A New Integrated Multi-Criteria Decision Making and Multi-Objective Programming Model for Sustainable Supplier Selection and Order Allocation

Shan-Yong You 1, Li-Jun Zhang 2, Xue-Guo Xu 2,* and Hu-Chen Liu 3,4

1 Jiangsu Branch of Comba Telecom Systems (China) Ltd., Nanjing 210019, China; youshanyong@comba.com.cn
2 School of Management, Shanghai University, Shanghai 200444, China; LiJunZ@shu.edu.cn
3 College of Economics and Management, China Jiliang University, Hangzhou 310018, China; huchenliu@tongji.edu.cn
4 School of Economics and Management, Tongji University, Shanghai 200092, China
* Correspondence: xuxueguo@shu.edu.cn

Received: 19 January 2020; Accepted: 11 February 2020; Published: 20 February 2020

Abstract: With the increasing pressure from global competition, manufacturers have realized that sustainable production is significant in supply chain management. Sustainable supplier selection and order allocation (SSS&OA) play a distinct and critical role for organizations to achieve sustainable development and build competitive advantage. In this paper, we aim to develop a novel SSS&OA model for selecting the most suitable sustainable suppliers and determining the optimal order sizes among them. First, double hierarchy hesitant linguistic term sets (DHHLTSs) are adopted to deal with uncertainty in evaluating the sustainable performance of alternative suppliers. Then, an extended decision field theory is proposed to choose efficient sustainable suppliers dynamically. Considering quantity discount, a multi-objective linear programming (MOLP) model is established to allocate reasonable order quantities among the selected suppliers. Finally, the applicability and effectiveness of the developed model are illustrated through its application in the electronic industry and through a comparative analysis with other methods.

Keywords: sustainable supplier selection; order allocation; hesitant linguistic term; decision field theory; PIPRECIA method

1. Introduction

With the increasing awareness of environmental protection, more and more enterprises have integrated green thinking into their daily production and operation management [1,2]. In such a context, the sustainable supply chain management (SSCM) concept emerged, which aims to improve the economic, environmental, and social performance while reducing environmental pollution and eliminating the waste of resources in procurement, manufacturing, distribution, and sales [3,4]. Many enterprises have recognized the necessity of adopting sustainable development measures and started to change their practices to achieve sustainable development [5–7]. Selecting qualified sustainable suppliers and determining optimal order quantities play a pivotal role in improving the performance of a sustainable supply chain, as companies are held responsible not only for their own actions, but for the adverse environmental impacts of their partners [8,9]. Recently, many researchers have tried to integrate sustainable supplier selection with order allocation to help enterprises enhance their sustainable performance [10–13].

For a sustainable supplier selection problem, the green performance of alternative suppliers is often evaluated based on multiple criteria. To handle ambiguity information in the sustainable
supplier selection, many uncertainty theories have been utilized in the literature, such as fuzzy sets [14], hesitant fuzzy sets [6], intuitionistic fuzzy sets [15], cloud mode [16], and interval type-2 fuzzy sets [17]. However, these methods are insufficient to describe complex evaluation information in detail. Besides, decision makers’ evaluation information may be lost in the information transform process. To address these issues, Gou et al. [18] proposed the double hierarchy hesitant linguistic term sets (DHHLTSs), which are composed of two hierarchy linguistic term sets. In a DHHLTS, the first hierarchy is a classical feature linguistic labels and the second hierarchy is the characteristic or detailed supplementary for the first hierarchy. Using the DHHLTSs, the complicated evaluation information from decision makers can be described more detail. In addition, decision makers can utilize DHHLTSs to express their opinions comprehensively. Given these advantages, many researchers have adopted the DHHLTSs to handle complex uncertain linguistic information in various decision-making problems [19–23].

Generally, sustainable supplier selection is regarded as a multi-criteria decision making (MCDM) problem. Therefore, a number of MCDM methods have been suggested to solve the sustainable supplier selection problems [24–27]. Decision field theory (DFT), proposed by Busemeyer et al. [28], is a dynamic MCDM approach that can better simulate decision making process under uncertain environment. Besides, the DFT method can formulate the change of decision makers’ preference intensity over time [29]. Recently, the DFT has been utilized for decision making in different fields. For example, Lee and Son [30] proposed an extended DFT with social learning for modeling and analyzing human behaviors in social networks. Song et al. [31] proposed a hesitant fuzzy DFT for the route selection of the arctic northwest passage. Hao et al. [32] developed an intuitionistic fuzzy decision-making framework based on DFT and applied it to address investment decision making problems. In addition, Abad et al. [33] estimated expected human attention weights based on the DFT and Qin et al. [34] analyzed park-and-ride decision behavior by using the DFT.

According to the above discussions, this paper first proposes a novel sustainable supplier selection model by combining DHHLTSs and DFT to select qualified sustainable suppliers to work with. Further, a multi-objective linear programming (MOLP) model is constructed for obtaining suitable order quantities for the selected sustainable suppliers. More specifically, the DHHLTSs are applied for evaluating the green performance of suppliers with respect to each evaluation criterion. An extended weighting method is developed to compute the weights of evaluation criteria according to comparative importance evaluations of decision makers. Then, the DFT is used to choose the best portfolio of sustainable suppliers among alternatives. Finally, a MOLP model based on quantity discount is constructed to obtain suitable order sizes for the appropriate sustainable suppliers. The remainder of this article is structured as below. Section 2 reviews the existing researches on sustainable supplier selection and order allocation (SSS&OA). Section 3 presents the basic concepts of DHHLTSs. The developed SSS&OA model is described in Section 4. In Section 5, an illustrative case application in the electronic industry is utilized to demonstrate the proposed model. Section 6 provides conclusions of this study and suggestions for future research.

2. Literature Review

The following subsections review the existing studies concerning sustainable supplier selection and the integration of supplier selection and order allocation.

2.1. Sustainable Supplier Selection

In SSCM, selecting the right suppliers for a manufacturer is a key success factor that will greatly reduce purchasing cost, improve customer satisfaction, and increase competitive ability. Under this context, sustainable supplier selection process can be described as one of the most significant processes and widely understood as a crucial management responsibility. Choosing the qualified suppliers is not an easy decision because it requires the simultaneous consideration of both quantitative and qualitative criteria, which generally contradict with each other. To help managers make this decision, a lot of single and integrated models have been proposed in the literature. As for single models,
Stević et al. [1] proposed a measurement of alternatives and ranking according to compromise solution (MARCOS) method for sustainable supplier selection in the healthcare industry. Keshavarz Ghorabaee et al. [35] utilized an extended complex proportional assessment (COPRAS) method to determine suitable material suppliers for a high-technology manufacturing company. You et al. [36] developed an interval 2-tuple linguistic VIKOR (VIsekriterijumska optimizacija i KOm-promisno Resenje) method to select the most sustainable supplier. Kannan et al. [37] applied the fuzzy technique for order preference by similarity to ideal solution (TOPSIS) for the selection of the best green supplier for a company from the electronics industry, and Meksavang et al. [3] employed a picture fuzzy VIKOR approach for sustainable supplier evaluation in the beef industry. Quan et al. [4] proposed an integrated approach by combining an ant colony algorithm, linear programming technique, and multi-objective optimization by a ratio analysis plus full multiplicative form (MULTIMOORA) to deal with the sustainable supplier selection problem. Based on heterogeneous criteria information and the multi-attributive border approximation area comparison (MABAC) method, Xu et al. [38] suggested a green supplier evaluation and selection methodology to select the optimal green supplier for an automotive enterprise. Liu et al. [2] proposed a combined method integrating best-worst method (BWM) and alternative queuing method (AQM) to evaluate and select green suppliers with interval-valued intuitionistic uncertain linguistic information. Liu et al. [17] integrated quality function deployment (QFD) with partitioned Bonferroni mean operator to select a superior bike-share supplier. In [39], the fuzzy analytic hierarchy process (AHP), cloud model and possibility degree were combined to determine the best sustainable supplier for a straw biomass power plant.

