is also composed of uncertain variables. Particularly, for the jth strategic action, its importance Y_j can be derived from W, R, and P as follows:

$$Y_j = \sum_{i=1}^{m} \sum_{k=1}^{n} W_i R_{ik} P_{kj}, \quad j = 1, 2, \ldots, n. \tag{16}$$

On the basis of Y_j, $j = 1, 2, \ldots, n$, we would like to compare and rank the importance of strategic actions in order to analyze their impacts on the service requirements. However, it is known that comparing uncertain variables is not as straightforward as crisp numbers. Therefore, in order to make the comparison meaningful, we use the expected value operator to convert the importance of SAs with uncertainty into crisp numbers as follows:

$$E\left[Y_j\right] = E\left[\sum_{i=1}^{m} \sum_{k=1}^{n} W_i R_{ik} P_{kj}\right], \quad j = 1, \ldots, n. \tag{17}$$

Concerning the expected values of the importance of SAs, we have the following conclusion.

Theorem 9. *Assume that the relative importance of SRs* (W)*, the relationship matrix* (R)*, and the correlation matrix* (P) *are all composed of independent linear uncertain variables, and the uncertainty distributions of* W_i, R_{ik}, *and* P_{kj} ($1 \le i \le m$, $1 \le k \le n$, $1 \le j \le n$) *are denoted by* $\mathscr{L}(a_i^W, b_i^W)$, $\mathscr{L}(a_{ik}^R, b_{ik}^R)$, *and* $\mathscr{L}(a_{kj}^P, b_{kj}^P)$*, respectively. Then the expected value of the importance of the* j*th strategic action can be calculated as follows:*

$$E\left[Y_j\right] = \sum_{i=1}^{m}\sum_{k=1}^{n}\left[\frac{1}{4}a_i^W a_{ik}^R a_{kj}^P + \frac{1}{12}a_i^W a_{ik}^R b_{kj}^P + \frac{1}{12}a_i^W b_{ik}^R b_{kj}^P + \frac{1}{12}a_i^W b_{ik}^R a_{kj}^P + \frac{1}{12}b_i^W a_{ik}^R a_{kj}^P + \frac{1}{12}b_i^W a_{ik}^R b_{kj}^P + \frac{1}{12}b_i^W b_{ik}^R a_{kj}^P + \frac{1}{4}b_i^W b_{ik}^R b_{kj}^P\right]. \tag{18}$$

Proof. Let Φ_i, Ψ_{ik}, and ϕ_{kj} denote the uncertainty distributions of W_i, R_{ik}, and P_{kj}, respectively. Since W_i, R_{ik}, and P_{kj} are independent linear uncertain variables, the distributions Φ_i, Ψ_{ik}, and ϕ_{kj} are regular. Moreover, the importance Y_j is strictly increasing with respect to W_i, R_{ik}, and P_{kj}, respectively. Consequently, according to the operational law for independent regular uncertain variables (Theorem 6), Y_j has an inverse uncertainty distribution

$$\Upsilon^{-1}(\alpha) = \sum_{i=1}^{m}\sum_{k=1}^{n}\Phi_i^{-1}(\alpha)\,\Psi_{ik}^{-1}(\alpha)\,\phi_{kj}^{-1}(\alpha), \tag{19}$$

where Φ_i^{-1}, Ψ_{ik}^{-1}, and ϕ_{kj}^{-1} are the inverse uncertainty distributions of W_i, R_{ik}, and P_{kj}, respectively, which can be calculated according to (6).

Then, following from Theorem 8, we have

$$\begin{aligned} E\left[Y_j\right] &= \int_0^1 \Upsilon^{-1}(\alpha)\,d\alpha \\ &= \int_0^1 \left(\sum_{i=1}^{m}\sum_{k=1}^{n}\Phi_i^{-1}(\alpha)\,\Psi_{ik}^{-1}(\alpha)\,\phi_{kj}^{-1}(\alpha)\right) d\alpha \\ &= \sum_{i=1}^{m}\sum_{k=1}^{n}\int_0^1 \Phi_i^{-1}(\alpha)\,\Psi_{ik}^{-1}(\alpha)\,\phi_{kj}^{-1}(\alpha)\,d\alpha \\ &= \sum_{i=1}^{m}\sum_{k=1}^{n}\int_0^1 \left[(1-\alpha)a_i^W + \alpha b_i^W\right] \cdot \left[(1-\alpha)a_{ik}^R + \alpha b_{ik}^R\right]\left[(1-\alpha)a_{kj}^P + \alpha b_{kj}^P\right] d\alpha \\ &= \sum_{i=1}^{m}\sum_{k=1}^{n}\left(\frac{1}{4}a_i^W a_{ik}^R a_{kj}^P + \frac{1}{12}a_i^W a_{ik}^R b_{kj}^P + \frac{1}{12}a_i^W b_{ik}^R b_{kj}^P + \frac{1}{12}a_i^W b_{ik}^R a_{kj}^P + \frac{1}{12}b_i^W a_{ik}^R a_{kj}^P + \frac{1}{12}b_i^W a_{ik}^R b_{kj}^P + \frac{1}{12} \cdot b_i^W b_{ik}^R a_{kj}^P + \frac{1}{4}b_i^W b_{ik}^R b_{kj}^P\right). \end{aligned} \tag{20}$$

