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*Article*

# Consistent and Sustainable Supplier Evaluation and Order Allocation: Evaluation Score based Model and Multiple Objective Linear Programming Model

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**Abstract.** This paper is to develop an integrated approach of supplier evaluation and order allocation to suppliers that suggests the buyer to place more orders to the supplier that has higher evaluation score (consistent order allocation) considering sustainability issues including economic, social, environmental, and disruption of supply chain issues. The proposed approach is handled by an Evaluation Score based Linear Programming (ESLP) Model. Performances of ESLP model is compared with those of Multiple Objective Linear Programming (MOLP) model that does not explicitly consider the evaluation scores of suppliers for order allocation. Experimental results show that ESLP model offers consistent order allocation while MOLP model offers inconsistent order allocation. Moreover, MOLP model has different priorities of suppliers for order allocation when the customer demands are changed. Inconsistent order allocation makes the purchasing process nontransparent, unexplainable, and susceptible for biased decisions. ESLP and MOLP models generate compromised solutions that are nondominated. They are better and worse for some performances. This paper emphasizes a need of further research that develops consistent order allocation methods.

**Keywords:** Order allocation, supplier evaluation, supplier selection, multiple objectives, sustainability, TOPSIS, linear programming, consistent order allocation to evaluation scores.

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## 1. Introduction

Supplier evaluation and selection, and optimal order allocation to suppliers are two problems that are closely related in practice. How are they related? The buyer evaluates suppliers and inform evaluation scores to suppliers. The suppliers with higher score will get more purchase orders. This makes the purchasing process transparent. The suppliers will use this information to improve themselves to get more purchase orders in the future.

However, these two problems are rather separated in research. There are two streams of research. First, supplier evaluation models are proposed and analyzed by various research works [1-3]. They proposed models to calculate weighted scores based on various criteria, e.g., cost, quality, delivery, social, and environmental issues. Then, the suppliers are ranked based on the weighted scores. Second, optimal order allocation models are proposed by various research works [4-6]. Recently multiple objective models have received more interest [7-9]. The objectives that are popular include cost, quality, and delivery performances. Many researches apply Multiple Objective Linear Programming (MOLP) models for optimal order allocation to suppliers [4, 8, 9].

There are limited research works that use the weighted scores obtained from supplier evaluation models to optimally allocate purchase orders to suppliers. There is a strong need for the research to integrate the supplier evaluation and optimal order allocation problems.

There are two motivations for this research. First, it tries to integrate the supplier evaluation and optimal allocation of purchase orders to suppliers. This means that the supplier who get higher evaluation score should get more orders. Second, the proposed model should consider sustainability issues. The concept of sustainability is composed of four issues: economy, environment, society, and disruption. The order allocation to suppliers should be economical, social and environmental conscious, and avoid disruption of the supply chain.

Specific objectives of this paper are as follows:

1. To develop a Multiple Objective Linear Programming (MOLP) model to optimally allocate purchase orders to suppliers considering sustainability issues.
2. To develop an Evaluation Score based Linear Programming (ESLP) model to optimally allocate purchase orders to suppliers based on the evaluation scores considering sustainability issues. This is an integration of supplier evaluation and order allocation to suppliers.
3. To compare results from MOLP and ESLP models and analyze strengths and weaknesses of both models.

This paper has limited scopes as follows:

1. Linear programming approach is used since it is simple to be applied and it requires short computational time.
2. All parameters are constant. However, the model can be easily extended to fuzzy model.
3. The method to determine supplier evaluation scores can be any method. However, this paper selects TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method which is well-known by researchers and industrial practitioners. For problems with fuzzy parameters, fuzzy TOPSIS [10] can be applied.
4. Sustainability issues under consideration include economy, environment, society, and disruption of supply chain [11, 12].

This paper has significant contributions. First, it proposes ESLP model, which optimally allocate purchase orders based on supplier evaluation scores obtained from well-known method, e.g., TOPSIS or AHP (Analytic Hierarchy Process). Second, it is an original paper that compares performances of MOLP and ESLP models and discusses strengths and weaknesses of both models.

The next section highlights differences between this paper and previous research. Methodology, mathematical models, and data of the case study are explained in Section 3. Results are presented and discussed in Section 4 and finally concluded in Section 5.

## 2. Literature Review

This paper is related to supplier evaluation and selection, optimal allocation of purchase orders to suppliers, and sustainability issues. The sustainability includes economic, social, and environment issues. Therefore, previous research works are reviewed based on these issues as shown in Table 1.

Many research works use a variety of methodologies to evaluate suppliers, and calculate weighted score of suppliers, e.g., TOPSIS [7, 13], Hybrid and Zimmerman approach [4], Greyscale and rough set methodology [14], VIKOR (VlseKriterijumska Optimizacija l Kompromisno Resenje) [15], Systems dynamics Bayesian framework [16], Bayesian theory and Monte Carlo simulation with a Gibbs sampler [17], ANP [18], a revised multi-choice goal programming [19], Fuzzy inference system [20], and AHP [9, 21, 22, 23]. Table 1 summarizes previous researches related to supplier evaluation under sustainability issues so most research works consider economic, social, and environmental factors for supplier evaluation.