2.2. Supplier Selection and Order Allocation

Supply chain efficiency depends on the performance and flexibility of all entities in the chain. Therefore, companies should not only select the best suppliers but also optimally allocate demand among the selected suppliers to minimize costs and improve competitive advantage. In response, many scholars integrated MCDM methods with mathematical programming for solving SSS&OA problems. For instance, Govindan et al. [13] integrated fuzzy TOPSIS with MOLP to select well-performing sustainable suppliers and to obtain reasonable order allocation for a low-carbon paper mill. Lo et al. [5] applied an integrated model based on BWM, fuzzy TOPSIS and fuzzy MOLP to deal with the SSS&OA problem for an electronic manufacturing firm. Mohammed et al. [40] presented a framework for handling an SSS&OA problem, where fuzzy AHP was adopted to calculate criteria weights, fuzzy TOPSIS was used to rank candidate suppliers, and multi-objective programming model was used to determine the optimal order size for each qualified supplier. Gören [41] developed an SSS&OA model, in which fuzzy decision-making trial and evaluation laboratory (DEMATEL) was adopted for determining criteria weights, Taguchi loss function was used for ranking each supplier and bi-objective model was constructed for allocating order quantities with lost sales. Duan et al. [11] proposed an integrated approach that integrated linguistic Z-numbers, AQM and MOLP model to select qualified suppliers and assign suitable order quantity. Cheraghalipour and Farsad [42] proposed a bi-objective decision-making framework by considering quantity discounts and disruption risks to handle the SSS&OA problem for a company from the plastic industry. In [10], a hybrid approach based on fuzzy TOPSIS, trapezoidal type-2 fuzzy AHP and goal programming was developed for supplier selection and order allocation under quantity discount and fast service options. Considering price discount and shortage conditions, Moheb-Alizadeh et al. [43] established a multi-objective mixed integer linear programming model to solve the SSS&OA problem with multiple periods, multiple products, and multi-modal transportation.

3. Preliminaries

The DHHLTSs were by proposed Gou et al. [18] based on double hierarchy linguistic term sets (DHLTSs) to represent decision makers’ evaluation information more precisely and completely. The definitions of the DHLTSs and the DHHLTSs are described below.
Definition 1 [18]. Suppose that \( S = \{ s_t| t = -\tau, \ldots, -1, 0, 1, \ldots, \tau \} \) and \( O = \{ o_k| k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \} \) are two independent linguistic term sets, where \( S \) is the first hierarchy and \( O \) is the second hierarchy. A DHLTS \( S_O \) is defined as follows:

\[
S_O = \{ s_{t, o_k}| t \in [-\tau, \tau]; k \in [-\varsigma, \varsigma] \},
\]

where \( O_k \) represents the second hierarchy linguistic term when the first hierarchy linguistic term is \( s_t \) and \( s_{t, o_k} \) is called the double hierarchy linguistic term (DHLT).

Definition 2 [18]. Suppose that \( S_O = \{ s_{t, o_k}| t = -\tau, \ldots, -1, 0, 1, \ldots, \tau; k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \} \) is a DHLTS. \( H_{S_O} \) is a DHLTS on \( X \) and it can be defined as:

\[
H_{S_O} = \{ < x_i, h_{S_O}(x_i)> | x_i \in X \},
\]

where \( h_{S_O}(x_i) \) is a collection of some values in \( S_O \), and expressed as:

\[
h_{S_O}(x_i) = \{ s_{\phi, o_{\gamma_l}}(x_i)| s_{\phi, o_{\gamma_l}} \in S_O; l = 1, 2, \ldots, L; \phi_l = -\tau, \ldots, -1, 0, 1, \ldots, \tau; \gamma_l = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \}.
\]

Here, \( L \) is the number of linguistic terms in \( h_{S_O} \) and \( s_{\phi, o_{\gamma_l}} \) in each \( h_{S_O}(x_i) \) is the continuous terms in \( S_O \); \( h_{S_O}(x_i) \) expresses the possible degree of the linguistic variable \( x_i \) to \( S_O \) and it is named as double hierarchy hesitant linguistic element (DHHLE).

Definition 3 [18]. Let \( S_O = \{ s_{t, o_k}| t = -\tau, \ldots, -1, 0, 1, \ldots, \tau; k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \} \) be a DHLTS, \( h_{S_O} = \{ s_{\phi_l, o_{\gamma_l}}| s_{\phi_l, o_{\gamma_l}} \in S_O; l = 1, 2, \ldots, L; \phi_l = -\tau, \ldots, -1, 0, 1, \ldots, \tau; \gamma_l = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \} \) be a DHHL, and \( h_{\gamma_l} = \{ \gamma_l| \gamma_l \in [0, 1]; l = 1, \ldots, L \} \) be a hesitant fuzzy element. The subscript \( \phi_l < \gamma_l \) of the DHLT \( s_{\phi_l, o_{\gamma_l}} \) and the membership degree \( \gamma_l \) expresses the equivalent information. They can be transformed into each other by the following functions:

\[
f : [-\tau, \tau] \times [-\varsigma, \varsigma] \to [0, 1]
\]

\[
f(\phi_l, \gamma_l) = \begin{cases} 
\frac{\phi_l + (1+\phi_l)\tau}{2\tau} = \gamma_l & \text{if } \phi_l \neq -\tau \\
\frac{\phi_l}{\tau} = \gamma_l & \text{if } \phi_l = -\tau 
\end{cases}
\]

\[
f^{-1} : [0, 1] \to [-\tau, \tau] \times [-\varsigma, \varsigma],
\]

\[
f^{-1}(\gamma_l) = \begin{cases} 
s_{t, o_k} & \text{if } \gamma_l = 1 \\
s_{|2\gamma_l-\tau|, o_{|2\gamma_l-\tau=|2\gamma_l-\tau|=}} & \text{if } 1 \leq 2\gamma_l - \tau \leq \tau \\
s_{0, e_{|2\gamma_l-\tau|=}} & \text{if } -1 \leq 2\gamma_l - \tau \leq 1 \\
s_{|2\gamma_l-\tau|+1, o_{|2\gamma_l-\tau=|2\gamma_l-\tau|=}} & \text{if } -\tau \leq 2\gamma_l - \tau \leq -1 \\
s_{t, o_k} & \text{if } \gamma_l = -1 
\end{cases}
\]

Furthermore, the transformation between the DHHL \( h_{S_O} \) and the hesitant fuzzy element \( h_{\gamma_l} \) can be determined by

\[
F(h_{S_O}) = F\left( \{ s_{\phi_l, o_{\gamma_l}}| s_{\phi_l, o_{\gamma_l}} \in S_O; l = 1, \ldots, L; \phi_l \in [-\tau, \tau]; \gamma_l \in [-\varsigma, \varsigma] \} \right) = \{ \gamma_l| \gamma_l = f(\phi_l, \gamma_l) \} = h_{\gamma_l}.
\]

\[
F^{-1}(h_{\gamma_l}) = F^{-1} \left( \{ \gamma_l| \gamma_l \in [0, 1]; l = 1, \ldots, L \} \right) = \{ s_{\phi_l, o_{\gamma_l}}| \phi_l < o_{\gamma_l} = f^{-1}(\gamma_l) \} = h_{S_O}.
\]
Definition 4 [18]. Suppose that $S_o = \{s_{l<\alpha_l}>| l = -\tau, \ldots, -1, 0, 1, \ldots, \tau; k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma\}$ be a DHLTS, $h_{S_{O_1}}$ and $h_{S_{O_2}}$ are two DHHLEs, $\lambda$ is a real number. The basic operations of DHHLEs can be defined as below:

1. $h_{S_{O_1}} \otimes h_{S_{O_1}} = F^{-1}\left(\bigcup_{\eta \in F(h_{S_{O_1}})} \{\eta_1 \eta_2\}\right)$
2. $(h_{S_o})^\lambda = F^{-1}\left(\bigcup_{\eta \in F(h_{S_o})} \{\eta^\lambda\}\right)$