□

Up to now, the expected values of the importance of strategic actions have been obtained by utilizing the expected value operator and the operational law for uncertain variables. On the basis of these expected values, the importance of each strategic action can be easily compared and ranked in terms of efficiency to meet the service requirements.

5.3. Prioritizing SAs Based on Benefit/Cost Analysis. Benefit/cost analysis, also referred to as cost-benefit analysis, is a systematic approach to evaluating alternatives by comparing the economic benefits with the economic costs associated with these options. As to the strategic management of logistics services, the benefit and cost of a strategic action refer to its impact on meeting the service requirements and the resources required for implementing this action, respectively. In other words, the benefit/cost analysis in this QFD approach for logistics strategic management assesses the SAs by comparing their importance to SRs with their costs. It provides us with an effective tool to obtain an appropriate trade-off between the importance of SAs and the limited resources.

Generally, the costs of the strategic actions are hard to be precisely determined before they have been actually implemented, but it is easy to obtain a rough estimation. By comparing with each other, some vague judgements on the costs such as "very high," "high," "low," and "very low" can be given to the strategic actions. Then, they are converted into uncertain variables according to Table 1.

From the idea behind benefit/cost analysis, the marginal utility of the jth strategic action to meet the service requirements is defined as the ratio between its expected importance and expected cost; that is,

$$U_j = \frac{E\left[Y_j\right]}{E\left[C_j\right]}, \quad j = 1, 2, \ldots, n, \tag{21}$$

where C_j is an uncertain variable transformed from linguistic judgement via Table 1, denoting the cost of the jth strategic action.

On the basis of the marginal utility, the strategic actions can be prioritized not by considering their importance only. The costs have also been taken into account.

6. Applications of the Approach

In this section, we present some numerical examples to illustrate the application of the methodology. The application refers to a third-party logistics (3PL) service provider, who aims to provide warehousing and distribution services for some large manufacturers. In order to improve the customer satisfaction of the provided services, some strategic actions are expected to be planned and implemented by the company. Therefore, the uncertain QFD approach is utilized to prioritize these strategic actions in terms of efficiency to meet the requirements of its customers.

6.1. Identification of SRs and SAs. The QFD approach starts from the identification of service requirements, in which the voice of customer is surveyed. For the services of this 3PL provider, four main customers, denoted by C_1, C_2, C_3, and C_4, were asked to take part in this survey. The proportions of profits benefited from these four customers are 35%, 30%,

Table 3: Judgements on the importance of SRs given by each customer.

Customers\SRs	SR_1	SR_2	SR_3	SR_4
C_1	VH	VH	H	H
C_2	VH	VH	H	L
C_3	VH	H	H	L
C_4	H	H	VH	L

Table 4: The importance of SRs denoted by uncertain variables (converted from Table 3).

Customers (weight)\SRs	SR_1	SR_2	SR_3	SR_4
C_1 (0.35)	(0.7, 1)	(0.7, 1)	(0.5, 0.7)	(0.5, 0.7)
C_2 (0.30)	(0.7, 1)	(0.7, 1)	(0.5, 0.7)	(0.3, 0.5)
C_3 (0.25)	(0.7, 1)	(0.5, 0.7)	(0.5, 0.7)	(0.3, 0.5)
C_4 (0.10)	(0.5, 0.7)	(0.5, 0.7)	(0.7, 1)	(0.3, 0.5)
Weighted relative importance	(0.68, 0.97)	(0.63, 0.895)	(0.52, 0.73)	(0.37, 0.57)

25%, and 10%, respectively. Therefore, the weight vector representing the importance of their attitudes is denoted by

$$I = [0.35, 0.30, 0.25, 0.10] . \quad (22)$$

Through the survey, four main service requirements were identified, including celerity, reliability, flexibility, and accessibility, which are denoted by SR_i, $i = 1, 2, 3, 4$, respectively. Moreover, each customer's judgements on the importance of these requirements were obtained as shown in Table 3. These judgements were made by using linguistic scale with four levels, that is, very high (VH), high (H), low (L), and very low (VL).