Some research works allocate purchase orders to suppliers considering various criteria, for example, purchase costs, quality levels, defective rates, on-time delivery, social related scores, and environmental related scores. This group of researches do not formally evaluate suppliers and do not calculate weighted scores of the suppliers [4, 9, 24, 25].

There are very limited research works that formally evaluate suppliers, report the weighted scores of suppliers, and use these scores as a basis to allocate purchase orders to suppliers [7, 19, 21, 22, 26, 27]. Their models apply the weighted scores of suppliers to create the objective function called the total value of purchase. They also consider other objectives and determine compromised solution among objectives. Thus, the compromised solution may suggest to purchase more from the suppliers with lower evaluation scores, which is inconsistent order allocation.

A main purpose of this paper is to analyze advantages and disadvantages of two approaches, namely, order allocation to suppliers without formal supplier evaluation, and integrated supplier evaluation and order allocation to suppliers. Both approaches consider sustainability issues including economic, social, environmental, and non-disruption issues. Therefore, two types of mathematical models are developed. Their results will be compared to highlight the advantages and disadvantages of both approaches. This paper will strengthen literatures of supplier evaluation and order allocation.

## 3. Methodology

This section proposes concepts of mathematical models to optimally allocate purchase orders among suppliers considering the sustainability issues, mathematical models, and data of case study.

### 3.1. Concepts of Mathematical Models

There are two proposed mathematical models

1. Multiple Objective Linear Programming (MOLP) model
2. Evaluation Score based Linear Programming (ESLP) model

Concept of MOLP model

Table 2 shows relationship between objectives and constraints of the proposed MOLP model versus the sustainability issues. It is clear that objectives 1, 2, and 3 are related to economy issues. Note that objective 2: minimize total defective units also contributes to environment since defective units increase waste and utilize more materials and energy. For objective 4, the environmental scores will be given to the suppliers based on the environmental characteristics of the supplied product as well as the goodness of environmental management of the supplier. Higher environmental score reflects an ability of the supplier and supplied product to save the environment and nature. Constraint 1: maintain at least two suppliers for each product is to reduce a chance of supply chain disruption due to disasters, e.g., flooding and short of supply. Constraint 2: each supplier that is selected should get not too low purchase quantity to ensure the sustainability (survival) of all selected suppliers.

Concept of ESLP model

The ESLP model is simpler than the MOLP model since the 4 objectives are handled by the supplier scores calculated by the supplier evaluation method that is applied. Suppose the supplier evaluation method is TOPSIS, the TOPSIS scores will be calculated based on the unit cost, defective rates, on-time performance, and environmental scores of the suppliers that can supply each product. The optimal allocation of purchase orders to the suppliers will be performed based on the TOPSIS scores. Note that the constraints of the MOLP and ESLP models are the same.

### 3.2. Mathematical Models

This section defines indexes, parameters, and decision variables, and proposes the mathematical models.

#### 3.2.1. Indexes

| | |
|---|---|
| *i* | Index of suppliers {1, 2, …, *I*} |
| *j* | Index of products {1, 2, …, *J*} |
| *k* | Index of performances {*c*:cost, *q*:quality, *d*:on-time delivery, *e*:environent} |

#### 3.2.2. Parameters

| | |
|---|---|
| *Cij* | Unit cost of product *j* from supplier *i* (Baht) |
| *Dij* | Defective fraction of product *j* from supplier *i* (unitless) |
| *Qij* | On-time delivery fraction of product *j* from supplier *i* (unitless) |
| *Eij* | Environmental score of product *j* from supplier *i* (unitless) |
| *TSij* | TOPSIS score of product *j* from supplier *i* (unitless) |
| *Dmj* | Demand of product *j* (unit) |
| *Fij* | 1 if supplier *i* supply product *j*, 0 otherwise (unitless) |
| *Aj* | Minimum order fraction of product *j* (unitless) |
| *M* | Big positive number (unitless) |
| *TCmax* | Maximum total cost (Baht) |
| *TCmin* | Minimum total cost (Baht) |
| *TQmax* | Maximum total defective units (unit) |
| *TQmin* | Minimum total defective units (unit) |
| *TDmax* | Maximum total units delivered on-time (unit) |
| *TDmin* | Minimum total units delivered on-time (unit) |
| *TEmax* | Maximum total environment score (unitless) |
| *TEmin* | Minimum total environment score (unitless) |
| $w_k$ | Weight of satisfaction of performance *k* (unitless) |

#### 3.2.3. Decision variables

| | |
|---|---|
| *Xij* | Purchased quantity of product *j* from supplier *i* (unit) |
| *Yij* | 1 if product *j* is purchased from supplier *i*, 0 otherwise (unitless) |
| *TC* | Total cost (Baht) |
| *TQ* | Total defective units (unit) |
| *TD* | Total units delivered on-time (unit) |
| *TE* | Total Environment score (unitless) |
| $S_k$ | Satisfaction of performance *k* (unitless) |