Definition 5 [18]. Let $S_O = \{s_{l<\alpha_l}>| l = -\tau, \ldots, -1, 0, 1, \ldots, \tau; k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma\}$ be a DHLTS, $h_{S_O} = \{h_{S_O} = \{s_{\phi<\alpha_l}>| s_{\phi<\alpha_l} \in S_O; l = 1, 2, \ldots, l_o; \phi_l = [-\tau, \tau]; \phi_l = [-\varsigma, \varsigma]\}$ be a DHHLE. Then, the expected value of $h_{S_O}$ is computed by

$$E(h_{S_o}) = \frac{1}{L} \sum_{i=1}^{L} f(s_{\phi<\alpha_l}>).$$

Definition 6 [44]. Suppose that $S_O = \{s_{l<\alpha_l}>| l = -\tau, \ldots, -1, 0, 1, \ldots, \tau; k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma\}$ is a DHLTS. $H_{S_O}^1 = \{h_{S_{O_1}} = \{h_{S_O}^1, h_{S_O}^2, \ldots, h_{S_O}^L\}$ and $H_{S_O}^2 = \{h_{S_{O_2}} = \{h_{S_O}^1, h_{S_O}^2, \ldots, h_{S_O}^L\}$ are two DHHLTSSs, where $h_{S_O}^1 = \{s_{\phi<\alpha_l}>| s_{\phi<\alpha_l} \in S_O; l = 1, 2, \ldots, \#h_{S_O}^1\} (j = 1, 2, \ldots, n)$ while $\#h_{S_O}^1$ is the number of DHLTS in $h_{S_O}^1$ and $h_{S_O}^2 = \{s_{\phi<\alpha_l}>| s_{\phi<\alpha_l} \in S_O; l = 1, 2, \ldots, \#h_{S_O}^2\} (j = 1, 2, \ldots, n)$ while $\#h_{S_O}^2$ is the number of DHLTS in $h_{S_O}^2$.

Then, the distance between $H_{S_O}^1$ and $H_{S_O}^2$ is defined by

$$d(H_{S_O}^1, H_{S_O}^2) = \left(\frac{1}{L} \sum_{i=1}^{L} \left|f(s_{\phi<\alpha_l}>^1) - f(s_{\phi<\alpha_l}>^2)\right|\right)^{\frac{1}{2}},$$

where $L$ is the maximum number of linguistic terms in $H_{S_O}^1$ and $H_{S_O}^2$.

Definition 7. Suppose that $H_{S_O} = \{h_{S_{O_1}}, h_{S_{O_2}}, \ldots, h_{S_{O_n}}\}$ is a collection of DHHLEs, then the double hierarchy hesitant weighted geometric (DHHWG) operator is defined as:

$$DHHWG(h_{S_{O_1}}, h_{S_{O_2}}, \ldots, h_{S_{O_n}}) = \bigotimes_{i=1}^{n} h_{S_{O_i}}^{\omega_i} = F^{-1}\left(\bigcup_{\gamma_i \in F(h_{S_{O_i}})} \left\{\prod_{i=1}^{n} \gamma_i^{\omega_i}\right\}\right).$$

4. The Developed SSS&OA Model

This section proposes a new integrated SSS&OA model for selecting qualified sustainable suppliers and optimally allocating reasonable order sizes to meet different procurement criteria. To sum up, three stages are included in the proposed model, which include computing the weights of selection criteria based on the PIPRECIA (pivot pairwise relative criteria importance assessment) method [45], determining the ranking of candidate sustainable suppliers by an extended DFT, and allocating reasonable order sizes to the selected suppliers using a MOLP model. Figure 1 displays a flow chart of the proposed SSS&OA model.
For a SSS&OA problem, suppose that there are \( m \) candidate suppliers \( A_i (i = 1, 2, \ldots, m) \), \( n \) considered criteria \( C_j (j = 1, 2, \ldots, n) \) and \( g \) decision makers \( DM_g (g = 1, 2, \ldots, q) \). Assume that \( H^g = \left[ h^g_{S_{ij}} \right]_{m \times n} \) is the double hierarchy hesitant linguistic (DHHL) evaluation matrix of \( DM_g \), where \( h^g_{S_{ij}} = \{ \phi^g_{ij}, \phi^{g'}_{ij} \} \in S_O \) is a DHHLLE denoting the evaluation for supplier \( A_i \) with respect to \( C_j \) based on the linguistic term sets \( S = \{ s_t | t = -\tau, \ldots, -1, 0, 1, \ldots, \tau \} \) and \( O = \{ o_k | k = -\varsigma, \ldots, -1, 0, 1, \ldots, \varsigma \} \). The decision makers’ weights are assumed as \( v^g (g = 1, 2, \ldots, q) \) with \( \sum_{g=1}^{q} v^g = 1 \) and \( 0 < v^g < 1 \). Next, the detailed procedure of the developed SSS&OA model is described.

**Stage 1.** Determine criteria weights by the PIPRCIA method.

The PIPRCIA method, developed by Stanujkic et al. [45], is a new subjective weighting method to determine criteria weights according to the judgements of decision makers. This method allows decision makers to evaluate criteria when the expected criteria importance ranking is difficult or impossible to reach a consensus [46]. It enables decision makers to easily involve in the evaluation process and can improve reliability of the collected data. Hence, the PIPRCIA method is adopted to obtain the subjective weights for the \( n \) evaluation criteria. The detailed steps are given as follows:

**Step 1.1.** Rank the selection criteria in descending order.

This step is to determine the order of the \( n \) evaluation criteria \( C_j (j = 1, 2, \ldots, n) \) in descending order based on their importance. Since the consensus on the expected importance of criteria is not easy to reach in the actual group supplier selection problem, decision makers are allowed to evaluate the criteria comparative importance without regard to their preliminary ordering.

**Step 1.2.** Determine the comparative importance of criteria.

Suppose \( \psi^g(C_j, C_{j+1}) = h^g_{S_{ij+1}} \) is the DHHL comparative importance between criteria \( C_j \) and \( C_{j+1} \) provided by decision maker \( DM_g \) using the linguistic term sets \( S' = \{ s'_t | t = -\tau', \ldots, -1, 0, 1, \ldots, \tau' \} \) and \( O' = \{ o'_k | k = -\varsigma', \ldots, -1, 0, 1, \ldots, \varsigma' \} \), for \( j = 1, 2, \ldots, n-1; g = 1, 2, \ldots, q \). Then, the aggregated comparative importance of criteria can be determined by

\[
\psi(C_j, C_{j+1}) = DHHWG(h^1_{S_{ij+1}}, h^2_{S_{ij+1}}, \ldots, h^q_{S_{ij+1}}) = F^{-1} \left( \bigcup_{g=1}^{q} \left( \prod_{g=1}^{q} \psi^g \right) \right)
\]

Figure 1. Flowchart of the developed SSS&OA model.
Step 1.3. Compute the relative weights of selection criteria.

The relative weight of each criterion $w_j$ ($j = 1, 2, \ldots, n$) is calculated through the following formula:

$$w_j = \begin{cases} 1 & j = n, \\ \frac{w_{j+1}}{2(1 - \gamma(C_j, C_{j+1}))} & j < n. \end{cases}$$

(12)

where $\gamma(C_j, C_{j+1})$ is the membership degree of $\psi(C_j, C_{j+1})$ determined by Equation (4).

Step 1.4. Calculate the normalized weights of selection criteria.

The normalized weights of the $n$ selection criteria $\overline{w}_j$ ($j = 1, 2, \ldots, n$) are determined by

$$\overline{w}_j = \frac{w_j}{\sum_{j=1}^{n} w_j}.$$  

(13)

Stage 2. Select qualified sustainable suppliers by the DFT.