On the basis of these identified service requirements, five possible strategic actions are proposed, including providing personalized services, demand forecasting optimization, distribution with JIT philosophy, improving information technology, and implementing customer relationship management, which are denoted by SA_i, $i = 1, 2, \ldots, 5$, respectively.

6.2. Calculation of Relative Importance of SRs. As discussed in Section 3.3, the linguistic judgements on the importance of SRs given by customers can be effectively dealt with by converting them into uncertain variables. According to the suggested relationship between these linguistic judgements and their corresponding uncertain variables (see Table 1), Table 3 is transformed into Table 4. The pairs represented by (a, b) in Table 4 (as well as the subsequent tables and figures) denote uncertain variables with linear distribution $\mathscr{L}(a, b)$, and the symbol $\mathscr{L}$ is omitted for simplicity.

Then, the weighted relative importance of SRs can be obtained following from (14) and (15), which is shown in the last row of Table 4. Taking the first service requirement

Table 5: The relationship matrix R.

SRs\SAs	SA_1	SA_2	SA_3	SA_4	SA_5
SR_1	(0, 0.3)	0	(0.5, 0.7)	(0.5, 0.7)	0
SR_2	0	(0.3, 0.5)	(0.5, 0.7)	(0.5, 0.7)	0
SR_3	(0.5, 0.7)	(0.3, 0.5)	(0.7, 1)	(0.5, 0.7)	0
SR_4	0	0	0	(0.7, 1)	(0.7, 1)

Table 6: The correlation matrix P.

SAs	SA_1	SA_2	SA_3	SA_4	SA_5
SA_1	1	(0.3, 0.5)	0	0	0
SA_2	(0.3, 0.5)	1	0	(0.5, 0.7)	0
SA_3	0	0	1	(0.7, 1)	0
SA_4	0	(0.5, 0.7)	(0.7, 1)	1	(0.3, 0.5)
SA_5	0	0	0	(0.3, 0.5)	1

SR_1 for example, its relative importance W_1 is calculated as follows:

$$\begin{aligned} W_1 &= \sum_{x=1}^{4} I_x w_{1x} \\ &\sim 0.35\mathscr{L}(0.7, 1) + 0.30\mathscr{L}(0.7, 1) \\ &\quad + 0.25\mathscr{L}(0.7, 1) + 0.10\mathscr{L}(0.5, 0.7) \\ &= \mathscr{L}(0.68, 0.97) . \end{aligned} \quad (23)$$

6.3. Calculation of Importance of SAs. The relationship matrix R between SRs and SAs and the correlation matrix P between pairs of SAs, expressed by experts' judgements, are shown in Figure 3. The judgements were made by using linguistic scale with four levels as well, that is, very strong (VS), strong (S), weak (WA), and very weak (VW). The absence of the element in the matrices implies that the corresponding pair of SR and SA (in R) or two SAs (in P) are totally independent, except the correlation of a SA with itself. Once the matrices R and P are determined, the core of the HoQ can be built (see Figure 3).

Similarly to the conversion from linguistic judgements into uncertain variables for the importance of SRs, the matrices R and P can be transformed into uncertain variables according to Table 1 as well, which are shown in Tables 5 and 6, respectively. Note that the elements in the diagonal of the correlation matrix P (Table 6) are all 1, which implies that one strategic action is completely positive correlated with itself, whereas the element with value of 0 in the matrices R (Table 5) and P (Table 6) denotes that the relationship is totally independent. The crisp numbers 1 and 0 can be seen as special linear uncertain variables and denoted by $\mathscr{L}(1, 1)$ and $\mathscr{L}(0, 0)$, respectively. Therefore, they can be dealt with by the proposed uncertain QFD approach as well.

Then, the expected values of the importance of SAs can be derived from W, R, and P according to Theorem 9, which are listed at the bottom of the HoQ in Figure 3. Taking the first

Table 7: Prioritization of strategic actions based on benefit/cost analysis.