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Table 1. Differences between this paper and previous works.

| Researches | Envi. | Soc. | Eco. | Supplier evaluation | Order alloc. | Multi period | Multi product | Methodology/Solution technique |
|---|---|---|---|---|---|---|---|---|
| Kannan et al. (2013) [7] | ● | | ● | ● | ● | | | FAHP, fuzzy TOPSIS and FMOLP |
| Shaw et al. (2012) [4] | ● | | ● | | ● | | | FAHP and fuzzy MOMILP |
| Fallahpour et al. (2017) [13] | ● | ● | ● | ● | | | | FAHP |
| Bai and Sarkis (2010) [14] | ● | ● | ● | ● | | | | Rough set theory and Grey system |
| Amindoust et al. (2012) [20] | ● | ● | ● | | | | | Fuzzy inference |
| Luthra et al. (2017) [15] | ● | ● | ● | ● | | | | AHP, VIKOR, multi-criteria optimization, compromise solution |
| Orji and Wei (2015) [16] | ● | ● | ● | ● | | | | Fuzzy logic, Systems dynamics Bayesian framework |
| Sarkis and Dhavale (2015) [17] | ● | ● | ● | ● | | | | Monte Carlo Markov Chain |
| Buyukozkan and Cifci (2011) [18] | ● | ● | ● | ● | | | | Fuzzy ANP, Incomplete preference relations |
| Kumar et al. (2017) [9] | ● | ● | ● | ● | ● | | | Fuzzy AHP and fuzzy multi-objective linear programming |
| Hamdan and Cheaitou (2017) [22] | ● | ● | ● | ● | ● | ● | | FAHP, fuzzy multi-objective integer linear programming |
| Aktin and Gergin (2016) [25] | ● | ● | ● | | ● | | ● | MILP, 3BL questionnaire,AHP |
| Azadnia et al. (2015) [21] | ● | ● | ● | ● | ● | ● | ● | Rule-based weighted fuzzy method, fuzzy AHP, MOPP |
| Cheraghalipour and Farsad (2018) [26] | ● | ● | ● | ● | ● | ● | ● | MILP, MCDM, Best word method |
| Shalke et al. (2017) [19] | ● | ● | ● | ● | ● | ● | ● | MODM |
| This paper | ● | ● | ● | ● | ● | | ● | TOPSIS, MOLP, ESLP |

Table 2. Relationships between objectives and constraints vs. sustainability issues.

| Sustainability issues | Economy | Society (suppliers) | Environment | Disruption of SC |
|---|---|---|---|---|
| Objectives: | | | | |
| 1. Minimize total purchase cost | Yes | | | |
| 2. Minimize total defective units | Yes | | Yes | |
| 3. Maximize total units delivered on-time | Yes | | | |
| 4. Maximize total environmental scores | | | Yes | |
| Constraints: | | | | |
| 1. Maintain at least 2 suppliers for each product | | | | Yes |
| 2. Each supplier gets not too low purchase quantity | | Yes | | |

#### 3.2.4. MOLP model

The MOLP model has four conflicting objectives, namely, to minimize total purchase cost (*TC*), minimize total defective units (*TQ*), maximize total units delivered on-time (*TD*), and maximize total environmental score (*TE*). *TC*, *TQ*, *TD* and *TE* are calculated by constraints (7) to (10), respectively. Note that the total environmental score (*TE*) is a sum of the product between the environmental score and purchase quantity. Since *TC*, *TQ*, *TD* and *TE* have different magnitude, the variable with relatively high magnitude will dominate other variables with lower magnitude. Therefore, *TC*, *TQ*, *TD* and *TE* are normalized to a common scale between 0.0 to 1.0 called a satisfaction level. Constraints (11-14) convert *TC*, *TQ*, *TD* and *TE* to the satisfaction level. Note that low values of *TC* and *TQ* result in higher satisfaction while high values of *TD* and *TE* result in higher satisfaction. Four objectives of the MOLP model are transformed into single objective by maximizing the weighted average of satisfactions of *TC*, *TQ*, *TD* and *TE* as shown by objective function (1). The weighted average method is applied by some previous works [27].

Demand constraint is presented by constraint (2). Constraint (3) states that at least two suppliers must be maintained for each product to avoid the disruption of the supply chain. Constraint (4) is a supply constraint to ensure that the purchase orders are placed to suppliers who can supply the products. Constraint (5) specifies that the suppliers that are selected will not get too low purchase quantity for sustainability and survival of the selected suppliers. Constraint (6) ensures that when the supplier is not selected, the purchase quantity must be zero. Binary and non-negativity conditions are specified by constraints (15) and (16).