The DFT, developed by Busemeyer et al. [28], is a dynamic decision-making approach. It describes how decision makers’ preferences evolve over time until a decision is reached. In this section, we extended the DFT with DHHLTSs to determine the ranking of green suppliers.

Step 2.1. Aggregate the decision makers’ evaluations.

In this step, the individual DHHL matrixes of decision makers $H^g (g = 1, 2, \ldots, q)$ are aggregated to construct a collective DHHL evaluation matrix $H = \left[ h_{SOij} \right]_{m \times n}$, where

$$h_{SOij} = DHHWG \left( h^1_{SOij}, h^2_{SOij}, \ldots, h^q_{SOij} \right) = \prod_{g=1}^{q} \left( h^g_{SOij} \right)^{v_g} = F^{-1} \left( \bigcup_{\gamma \in E(h^g_{SOij})} \left( \prod_{g=1}^{q} \gamma_g \right) \right).$$

(14)

Step 2.2. Calculated the distance matrix $\hat{D}$ between sustainable suppliers.

The distance matrix $\hat{D} = \left[ d_{iu} \right]_{m \times m}$ between the $m$ sustainable suppliers can be obtained by

$$d_{iu} = \sum_{j=1}^{n} d(h_{SOij}, h_{SOuj}), \quad i, u = 1, 2, \ldots, m.$$  

(15)

Step 2.3. Determine the feedback matrix $\hat{F}$.

The feedback matrix $\hat{F} = \left[ f_{ij} \right]_{m \times m}$ describes the memorizing effect of the competitive relationship between different sustainable suppliers, in which diagonal elements represent the self-impact of a supplier, while non-diagonal elements express the competitive effects between suppliers. The feedback matrix $\hat{F}$ is determined by

$$\hat{F} = I - \varphi \cdot e^{-\delta \hat{D}^2},$$

(16)

where $I$ is an identity matrix. The parameter $\delta$ describes the discriminable capability and it lies in the interval $[0.01, 1000]$ [32], and parameter $\varphi$ represents the competitive impact between suppliers and belongs to $[0, 1]$ [47].

Step 2.4. Determine the contract matrix $\hat{C}$.

The contract matrix $\hat{C} = \left[ \hat{c}_{ij} \right]_{m \times n}$ is determined as follows:

$$\hat{c}_{ij} = \begin{cases} 1 & \text{if } i = j, \\ -\frac{1}{n-1} & \text{if } i \neq j. \end{cases}$$

(17)

Step 2.5. Obtain the ranking of sustainable suppliers.
Suppose \( P(t) = \{\hat{p}_1(t), \hat{p}_2(t), \ldots, \hat{p}_m(t)\} \) is a preference vector of sustainable suppliers at the time \( t \), where \( \hat{p}_i(t) \) represents the preference value of \( A_i \) at the time \( t \) and can be calculated by

\[
\hat{p}_i(t) = \sum_{j=1}^{n} \overline{w}_{ij} E(h_{Sc_{ij}}(t)) \quad i = 1, 2, \ldots, m.
\]  

(18)

Then, the preference vector \( P(t+h) \) at the time \( t+h \) is calculated by

\[
P(t+h) = FP(t) + V(t+h),
\]

where \( h \) represents an arbitrary short time step and \( P(t+h) \) will approximate the diffusion process when \( h \) approaches zero. \( V(t+h) \) is the DHHL valence vector and it can be computed by

\[
V(t+h) = \hat{C} \otimes H' \otimes \overline{w}_j(t+h),
\]

(20)

where \( H' = \left[ E(h_{Sc_{ij}}) \right]_{\text{norm}} \), \( \overline{w}_j(t+h) \) is the considered criteria weights at time \( t+h \), and \( \overline{w}_j(t+h) \) is randomly generated in the interval \([\overline{w}_j - 0.05, \overline{w}_j + 0.05]\).

The final decision results are concluded when the decision time \( t \) reaches the threshold criteria [32]. The ranking of the \( m \) sustainable suppliers are determined according to the decreasing order of the \( \hat{p}_j(t+h)(i = 1, 2, \ldots, m) \) values and the largest \( \hat{p}_j(t+h) \) corresponds to the best supplier.

Stage 3. Allocate order sizes to the qualified sustainable suppliers.

In this stage, we establish an MOLP model with quantity discount to determine the order size for each selected sustainable supplier. The objectives of the developed model include minimizing the total cost of purchasing, minimizing the total defect quantity of product, minimizing the total delay delivery quantity of product, and maximizing the total sustainable value of purchasing simultaneously.

The developed MOLP model is given below.

Step 3.1. Define related indexes and parameters.

**Indexes**

- \( p \): Index of products \( p, p = 1, 2, \ldots, \lambda \).
- \( i \): Index of supplier \( i, i = 1, 2, \ldots, m \).
- \( r \): Index of discount intervals, \( r = 1, 2, \ldots, R \).

**Parameters:**

- \( O_p \): Ordering cost of product \( p \) offered by green supplier.
- \( P_{\text{pr}} \): Purchase price of product \( p \) offered by green supplier \( i \) in discount interval \( r \)
- \( B_{\text{pr}} \): Lower quantity bound of the discount interval \( r \) in product \( p \) provided by supplier \( i \).
- \( T_p \): Unit transportation cost of product \( p \) offered by green supplier \( i \).
- \( H_p \): Unit holding cost of product \( p \).
- \( D_p \): Demand of product \( p \).
- \( C_p \): Capacity of \( p \)th product for \( i \)th green supplier.
- \( Q_p \): Defective rate of product \( p \) offered by green supplier \( i \).
- \( Q_p \): Maximum defective rate of product \( p \) can be accepted.
- \( L_{\text{pr}} \): Delay rate of supplier \( p \) in product \( i \).
- \( L_p \): Maximum acceptable delay rate of product \( p \).
- \( P_i \): Priority value of sustainable supplier \( i \) obtained by the DFT.

**Decision variables:**

- \( X_{pir} \): Order size of product \( p \) purchased from sustainable supplier \( i \) at discount interval \( r \).
• \( Y_{pir} \): Binary variable (=1) if product \( p \) is offered by sustainable supplier \( i \) at discount interval \( r \), 0 otherwise.

**Step 3.2.** Construct an MOLP model considering multiple objectives.

To allocate order for each selected sustainable supplier, the following MOLP model can be established:

\[
\begin{align*}
\text{min } & z_1 = \sum_{k=1}^{n} \sum_{i=1}^{m} P_{pir}X_{pir} \\
\text{min } & z_2 = \sum_{p=1}^{n} \sum_{i=1}^{m} Q_{pi}X_{pir} \\
\text{min } & z_3 = \sum_{p=1}^{n} \sum_{i=1}^{m} L_{pi}X_{pir} \\
\text{max } & z_4 = \sum_{i=1}^{m} P^{*}_iX_{pir}
\end{align*}
\]

Subject to:

\[
\begin{align*}
\sum_{p=1}^{n} X_{pir} & \geq D_p \forall i \\
X_{pir} & < C_{pi} \forall p, i \\
B_{pir} & \leq X_{pir} \leq B_{pir+1} \forall p, i, r \\
\sum_{r=1}^{R} Y_{pir} & \leq 1 \forall p, i \\
\sum_{p=1}^{n} \sum_{i=1}^{m} Q_{pi}X_{pir} & \leq Q_pD_p \\
\sum_{p=1}^{n} \sum_{i=1}^{m} L_{pi}X_{pir} & \leq L_pD_p \\
X_{pir} & \geq 0 \forall p, i
\end{align*}
\]

The objective function Equation (21) is established for minimizing the entire cost of purchasing. Equations (22) and (23) are the measure of defective quantity and delayed delivery quantity of product, respectively. The objective function of Equation (24) maximizes the total sustainable value of purchasing. Constraint sets in Equation (25) state that the total purchase number of each product must satisfy the demand quantity of the product. The capacity constraint sets described in Equation (26) show that the total quantity of product \( p \) purchased from the \( i \)th supplier should not exceed its capacity. Equations (27) and (28) are the constraints of discount interval, where the product is allowed to purchase at a certain price value. The constraint sets in Equation (29) represent that the total defective amount of product \( p \) must be lower than the maximum acceptable defective amount. The total delayed delivery number of product \( p \) cannot exceed the maximum acceptable delayed amount as given in Equation (30).