Strategic actions	SA_1	SA_2	SA_3	SA_4	SA_5
Expected importance: $E[Y_j]$	0.742	1.828	3.012	3.556	1.122
Linguistic judgements on costs	H	L	H	VH	L
Costs converted into uncertain variables: C_j	(0.5, 0.7)	(0.3, 0.5)	(0.5, 0.7)	(0.7, 1)	(0.3, 0.5)
Expected values of costs: $E[C_j]$	0.6	0.4	0.6	0.85	0.4
Marginal utilities: U_j	1.237	4.570	5.020	4.184	2.805
Prioritization of strategic actions	5	2	1	3	4

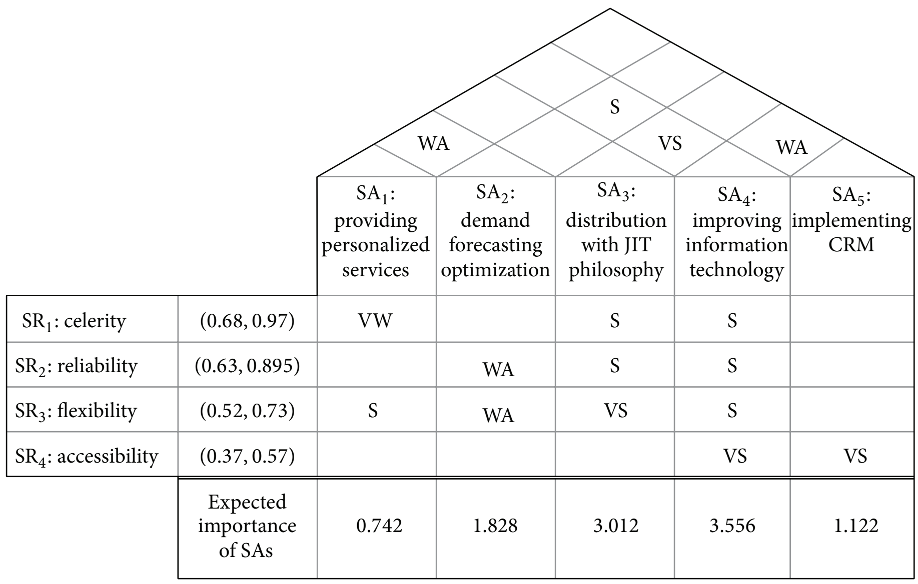

Figure 3: The house of quality for the application in logistics services.

strategic action SA_1, for instance, its expected importance Y_1 is calculated as follows:

$$E[Y_1] = \sum_{i=1}^{4}\sum_{k=1}^{5}\left[\frac{1}{4}a_i^W a_{ik}^R a_{k1}^P + \frac{1}{12}a_i^W a_{ik}^R b_{k1}^P + \frac{1}{12}a_i^W b_{ik}^R b_{k1}^P + \frac{1}{12}a_i^W b_{ik}^R a_{k1}^P + \frac{1}{12}b_i^W a_{ik}^R a_{k1}^P + \frac{1}{12}b_i^W a_{ik}^R b_{k1}^P + \frac{1}{12}b_i^W b_{ik}^R a_{k1}^P + \frac{1}{4}b_i^W b_{ik}^R b_{k1}^P\right] = 0.742. \quad (24)$$

6.4. Prioritization of SAs. Considering the costs of implementing these strategic actions, benefit/cost analysis can be further conducted. The results of the prioritization of SAs based on benefit/cost analysis are shown in Table 7.

From Table 7, it can be found that the third strategic action, namely, distribution with JIT philosophy, has the highest priority compared to other SAs. The prioritization of these five strategic actions are $SA_3 \succ SA_2 \succ SA_4 \succ SA_5 \succ SA_1$ in terms of efficiency to meet the customer requirements with limited resources, where "$\succ$" indicates the higher priority.

7. Conclusions

Logistics service increasingly contributes to the core competence of an enterprise or product. In order to gain more competitive advantage, decision makers have to figure out and meet the requirements of their customers with limited resources, which calls the most effective strategic actions to be executed.