Objective function

$$\text{Maximize } \sum_k w_k S_k \quad (1)$$

Constraints

$$\sum_i X_{ij} = Dm_j, \forall j \quad (2)$$
$$\sum_i Y_{ij} \geq 2, \forall j \quad (3)$$
$$Y_{ij} \leq F_{ij}, \forall i, j \quad (4)$$
$$X_{ij} \geq A_j Dm_j Y_{ij}, \forall i, j \quad (5)$$
$$X_{ij} \leq M\, Y_{ij}, \forall i, j \quad (6)$$
$$TC = \sum_i \sum_j C_{ij} X_{ij} \quad (7)$$
$$TQ = \sum_i \sum_j Q_{ij} X_{ij} \quad (8)$$
$$TD = \sum_i \sum_j D_{ij} X_{ij} \quad (9)$$
$$TE = \sum_i \sum_j E_{ij} X_{ij} \quad (10)$$
$$S_c = (TCmax - TC)/(TCmax - TCmin) \quad (11)$$
$$S_q = (TQmax - TQ)/(TQmax - TQmin) \quad (12)$$
$$S_d = (TDmax - TD)/(TDmax - TDmin) \quad (13)$$
$$S_e = (TEmax - TE)/(TEmax - TEmin) \quad (14)$$
$$Y_{ij} \text{ is binary} \quad (15)$$
$$X_{ij} \geq 0 \quad (16)$$

#### 3.2.5. ESLP model

The ESLP model has single objective by nature. The objective function (17) is to maximize the sum of the product of supplier scores evaluated using TOPSIS method and the purchase quantity. This objective function tends to allocate more purchase quantity to the supplier with higher evaluation score. Note that if a buyer company currently uses other techniques, e.g., AHP and VIKOR, to evaluate the suppliers, the supplier scores from the techniques can be used to replace the TOPSIS scores. Constraints of ESLP model are the same as those of the MOLP model, except constraints (7-14) that are not required.

Objective function

$$\text{Maximize } \sum_i \sum_j TS_{ij} X_{ij} \quad (17)$$

Subject to

Constraints (2-6, 15, and 16)

#### 3.2.6. Single Objective Linear Programming (SOLP) models

There are four SOLP models with different objective functions. Each SOLP model has only one objective function as shown by objective functions (18-21). They have the same sets of constraints. Four SOLP models are solved separately to yield 4 extreme solutions. For example, the SOLP model that minimize *TC* will yield the solution that has the best *TC* but not the best or the worst for other objectives. The solutions from four SOLP models are not compromised solutions among multiple objectives. They are used to determine, $TCmax, TCmin, TQmax, TQmin, TDmax, TDmin, TEmax,$ and $TEmin$ which are the parameters of the satisfactions of performance *k*, $S_k$, used in MOLP model.

Objective functions

$$\text{Minimize } TC = \sum_i \sum_j C_{ij} X_{ij} \quad (18)$$
$$\text{Minimize } TQ = \sum_i \sum_j Q_{ij} X_{ij} \quad (19)$$
$$\text{Maximize } TD = \sum_i \sum_j D_{ij} X_{ij} \quad (20)$$
$$\text{Maximize } TE = \sum_i \sum_j E_{ij} X_{ij} \quad (21)$$

Subject to

Constraints (2-6, 15, and 16)

### 3.3. Data of Case Study

The case study under consideration is described in this section. There is a buyer company that concerns about the sustainability of the supply chain. The buyer company purchases 10 products (P1 to P10) from 5 suppliers (S1 to S5). The unit costs, defective fractions, on-time delivery fractions, and environmental scores are estimated based on real data of a company and are presented in Tables 3 to 6, respectively. Note that n/a in the tables means that the supplier cannot supply the products. The environmental scores in Table 6 reflect the goodness for environment of the product, process, and activities of the supplier. Some products from some suppliers may contain some ingredients that are not environmentally friendly. Production process of some supplier may not be environmentally friendly. Some suppliers may conduct corporate social responsibility (CSR) activities that are good for environments. These issues are related to the environmental scores in Table 6. The supplier evaluation scores called TOPSIS scores in Table 7 are calculated using TOPSIS method based on unit costs, defective fractions, on-time delivery fractions, and environmental scores presented in Tables 3 to 6. How to calculate the supplier evaluation scores using TOPSIS method are presented by Fallahpour et al. (2017) [13].

Behaviors of MOLP and ESLP models will be analyzed using two data sets of demands, which are presented in Tables 8 and 9. The MOLP model needs parameters of $w_k$, weight of satisfaction of performance k. Management team of the buyer company feels that all performances have nearly equal weights. Thus, $w_k$ are set at 0.25 for all *k*. This set of weights are also used to calculated TOPSIS scores of suppliers.

The buyer company set the minimum order policy that all suppliers that are selected will receive a purchase quantity not less than 30% of the demand of the product that is purchased from that supplier. Therefore, A*j*, minimum order fraction of product *j*, is set at 0.3 for all products.