**Step 3.3:** Determine optimum order quantities of the selected suppliers.

In the MOLP model, all goals may not be realized under system constraints simultaneously. Thus, the priority and importance of objectives need to be considered. In this paper, the LP-metrics method \([40]\) is utilized to solve the established MOLP model.

Suppose \( z^{*}_{b}(b = 1, 2, 3, 4) \) are the optimal solutions of four objective functions subject to Equations (25)–(31), respectively. Let \( \omega_{b}(b = 1, 2, 3, 4) \) be the relative importance of four objective
functions given by decision makers, satisfying $0 \leq w_{bj} \leq 1$ and $\sum_{b=1}^{4} w_{bj} = 1$. The MOLP model constructed in the last step can be transformed into a single objective programming by

$$\min z = \left[ w_1 \frac{z_1 - z_1'}{z_1} + w_2 \frac{z_2 - z_2'}{z_2} + w_3 \frac{z_3 - z_3'}{z_3} - w_4 \frac{z_4 - z_4'}{z_4} \right].$$

Through solving this single objective programming model, the order quantity of each selected sustainable supplier can be determined.

5. Case Study

In this section, we first present an example to illustrate the performance of our SSS&OA model, and then conduct further analysis to compare the proposed model with other methods.

5.1. Illustration of the Proposed Model

This section applies the developed SSS&OA model to an electronics manufacturing firm located in Shanghai, China. The company’s products include semiconductors, sensors, electronic components, and industrial control products. Under great competitive pressure from the global electronics market, the company decided to manufacture sustainable and environment friendly products to improve its performance of sustainable supply chain management. Selecting qualified sustainable suppliers and allocating optimal orders are two significant activities to solve this problem.

In this case, five potential suppliers $A_i (i = 1, 2, \ldots, 5)$ are selected for the further evaluation. These sustainable suppliers are evaluated according to 10 criteria $C_j (j = 1, 2, \ldots, 10)$ from three different dimensions (see Table 1). Then, five decision makers $DM_g (g = 1, 2, \ldots, 5)$ are involved in the evaluation process based on the linguistic term sets $S$ and $O$ as defined below. The relative importance of criteria is evaluated by utilizing the linguistic term sets $S'$ and $O'$. Due to their different backgrounds and expertise, the weight vector of the five decision makers is given as $v = (0.3, 0.2, 0.2, 0.15, 0.15)$.

$$S = \left\{ s_{-3} = \text{very poor}, s_{-2} = \text{poor}, s_{-1} = \text{slightly poor}, s_0 = \text{fair}, s_1 = \text{slightly good}, s_2 = \text{good}, s_3 = \text{very good} \right\},$$

$$O = \left\{ o_{-3} = \text{far from}, o_{-2} = \text{only a little}, o_{-1} = \text{a little}, o_0 = \text{just right}, o_1 = \text{much}, o_2 = \text{very much}, o_3 = \text{extremely} \right\},$$

$$S' = \left\{ s'_{-3} = \text{very unimportant}, s'_{-2} = \text{unimportant}, s'_{-1} = \text{slightly unimportant}, s'_0 = \text{equally important}, s'_1 = \text{slightly important}, s'_2 = \text{important}, s'_3 = \text{very important} \right\},$$

$$O' = \left\{ o'_{-3} = \text{extremely}, o'_{-2} = \text{very much}, o'_{-1} = \text{much}, o'_0 = \text{just right}, o'_1 = \text{a little}, o'_2 = \text{only a little}, o'_3 = \text{far from} \right\}.$$

The DHHL comparative importance information of the 10 criteria assessed by the decision makers is displayed in Table 2. Moreover, we can obtain the DHHL evaluation matrixes of the five decision makers $H^g \in \mathbb{R}^{5 \times 10}$ for example, the evaluation information of the first decision maker $DM_1$ is shown in Table 3.

In what follows, the developed SSS&OA model is adopted to choose qualified sustainable suppliers and allocate suitable order sizes for the case study.

**Stage 1.** Determine criteria weights by the PIPRCIA method.

**Step 1.1.** Based on their estimated importance to supplier sustainable performance, the 10 criteria are ranked in descending order as: $C_1 \succ C_8 \succ C_3 \succ C_2 \succ C_4 \succ C_6 \succ C_9 \succ C_{10} \succ C_7$.

**Step 1.2.** Through Equation (11), the comparative importance evaluation information of criteria is aggregated and the result is given in Table 2.

**Step 1.3.** Using Equation (12), the relative weights of criteria $w_j (j = 1, 2, \ldots, 10)$ are computed as shown in Table 4.
Table 1. Sustainable supplier selection criteria.

| Dimension            | Criteria              | Definition                                                                 |
|----------------------|-----------------------|-----------------------------------------------------------------------------|
| Supplier performance |                       |                                                                             |
|                      | Product quality (C\textsubscript{1}) | Ensure the quality of products in accordance with ISO 19000, QS9000 and other relevant requirements and specifications |
|                      | Green manufacturing (C\textsubscript{2}) | Committed to the production of clean and environmentally friendly products. Products need to meet customer requirements and can ensure on-time delivery when orders are changed |
|                      | Service flexibility (C\textsubscript{3}) |                                                                             |
| Environmental protection | Environmental performance (C\textsubscript{4}) | The ability of environmental protection and to observe environmental supervision for products and reduce waste as much as possible. |
|                      | Innovation ability (C\textsubscript{5}) | Innovative product design to ensure the product detachable, recyclable and sustainable |
|                      | Green logistic (C\textsubscript{6}) | The ability to reduce transportation cost and pollution through logistics planning |
| Supplier risk        | Labor intensive (C\textsubscript{7}) | The extent to which a supplier relies on labor in productive activities |
|                      | Financial stability (C\textsubscript{8}) | The financial status and financial stability of supplier |
|                      | Supplier reputation (C\textsubscript{9}) | The reputation of supplier in the industry, as well as past cooperation experience |
|                      | Information safety (C\textsubscript{10}) | Suppliers’ ability to protect product information |

**Step 1.4.** According to Equation (13), the normalized weights of criteria $\overline{w}_j (j = 1, 2, \ldots, 10)$ are calculated and displayed in Table 4.

**Stage 2.** Select qualified sustainable suppliers by the DFT.

**Step 2.1.** By Equation (14), the collective DHHL evaluation matrix $H = \begin{bmatrix} h_{S\textsubscript{ij}} \end{bmatrix}_{5 \times 10}$ is established as shown in Table 5.