For this purpose, an uncertain QFD approach for selecting the most effective SAs to achieve customer satisfaction in practical logistics management was developed in this paper, which integrates uncertainty theory into the traditional QFD methodology in order to rationally deal with many imprecise quantities represented by linguistic judgements behaving neither like randomness nor like fuzziness in the QFD process. These linguistic inputs related to the QFD system for logistics strategic management are converted into linear uncertain variables and then can be dealt with in the framework of uncertainty theory. Furthermore, in order to prioritize the strategic actions in terms of efficiency to meet the customer requirements with limited resources, benefit/cost analysis was integrated into the proposed approach as well. On the basis of benefit/cost analysis, not only the importance of SAs with respect to customer requirements, but also the costs of implementing these strategic actions are taken into account while determining the most effective strategic actions.

Conflict of Interests

The authors declare that they do not have any commercial or associative interest that represents a conflict of interests in connection with the work submitted.

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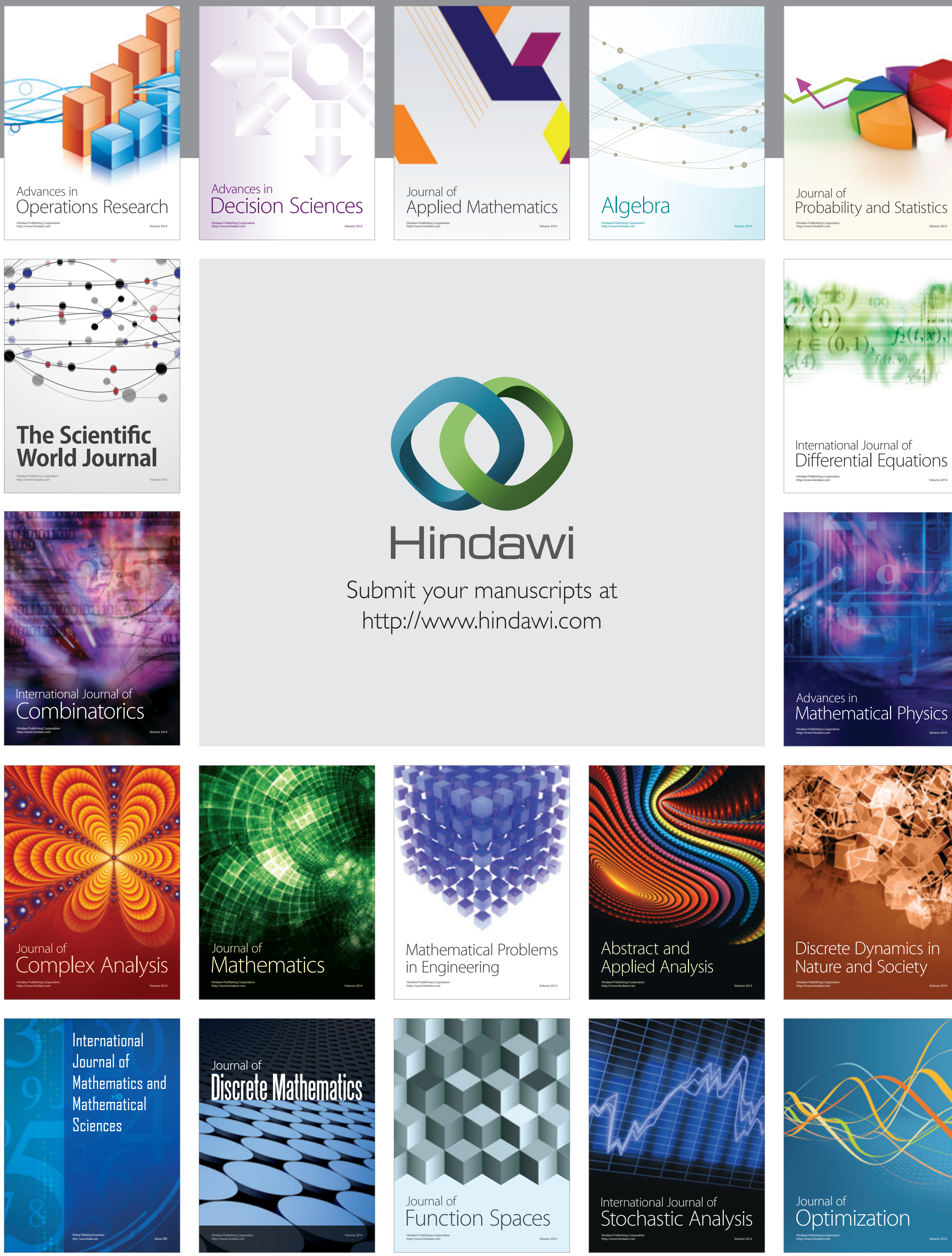
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