Table 3. Unit costs.

| **Unit cost (*Cij*)** | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** | **P8** | **P9** | **P10** |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 120 | 50 | 30 | 150 | 180 | n/a | 80 | n/a | 70 | 50 |
| S2 | n/a | 60 | 50 | 200 | 110 | 55 | n/a | 180 | 85 | 30 |
| S3 | n/a | 75 | 40 | 170 | 130 | 65 | 58 | 200 | 75 | 40 |
| S4 | 110 | n/a | 25 | 250 | 150 | 80 | 67 | 190 | 90 | 60 |
| S5 | 90 | n/a | 20 | 190 | n/a | 50 | 73 | 210 | 100 | n/a |

Table 4. Defective fractions.

| **Defective fraction (*Dij*)** | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** | **P8** | **P9** | **P10** |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 0.0122 | 0.0213 | 0.0299 | 0.0156 | 0.0148 | n/a | 0.0289 | n/a | 0.0124 | 0.0300 |
| S2 | n/a | 0.0169 | 0.0147 | 0.0103 | 0.0100 | 0.0158 | n/a | 0.0236 | 0.0158 | 0.0248 |
| S3 | n/a | 0.0245 | 0.0277 | 0.0300 | 0.0148 | 0.0138 | 0.0147 | 0.0101 | 0.0224 | 0.0278 |
| S4 | 0.0131 | n/a | 0.0107 | 0.0164 | 0.0122 | 0.0192 | 0.0184 | 0.0147 | 0.0168 | 0.0101 |
| S5 | 0.0224 | n/a | 0.0235 | 0.0246 | n/a | 0.0300 | 0.0147 | 0.0139 | 0.0265 | n/a |

Table 5. On-time delivery fractions.

| **On-time delivery fraction (*Qij*)** | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** | **P8** | **P9** | **P10** |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 1.000 | 0.901 | 0.988 | 0.916 | 0.904 | n/a | 0.989 | n/a | 0.925 | 0.999 |
| S2 | n/a | 0.945 | 0.989 | 0.993 | 0.916 | 0.935 | n/a | 0.966 | 0.975 | 0.902 |
| S3 | n/a | 0.972 | 0.985 | 0.947 | 0.981 | 0.945 | 0.905 | 0.987 | 0.925 | 0.955 |
| S4 | 0.981 | n/a | 0.976 | 0.983 | 0.985 | 0.943 | 0.975 | 0.935 | 0.988 | 1.000 |
| S5 | 0.929 | n/a | 0.961 | 0.981 | n/a | 0.915 | 0.936 | 0.985 | 1.000 | n/a |

Table 6. Environment scores.

| Env. Score (*Eij*) | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 4 | 0 | 1 | 1 | 4 | n/a | 1 | n/a | 1 | 2 |
| S2 | n/a | 1 | 1 | 4 | 3 | 2 | n/a | 1 | 3 | 1 |
| S3 | n/a | 3 | 1 | 2 | 2 | 3 | 1 | 3 | 2 | 2 |
| S4 | 3 | n/a | 2 | 2 | 4 | 3 | 2 | 1 | 3 | 4 |
| S5 | 2 | n/a | 2 | 4 | n/a | 1 | 1 | 4 | 4 | n/a |

Table 7. TOPSIS scores.

| TOPSIS Score (*TSij*) | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 0.762 | 0.205 | 0.339 | 0.445 | 0.493 | n/a | 0.075 | n/a | 0.428 | 0.276 |
| S2 | n/a | 0.387 | 0.378 | 0.849 | 0.688 | 0.673 | n/a | 0.099 | 0.678 | 0.336 |
| S3 | n/a | 0.754 | 0.208 | 0.312 | 0.332 | 0.832 | 0.505 | 0.740 | 0.365 | 0.352 |
| S4 | 0.636 | n/a | 0.900 | 0.450 | 0.674 | 0.646 | 0.807 | 0.318 | 0.645 | 0.692 |
| S5 | 0.238 | n/a | 0.666 | 0.609 | n/a | 0.292 | 0.476 | 0.823 | 0.572 | n/a |

Table 8. Set 1 of demands.

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Demand ($Dm_j$) | 6000 | 8000 | 10000 | 4000 | 6000 | 9000 | 8000 | 4000 | 8000 | 9000 |

Table 9. Set 2 of demands.

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Demand ($Dm_j$) | 7000 | 9000 | 15000 | 6000 | 8000 | 10000 | 5000 | 6000 | 7000 | 10000 |

## 4. Results and Discussions

This section is divided into 4 parts. First, the results from SOLP models are presented. Then, the solution of MOLP model is discussed. Third, solutions from MOLP and ESLP models are compared. Finally, managerial insights obtained from results are discussed.

### 4.1. Results from SOLP Models

There are 4 SOLP models. When an SOLP model is solved to obtain an optimal solution, four performance measures (*TC*, *TQ*, *TD*, and *TE*) are determined. Table 10 summarizes performance measures of the solutions from 4 SOLP models. It is seen that the model that minimize *TC* results in the best *TC* but the worst *TQ*, *TD*, and *TE*. In general, when a performance measure is optimized, that performance measure will be the best but other performance measures may not be the best. The SOLP models provide extreme solutions that are the best for one or more objectives but not the best or may be the worst for other objectives. There is no solution that is the best for all performance measures because some performance measures are conflicting. Therefore, compromised solutions among multiple objectives should be determined from MOLP or ESLP models.