**Step 2.2.** Via Equation (15), the distance matrix of the five sustainable suppliers $\hat{D}$ is computed as follows:

$$\hat{D} = \begin{bmatrix} 0.00 & 0.26 & 0.33 & 0.19 & 0.32 \\ 0.26 & 0.00 & 0.30 & 0.27 & 0.15 \\ 0.33 & 0.30 & 0.00 & 0.25 & 0.19 \\ 0.19 & 0.27 & 0.27 & 0.00 & 0.32 \\ 0.32 & 0.15 & 0.15 & 0.32 & 0.00 \end{bmatrix}.$$

**Step 2.3.** Let $\varphi = 0.1$ and $\delta = 20$, and by Equation (16), the feedback matrix $\hat{F}$ is determined as:

$$\hat{F} = \begin{bmatrix} 0.990 & -0.014 & -0.016 & -0.008 & -0.010 \\ -0.014 & 0.990 & -0.016 & -0.018 & -0.010 \\ -0.016 & -0.016 & 0.990 & -0.013 & -0.003 \\ -0.008 & -0.018 & -0.013 & 0.990 & -0.022 \\ -0.020 & -0.010 & -0.010 & -0.022 & 0.990 \end{bmatrix}.$$

**Step 2.4.** Based on Equation (17), the contract matrix $\hat{C}$ is obtained as follows:

$$\hat{C} = \begin{bmatrix} 1 & -0.25 & -0.25 & -0.25 & -0.25 \\ -0.25 & 1 & -0.25 & -0.25 & -0.25 \\ -0.25 & -0.25 & 1 & -0.25 & -0.25 \\ -0.25 & -0.25 & -0.25 & 1 & -0.25 \\ -0.25 & -0.25 & -0.25 & -0.25 & 1 \end{bmatrix}.$$
Table 2. Comparative importance evaluation of criteria given by decision makers.

| Criteria | Decision Makers | Aggregated Vector |
|----------|-----------------|------------------|
|          | $DM_1$          | $DM_2$           | $DM_3$           | $DM_4$           | $DM_5$           |
| (C_{1}, C_{3}) | $s'_{1,0.12}$   | $s'_{1,0.09}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,0.12}$   |
| (C_{1}, C_{2}) | $s'_{0,0.12}$   | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,0.12}$   |
| (C_{2}, C_{4}) | $s'_{0,0.12}$   | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,0.12}$   |
| (C_{4}, C_{6}) | $s'_{0,12}$     | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,12}$     |
| (C_{6}, C_{8}) | $s'_{0,12}$     | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,12}$     |
| (C_{8}, C_{10}) | $s'_{0,12}$     | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,12}$     |
| (C_{10}, C_{9}) | $s'_{0,12}$     | $s'_{1,0.12}$    | $s'_{1,0.12}$   | $s'_{1,0.12}$   | $s'_{0,12}$     |

Table 3. The DHHN evaluation matrix $H^1$.

| Suppliers | C_{1} | C_{2} | C_{3} | C_{4} | C_{5} | C_{6} | C_{7} | C_{8} | C_{9} | C_{10} |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| A_{1}     | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ |
| A_{2}     | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ |
| A_{3}     | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ |
| A_{4}     | $s_{2,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ |
| A_{5}     | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ | $s_{1,0.12}$ | $s_{2,0.12}$ |
Table 4. Computation result of the PIPRCIA method.

| Criteria | Relative Weights | Normalized Weights |
|----------|------------------|--------------------|
| C₁       | 3.71             | 0.19               |
| C₅       | 2.62             | 0.13               |
| C₃       | 1.9              | 0.1                |
| C₂       | 1.74             | 0.09               |
| C₄       | 1.95             | 0.1                |
| C₆       | 2.04             | 0.1                |
| C₈       | 2.02             | 0.1                |
| C₁₀      | 1.16             | 0.06               |
| C₉       | 1.4              | 0.07               |
| C₇       | 1                | 0.05               |

Table 5. The collective DHHL evaluation matrix $H$. 

| Suppliers | C₁ | C₂ | C₃ | C₄ | C₅ | C₆ | C₇ | C₈ | C₉ | C₁₀ |
|-----------|----|----|----|----|----|----|----|----|----|-----|
| A₁        | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> | [5.0<0.10,0.20> |
| A₂        | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> | [8.1<0.12,0.20> |
| A₃        | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> | [8.0<0.12,0.20> |
| A₄        | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> | [5.1<0.12,0.20> |
| A₅        | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> | [9.0<0.12,0.20> |
**Step 2.5.** Using Equation (19) and let \( t = 1000 \), the final preference vector of five sustainable suppliers is obtained as: \( P = (1490, -910, -460, 1770, -1880) \). As a result, the five sustainable suppliers are ranked as: \( A_4 \succ A_1 \succ A_3 \succ A_2 \succ A_5 \).

**Stage 3.** Allocate order sizes to the qualified sustainable suppliers.

**Steps 3.1–3.2.** Based on the ranking of sustainable suppliers, the suppliers \( A_4 \) and \( A_1 \) are selected to participate in the following order allocation process. The supplier data used in the MOLP model are given in Table 6. The product demand, maximum defective rate, and maximum delay rate are given as: \( D = 12500, Q = 3.0\% \), \( L = 2.8\% \), respectively. In order to maintain a friendly relationship with the suppliers, it is assumed that the two suppliers can obtain an order quantity of at least 10\% of the total demand.

**Table 6. Supplier quantitative data.**

| Suppliers | Raw Material Data |
|-----------|-------------------|
|           | \( r \) | \( P_{ir} \) | \( L_{ij} \) | \( C_{ij} \) | \( Q_{ij}(\%) \) |
| \( A_1 \) | \( 0–5000 \) | 28.5 | 2.2 | 8500 | 2.3 |
|           | \( \geq 5000 \) | 26.5 |           |         |       |
| \( A_4 \) | \( 0–6500 \) | 28 | 3 | 10,000 | 1.8 |
|           | \( \geq 6500 \) | 26 |           |         |       |

**Step 3.3.** According to decision makers’ opinions, the relative importance of the four objective functions are given as: \( \omega_1 = 0.3, \omega_2 = 0.2, \omega_3 = 0.2 \) and \( \omega_4 = 0.3 \). By solving the following single objective programming model, the order allocation results of the two selected sustainable suppliers are presented in Table 7.

\[
\begin{align*}
\min z &= 0.00340X_{111} + 0.00320X_{112} + 0.00328X_{141} + 0.00328X_{142} \\
&+ 2.3X_{111} + 2.3X_{112} + 1.8X_{141} + 1.8X_{142} \leq 37500 \\
&+ 2.2X_{111} + 2.2X_{112} + 3.0X_{141} + 3.0X_{142} \leq 35000 \\
&+ 1250 \leq X_{111} + X_{112} \leq 8500 \\
\text{s.t.} &+ 1250 \leq X_{141} + X_{142} \leq 10000 \\
&0 \leq X_{111} < 5000 \\
&5000 \leq X_{112} < 8500 \\
&0 \leq X_{141} < 6500 \\
&6500 \leq X_{142} < 10000 \\
\end{align*}
\]

**Table 7. Order allocation result.**

| Suppliers | Order Sizes |
|-----------|-------------|
| \( A_1 \) | \( X_{111} = 0; X_{112} = 5000 \) |
| \( A_4 \) | \( X_{141} = 0; X_{142} = 7500 \) |

| Objective function result |
|---------------------------|
| \( Z_1 \) | 327,500 |
| \( Z_2 \) | 250 |
| \( Z_3 \) | 335 |
| \( Z_4 \) | 20,725,000 |

As shown in Table 7, the order quantity assigned to \( A_1 \) is 5000 units with a unit price of 26.5. At the same time, \( A_4 \) received the order of 7500 units at a unit price of 26. For the first objective function, the minimum purchase cost is 327,500.
5.2. Comparison and Discussion

In this section, to further illustrate the usefulness and advantages of the proposed SSS&OA model, a comparison analysis with the hesitant fuzzy DFT [31], the intuitionistic fuzzy VIKOR [48] and the fuzzy GRA [49], is performed based on the above case study. Through the four methods, the ranking results of the five sustainable suppliers are obtained as presented in Figure 2.

As visualized in Figure 2, the ranking orders of the sustainable suppliers obtained by the developed model and the intuitionistic fuzzy VIKOR are consistent. The last sustainable supplier determined by the four methods is exactly the same (i.e., A5). Moreover, the orders for three of the five sustainable suppliers by the hesitant fuzzy DFT (i.e., A2, A3, and A5) and the fuzzy GRA (i.e., A1, A4, and A5) are consistent with those obtained by the developed model. Therefore, the effectiveness of the proposed SSS&OA approach is validated.