From Table 10, maximum and minimum values of *TC* ($TCmax$ and $TCmin$) are determined form the entries in *TC* column, which are 6,765,300 and 5,085,100, respectively. Similarly, $TQmax, TQmin, TDmax, TDmin, TEmax,$ and $TEmin$ are 1,419, 984, 70,711, 67,131, 217,000, and 105,800, respectively. These values are input parameters needed by the MOLP model.

### 4.2. Results from MOLP Model

The MOLP model tries to determine a compromised solution by maximizing weighted average satisfactions of four performance measures. Table 11 shows that the weighted average satisfaction is 0.69, which is relatively high. However, the satisfaction of cost is relatively low (0.36) while the satisfactions of quality, delivery, and environmental score are relatively high (0.83, 0.76, and 0.79, respectively). The reason for low satisfaction of cost is that when the cost is the best, the quality, delivery and environmental score are the worst. Thus, to maximize the weighted average when all weights are equal, the satisfactions of quality, delivery, and environmental score have higher priority and the satisfaction of cost is scarified. If a supply chain planner would like to get higher satisfaction of cost, the weight of cost should be increased and other weights are decreased. However, this weight adjustment may result in a reduction of the weighted average satisfactions. Another simple method to increase the satisfaction of cost is to add a constraint to specify a minimum limit of the satisfaction of cost.

## 4.3. Comparison of Results from MOLP and ESLP Models

Table 12 shows purchase quantities of 10 products from 5 suppliers based on MOLP and ESLP models for demand set 1. It can be observed that each product is purchased from 2 suppliers because both models have a constraint that the minimum number of suppliers equals to two to avoid the disruption of supply chain when one of the suppliers cannot deliver due to disaster. The bold entries show different purchase quantities of both models. Four out of ten products (products 2, 3, 8, and 10) have different purchase quantities, for example, MOLP model suggests to purchase more units from supplier 2 than from supplier 3 while ESLP model suggests to purchase more from supplier 3 than from supplier 2. The TOPSIS scores in Table 7 show that supplier 3 has higher evaluation score than supplier 2. Thus, the purchase quantities from ESLP model is consistent to the TOPSIS scores. Table 12 indicates that ESLP model always suggests to purchase more from the supplier that has higher evaluation score while for MOLP model, four out of ten products have inconsistent purchase decisions.

Results in Table 2 also show that two sources of suppliers are maintained for each product, which reduce a chance of disruption when a supplier cannot deliver products to the buyer. Moreover, the minor supplier gets 30% of total demand which is not too low for survival. This is a social issue of the sustainability.

Table 13 presents purchase quantities from MOLP model when the customer demands are changed. It indicates that when demands are changed, three out of ten products (products 2,5, and 7) have different priorities of purchasing. For example, product 2 is purchased more from supplier 2 than from supplier 3 for demand set 1 while it is purchased more from supplier 3 than from supplier 2 for demand set 2. In addition, product 7 is purchased from suppliers 4 and 3 for demand set 1 but purchased from suppliers 4 and 5 for demand set 2. Results in Table 13 clearly show that the priority of purchasing may be changed when the demands are changed. When TOPSIS scores in Table 7 are considered, it is seen that MOLP solutions for both data sets are not consistent to the TOPSIS scores. Note that when demands are changed, the supplier evaluation scores from TOPSIS model are not changed.

Table 10. Results from SOLP models.

| | $TC$ (Baht) | $TQ$ (units) |
|---|---|---|
| Minimize $TC$ | 5,085,100 | 1,419 |
| Minimize $TQ$ | 5,928,000 | 981 |
| Maximize $TD$ | 6,765,300 | 1,295 |
| Maximize $TE$ | 6,607,900 | 1,202 |
| Max. value | 6,765,300 | 1,419 |
| Min. value | 5,085,100 | 981 |
| | **$TD$ (units)** | **$TE$ (unitless)** |
| Minimize $TC$ | 67,131 | 105,800 |
| Minimize $TQ$ | 68,800 | 163,200 |
| Maximize $TD$ | 70,711 | 196,200 |
| Maximize $TE$ | 70,026 | 217,000 |
| Max. value | 70,711 | 217,000 |
| Min. value | 67,131 | 105,800 |

Table 11. Results from MOLP model.

| Items | Values |
|---|---|
| Total cost, $TC$ | 6,152,400 |
| Max total cost, $TCmax$ | 6,765,300 |
| Min total cost, $TCmin$ | 5,085,100 |
| Total defective units, $TQ$ | 1,056 |
| Max total defective units, $TQmax$ | 1,419 |
| Min total defective units, $TQmin$ | 981 |
| Total units delivered on-time, $TD$ | 69,838 |
| Max total units delivered on-time, $TDmax$ | 70,711 |
| Min total units delivered on-time, $TDmin$ | 67,131 |
| Total environment score, $TE$ | 193,500 |
| Max total environment score, $TEmax$ | 217,000 |
| Min total environment score, $TEmin$ | 105,800 |
| Satisfaction of cost, $S_c$ | 0.36 |
| Satisfaction of quality, $S_q$ | 0.83 |
| Satisfaction of delivery, $S_d$ | 0.76 |
| Satisfaction of environment score, $S_e$ | 0.79 |
| Weight of satisfaction of cost, $w_c$ | 0.25 |
| Weight of satisfaction of quality, $w_q$ | 0.25 |
| Weight of satisfaction of delivery, $w_d$ | 0.25 |
| Weight of satisfaction of environment score, $w_e$ | 0.25 |
| Weighted average satisfactions | 0.69 |

Table 14 shows ESLP solutions when demands are changed. When the demands are changed, the purchase quantities are changed but the priority of purchasing is always the same and consistent with the TOPSIS scores.

This means that the supplier with higher TOPSIS score will always get higher purchase quantity.

Tables 15 and 16 present performances of MOLP and ESLP models for data sets 1 and 2, respectively. For both data sets, MOLP is better for total defective units and total units delivered on-time while ESLP is better for total costs and total environmental scores. The percentages of difference for each performance are shown in both tables. It is concluded that solutions from MOLP and ESLP models are comparable based on four performances measures. Both solutions are nondominated solutions.

Table 12. Purchase quantities from MOLP and ESLP models for demand set 1.

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **MOLP solution** | | | | | | | | | | |
| S1 | 4200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **2700** |
| S2 | 0 | **5600** | **3000** | 2800 | 4200 | 2700 | 0 | 0 | 5600 | 0 |
| S3 | 0 | **2400** | 0 | 0 | 0 | 6300 | 2400 | **2800** | 0 | 0 |
| S4 | 1800 | 0 | 7000 | 0 | 1800 | 0 | 5600 | 0 | 2400 | 6300 |
| S5 | 0 | 0 | 0 | 1200 | 0 | 0 | 0 | **1200** | 0 | 0 |
| **ESLP solution** | | | | | | | | | | |
| S1 | 4200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S2 | 0 | **2400** | 0 | 2800 | 4200 | 2700 | 0 | 0 | 5600 | 0 |
| S3 | 0 | **5600** | 0 | 0 | 0 | 6300 | 2400 | **1200** | 0 | **2700** |
| S4 | 1800 | 0 | 7000 | 0 | 1800 | 0 | 5600 | 0 | 2400 | 6300 |
| S5 | 0 | 0 | **3000** | 1200 | 0 | 0 | 0 | **2800** | 0 | 0 |

Table 13. MOLP solutions when demands are changed.

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **MOLP solution for demand set 1** | | | | | | | | | | |
| S1 | 4200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2700 |
| S2 | 0 | **5600** | 3000 | 2800 | **4200** | 2700 | 0 | 0 | 5600 | 0 |
| S3 | 0 | **2400** | 0 | 0 | 0 | 6300 | **2400** | 2800 | 0 | 0 |
| S4 | 1800 | 0 | 7000 | 0 | **1800** | 0 | 5600 | 0 | 2400 | 6300 |
| S5 | 0 | 0 | 0 | 1200 | 0 | 0 | 0 | 1200 | 0 | 0 |
| **MOLP solution for demand set 2** | | | | | | | | | | |
| S1 | 4900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3000 |
| S2 | 0 | **2700** | 4500 | 4200 | **2400** | 3000 | 0 | 0 | 4900 | 0 |
| S3 | 0 | **6300** | 0 | 0 | 0 | 7000 | 0 | 4200 | 0 | 0 |
| S4 | 2100 | 0 | 10500 | 0 | **5600** | 0 | 3500 | 0 | 2100 | 7000 |
| S5 | 0 | 0 | 0 | 1800 | 0 | 0 | **1500** | 1800 | 0 | 0 |

Table 14. ESLP solutions when demands are changed.

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **ESLP solution with demand set 1** | | | | | | | | | | |
| S1 | 4200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S2 | 0 | 2400 | 0 | 2800 | 4200 | 2700 | 0 | 0 | 5600 | 0 |
| S3 | 0 | 5600 | 0 | 0 | 0 | 6300 | 2400 | 1200 | 0 | 2700 |
| S4 | 1800 | 0 | 7000 | 0 | 1800 | 0 | 5600 | 0 | 2400 | 6300 |
| S5 | 0 | 0 | 3000 | 1200 | 0 | 0 | 0 | 2800 | 0 | 0 |
| **ESLP solution with demand set 2** | | | | | | | | | | |
| S1 | 4900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| S2 | 0 | 2700 | 0 | 4200 | 5600 | 3000 | 0 | 0 | 4900 | 0 |
| S3 | 0 | 6300 | 0 | 0 | 0 | 7000 | 1500 | 1800 | 0 | 3000 |
| S4 | 2100 | 0 | 10500 | 0 | 2400 | 0 | 3500 | 0 | 2100 | 7000 |
| S5 | 0 | 0 | 4500 | 1800 | 0 | 0 | 0 | 4200 | 0 | 0 |