In addition, we can see that there are still some differences between the ranking by the proposed model and those by the hesitant fuzzy DFT and the fuzzy GRA methods. For example, according to the hesitant fuzzy DFT method, A1 has a higher priority in comparison with A4, and is the best option for the considered sustainable supplier selection problem. However, A4 is assumed to be the best choice, which is more important than A1 according to our proposed model. For the two sustainable suppliers, giving a higher priority to A4 is also verified by the other two methods. Similarly, the result of the fuzzy GRA method suggests that A4 has a higher priority compared with A3. But, A3 is better than A2 as indicated by our proposed model, the hesitant fuzzy DFT and the intuitionistic fuzzy VIKOR methods. Actually, A4 is the best sustainable supplier since it is given high evaluation values on C3, C4, C6, and C8 while A1 obtains low evaluation on these criteria. A3 is better than A2 because it is evaluated with higher values than A2 on important criteria (e.g., C1, C6 and C8).

Based on the above analyses, it can be concluded that a more reasonable and credible ranking result of sustainable suppliers can be obtained by employed the proposed SSS&OA framework. Compared with the listed methods, the advantages of our developed model are summarized as follows:

1. By applying the DHHLTSs, the hesitant evaluation information from each decision maker can be expressed more accurately and comprehensively. Thus, the proposed model can reduce information distortion and improve the accuracy of evaluation in the sustainable supplier selection process.

2. Using the DFT, the decision behaviors of decision makers can be depicted preferably. Further, the preference values of the proposed model are obtained with a dynamic process, which overcomes the disadvantages of the previous methods that just rely on the information processing at a certain time.

3. After determining the ranking of sustainable suppliers, the order sizes for the selected suppliers can be determined according to their preference values based on the constructed MOLP model considering quantity discount.
6. Conclusions

In this study, we develop a hybrid SSS&OA model for selecting qualified sustainable suppliers and allocating reasonable order quantities under uncertain information environment. In the model, the DHHTLTSs were utilized to express the complex evaluation information from decision makers. A new weighting method was used to calculate the optimal weight for each selection criterion. An extended DFT method was proposed to rank the candidate sustainable suppliers. Then, a MOLP model with quantity discount was constructed to allocate suitable order quantities for the selected sustainable suppliers. Finally, using a case study from the electronic industry, the validity of the developed SSS&OA model has been demonstrated. The results show that the developed model can get a more reasonable ranking result of sustainable suppliers, and allocate the orders of the qualified sustainable suppliers more reasonably.

Despite its advantages, the proposed model has some limitations that need to be addressed in future researches. First, the evaluation values of alternative suppliers on different criteria are all represented via linguistic expressions in this paper. When dealing with practical problems, however, the sustainable supplier evaluation information may be heterogeneous because of different characteristic of selection criteria. Thus, future research can focus on how to deal with heterogeneous evaluation information in the process of sustainable supplier assessment. Second, although the model is designed to consider multiple decision makers, only five experts are involved in the case study. In the future, a large group of decision makers from different backgrounds is suggested to be involved to improve the reliability of sustainable supplier selection. In addition, we can incorporate inventory control issues into the MOLP model to handle more complex order allocation problems in future research.

Author Contributions: The individual contribution and responsibilities of the authors were as follows: S.-Y.Y. and L.-J.Z. together designed research; X.-G.X. and H.-C.L. provided extensive advices throughout the study regarding to abstract, introduction, research design, research methodology, findings and revise the manuscript. The discussion was a team task. All authors have read and approved the final manuscript.

Funding: This work was partially supported by the National Natural Science Foundation of China (No. 71701153), the Shanghai Soft Science Key Research Program (No. 19692108000), and the 2019 Yangtze River Delta High-Quality Integration Major Issues Research Project.

Acknowledgments: The authors are very grateful to the editor and reviewers for their insightful and constructive comments and suggestions, which are very helpful in improving the quality of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Stević, Ž.; Pamučar, D.; Puška, A.; Chatterjee, P. Sustainable supplier selection in healthcare industries using a new MCDM method: Measurement of alternatives and ranking according to COmpromise solution (MARCOS). Comput. Ind. Eng. 2020, 140, 106231. [CrossRef]
2. Liu, H.C.; Quan, M.Y.; Li, Z.; Wang, Z.L. A new integrated MCDM model for sustainable supplier selection under interval-valued intuitionistic uncertain linguistic environment. Inf. Sci. 2019, 486, 254–270. [CrossRef]
3. Meksavang, P.; Shi, H.; Lin, S.M.; Liu, H.C. An extended picture fuzzy VIKOR approach for sustainable supplier management and its application in the beef industry. Symmetry 2019, 11, 468. [CrossRef]
4. Quan, M.; Wang, Z.; Liu, H.; Shi, H. A hybrid MCDM approach for large group green supplier selection with uncertain linguistic information. IEEE Access 2018, 6, 50372–50383. [CrossRef]
5. Lo, H.W.; Liou, J.J.H.; Wang, H.S.; Tsai, Y.S. An integrated model for solving problems in green supplier selection and order allocation. J. Clean. Prod. 2018, 190, 339–352. [CrossRef]
6. Liu, Y.; Jin, L.; Zhu, F. A multi-criteria group decision making model for green supplier selection under the ordered weighted hesitant fuzzy environment. Symmetry 2019, 11, 17. [CrossRef]
7. Wang, J.; Gao, H.; Wei, G.; Wei, Y. Methods for multiple-attribute group decision making with q-rung interval-valued orthopair fuzzy information and their applications to the selection of green suppliers. Symmetry 2019, 11, 56. [CrossRef]
8. Shi, H.; Quan, M.Y.; Liu, H.C.; Duan, C.Y. A novel integrated approach for green supplier selection with interval-valued intuitionistic uncertain linguistic information: A case study in the agri-food industry. *Sustainability* 2018, 10, 733. [CrossRef]

9. Wang, K.Q.; Liu, H.C.; Liu, L.; Huang, J. Green supplier evaluation and selection using cloud model theory and the QUALIFLEX method. *Sustainability* 2017, 9, 688. [CrossRef]

10. Alegoz, M.; Yapicioglu, H. Supplier selection and order allocation decisions under quantity discount and fast service options. *Sustain. Prod. Consum.* 2019, 18, 179–189. [CrossRef]

11. Duan, C.Y.; Liu, H.C.; Zhang, L.J.; Shi, H. An extended alternative queuing method with linguistic Z-numbers and its application for green supplier selection and order allocation. *Int. J. Fuzzy Syst.* 2019, 21, 2510–2523. [CrossRef]

12. Esmaeili-Najafabadi, E.; Fallah Nezhad, M.S.; Pourmohammadi, H.; Honarvar, M.; Vahdatzad, M.A. A joint supplier selection and order allocation model with disruption risks in centralized supply chain. *Comput. Ind. Eng.* 2019, 127, 734–748. [CrossRef]

13. Govindan, K.; Sivakumar, R. Green supplier selection and order allocation in a low-carbon paper industry: Integrated multi-criteria heterogeneous decision-making and multi-objective linear programming approaches. *Ann. Oper. Res.* 2016, 238, 243–276. [CrossRef]

14. dos Santos, B.M.; Godoy, L.P.; Campos, L.M.S. Performance evaluation of green suppliers using entropy-TOPSIS-F. *J. Clean. Prod.* 2019, 207, 498–509. [CrossRef]

15. Memari, A.; Dargi, A.; Akbari Jokar, M.R.; Ahmad, R.; Abdul Rahim, A.R. Sustainable supplier selection: A multi-criteria intuitionistic fuzzy TOPSIS method. *J. Manuf. Syst.* 2019, 50, 9–24. [CrossRef]

16. Li, J.; Fang, H.; Song, W. Sustainable supplier selection based on SSCM practices: A rough cloud TOPSIS approach. *J. Clean. Prod.* 2019, 222, 606–621. [CrossRef]

17. Liu, P.; Gao, H.; Ma, J. Novel green supplier selection method by combining quality function deployment with partitioned Bonferroni mean operator in interval type-2 fuzzy environment. *Inf. Sci.* 2019, 490, 292–316. [CrossRef]

18. Gou, X.; Liao, H.; Xu, Z.; Herrera, F. Double hierarchy hesitant fuzzy linguistic term set and MULTIMOORA method: A case of study to evaluate the implementation status of haze controlling measures. *Inf. Fusion* 2017, 38, 22–34. [CrossRef]

19. Wang, X.; Gou, X.; Xu, Z. Assessment of traffic congestion with ORESTE method under double hierarchy hesitant fuzzy linguistic environment. *Appl. Soft Comput.* 2020, 86, 105864. [CrossRef]

20. Duan, C.Y.; Chen, X.Q.; Shi, H.; Liu, H.C. A new model for failure mode and effects analysis based on k-means clustering within hesitant linguistic environment. *IEEE Trans. Eng. Manag.* 2019. [CrossRef]

21. Krishankumar, R.; Subraja, L.S.; Ravichandran, K.S.; Kar, S.; Saeid, A.B. A framework for multi-attribute group decision-making using double hierarchy hesitant fuzzy linguistic term set. *Int. J. Fuzzy Syst.* 2019, 21, 1130–1143. [CrossRef]

22. Liu, N.; He, Y.; Xu, Z. Evaluate public-private-partners’ advancement using double hierarchy hesitant fuzzy linguistic PROMETHEE with subjective and objective information from stakeholder perspective. *Technol. Econ. Dev. Econ.* 2019, 25, 386–420. [CrossRef]

23. Montserrat-Adell, J.; Xu, Z.; Gou, X.; Agell, N. Free double hierarchy hesitant fuzzy linguistic term sets: An application on ranking alternatives in GDM. *Inf. Fusion* 2019, 47, 45–59. [CrossRef]

24. Bai, C.; Kusi-Sarpong, S.; Badri Ahmadi, H.; Sarkis, J. Social sustainable supplier evaluation and selection: A group decision-support approach. *Int. J. Prod. Res.* 2019, 57, 7046–7067. [CrossRef]

25. Liang, Y.; Liu, J.; Qin, J.; Tu, Y. An improved multi-granularity interval 2-tuple TODIM approach and its application to green supplier selection. *Int. J. Fuzzy Syst.* 2019, 21, 129–144. [CrossRef]

26. Phochanikorn, P.; Tan, C. An integrated multi-criteria decision-making model based on prospect theory for green supplier selection under uncertain environment: A case study of the Thailand palm oil products industry. *Sustainability* 2019, 11, 1872. [CrossRef]

27. Wu, Q.; Zhou, L.; Chen, Y.; Chen, H. An integrated approach to green supplier selection based on the interval type-2 fuzzy best-worst and extended VIKOR methods. *Inf. Sci.* 2019, 502, 394–417. [CrossRef]

28. Busemeyer, J.R.; Townsend, J.T. Decision field theory: A dynamic-cognitive approach to decision making in an uncertain environment. *Psychol. Rev.* 1993, 100, 432–459. [CrossRef]

29. Lee, S.; Son, Y.J.; Jin, J. Decision field theory extensions for behavior modeling in dynamic environment using Bayesian belief network. *Inf. Sci.* 2008, 178, 2297–2314. [CrossRef]
30. Lee, S.; Son, Y.J. Extended decision field theory with social-learning for long-term decision-making processes in social networks. *Inf. Sci.* 2020, 512, 1293–1307. [CrossRef]
31. Song, C.; Zhang, Y.; Xu, Z.; Hao, Z.; Wang, X. Route selection of the Arctic northwest passage based on hesitant fuzzy decision field theory. *IEEE Access* 2019, 7, 19979–19989. [CrossRef]
32. Hao, Z.; Xu, Z.; Zhao, H.; Zhang, R. Novel intuitionistic fuzzy decision making models in the framework of decision field theory. *Inf. Fusion* 2017, 33, 57–70. [CrossRef]
33. Abad, A.G.; Jin, J.; Son, Y.J. Estimation of expected human attention weights based on a decision field theory model. *Inf. Sci.* 2014, 278, 520–534. [CrossRef]
34. Qin, H.; Guan, H.; Wu, Y.J. Analysis of park-and-ride decision behavior based on decision field theory. *Transp. Res. Part F Traffic Psychol. Behav.* 2013, 18, 199–212. [CrossRef]
35. Keshavarz Ghorabaee, M.; Amiri, M.; Salehi Sadaghiani, J.; Hassani Goodarzi, G. Multiple criteria group decision-making for supplier selection based on COPRAS method with interval type-2 fuzzy sets. *Int. J. Adv. Manuf. Technol.* 2014, 75, 1115–1130. [CrossRef]
36. You, X.Y.; You, J.X.; Liu, H.C.; Zhen, L. Group multi-criteria supplier selection using an extended VIKOR method with interval 2-tuple linguistic information. *Expert Syst. Appl.* 2015, 42, 1906–1916. [CrossRef]
37. Kannan, D.; Jabbour, A.B.L.d.S.; Jabbour, C.J.C. Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. *Eur. J. Oper. Res.* 2014, 233, 432–447. [CrossRef]
38. Xu, X.G.; Shi, H.; Zhang, L.J.; Liu, H.C. Green supplier evaluation and selection with an extended MABAC method under the heterogeneous information environment. *Sustainability* 2019, 11, 6616. [CrossRef]
39. Lu, Z.; Sun, X.; Wang, Y.; Xu, C. Green supplier selection in straw biomass industry based on cloud model and possibility degree. *J. Clean. Prod.* 2019, 209, 995–1005. [CrossRef]
40. Mohammed, A.; Setchi, R.; Filip, M.; Harris, I.; Li, X. An integrated methodology for a sustainable two-stage supplier selection and order allocation problem. *J. Clean. Prod.* 2018, 192, 99–114. [CrossRef]
41. Goren, H.G. A decision framework for sustainable supplier selection and order allocation with lost sales. *J. Clean. Prod.* 2018, 183, 1156–1169. [CrossRef]
42. Cheraghalipour, A.; Farsad, S. A bi-objective sustainable supplier selection and order allocation considering quantity discounts under disruption risks: A case study in plastic industry. *Comput. Ind. Eng.* 2018, 118, 237–250. [CrossRef]
43. Moheb-Alizadeh, H.; Handfield, R. Sustainable supplier selection and order allocation: A novel multi-objective programming model with a hybrid solution approach. *Comput. Ind. Eng.* 2019, 129, 192–209. [CrossRef]
44. Gou, X.; Xu, Z.; Liao, H.; Herrera, F. Multiple criteria decision making based on distance and similarity measures under double hierarchy hesitant fuzzy linguistic environment. *Comput. Ind. Eng.* 2018, 126, 516–530. [CrossRef]
45. Stanujkic, D.; Zavadska, E.K.; Karabasevic, D.; Smarandache, F.; Turskis, Z. The use of the pivot pairwise relative criteria importance assessment method for determining the weights of criteria. *Rom. J. Econ. Forecast.* 2017, 20, 116–133.
46. Stević, Ž.; Stepanović, Ž.; Božičković, Z.; Das, D.K.; Stanujić, D. Assessment of conditions for implementing information technology in a warehouse system: A novel fuzzy PIPRECIA method. *Symmetry* 2018, 10, 586. [CrossRef]
47. Berkowitsch, N.A.J.; Scheibeheenne, B.; Rieskamp, J. Rigorously testing multialternative decision field theory against random utility models. *J. Exp. Psychol. Gen.* 2014, 143, 1331–1348. [CrossRef]
48. Zhao, J.; You, X.Y.; Liu, H.C.; Wu, S.M. An extended VIKOR method using intuitionistic fuzzy sets and combination weights for supplier selection. *Symmetry* 2017, 9, 169. [CrossRef]
49. Banaeian, N.; Mobli, H.; Rahimnia, B.; Nielsen, I.E.; Omid, M. Green supplier selection using fuzzy group decision making methods: A case study from the agri-food industry. *Comput. Oper. Res.* 2018, 89, 337–347. [CrossRef]