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Table 15. Performances of MOLP and ESLP for demand set 1.

| Performances | MOLP | ESLP | % difference |
|---|---|---|---|
| Total costs (Baht) | 6,152,400 | **6,099,400** | MOLP is worse by 0.87 % |
| Total defective units | **1,055** | 1,107 | ESLP is worse by 4.93 % |
| Total units delivered on-time | **69,838** | 69,719 | ESLP is worse by 0.17 % |
| Total environment scores | 193,500 | **204,500** | MOLP is worse by 5.38 % |

Table 16. Performances of MOLP and ESLP for demand set 2.

| Performances | MOLP | ESLP | % difference |
|---|---|---|---|
| Total costs (Baht) | 7,584,500 | **7,293,000** | MOLP is worse by 4.00 % |
| Total defective units | **1,217** | 1,252 | ESLP is worse by 2.88 % |
| Total units delivered on-time | **80,974** | 80,446 | ESLP is worse by 0.65 % |
| Total environment scores | 236,900 | **240,600** | MOLP is worse by 1.54 % |

### 4.4. Managerial Insights Obtained from the Results

The result of SOLP models indicates that a normal practice, which tries to minimize total purchase cost, is not a sustainable solution because when the total purchase cost is minimized, other performance measures, especially environmental performance are not good, or may be worst. Minimizing total purchase cost may result in a high short-term profit but the supply chain may not last until next generations or unsustainable.

Although MOLP models receive high attentions from many researchers and the models have complicated multiple objectives and constraints. Many models do not provide consistent solutions with the supplier evaluation scores. This means that the supplier with higher evaluation score may not get more purchase orders from the buyer. By concept, MOLP models optimize overall performance measures set by the buyers, which is very reasonable for the buyer organization. However, purchasing managers and top management of the buyer organization may not be convinced to believe in the results from complicated mathematical models that cannot be easily explained verbally. As long as the supplier with lower score may get more purchase orders, the purchasing manager may be suspected for corruption or bias. Another weakness of the MOLP models is that the suppliers may lack of motivation to improve performances based on the supplier evaluation scores since higher score may not be directly related to more purchase orders. The suppliers may try to make good personal relationships with the purchasing department instead.

The ESLP model presented in this paper is simpler than the MOLP model since it has only one simple objective. Its solutions can be easily verified. It always generates the consistent solution that suppliers with higher evaluation score will get more purchase orders. Comparison of satisfactions of cost, quality, delivery, and environmental scores of MOLP and ESLP models reveal that they are better and worse for some aspects. One does not outperform another. The ESLP model can handle multiple issues of sustainability using evaluation scores of suppliers and some simple constraints. The ESLP model can be further extended to include more issues related to social, environment, and disruption of the supply chain.

## 5. Conclusions

This paper addresses an important issue that the order allocation to suppliers should be consistent to the supplier evaluation scores. It proposes two models, namely, MOLP and ESLP models. The MOLP model has four objective functions of maximizing total purchase cost, minimizing total defective unit, maximizing total units delivered on-time, and maximizing total environmental scores. The method to compromise among four objectives is maximizing weighted average satisfactions of four objectives. The ESLP model utilizes supplier evaluation scores obtained from TOPSIS method as a basis to allocate the orders to suppliers. It maximizes a sum of product of evaluation scores and purchase quantities. Both models have similar constraints where some of them are used to handle social and disruption issues of the supply chain. Both models are solved by an OpenSolver, which is an add-in software in Microsoft Excel software. This solver and software are readily available in most companies. Experimental results based on a simplified real case reveal that both models offer reasonable solutions. MOLP model results in inconsistent order allocation based on the supplier evaluation scores and priority of orders to suppliers may be changed when the customer demands are changed. ESLP model always results in consistent order allocation although customer demands are changed. Both models offer non-dominated solutions, which means that they are better and worse for some aspects but not all aspects. Performances of both models are comparable. This paper highlights the importance of developing the integrated supplier evaluation and order allocation method that offers consistent order allocation to suppliers based on the supplier evaluation scores.

This paper has significant contributions. First, it is an original study that analyzes and compares performances of MOLP and ESLP models for supplier selection and order allocation to suppliers. It highlights advantages and disadvantages of both models. Second, this paper proposes an important issue, which is very important in practice but may be overlooked by previous research works, that the order allocation to suppliers should be consistent to the supplier evaluation scores. The supplier with higher evaluation score should get more purchase orders from the buyer. Practically, the supplier evaluation scores are publicly announced and all suppliers believe that higher evaluation score will lead to more orders. A recent previous work develops a fuzzy supplier selection and order allocation model that generates a weight-consistent solution [28]. The weight-consistent solution is the solution that has higher satisfaction or achievement level for the objective with higher weight. The weight-consistent solution is different from the solution with consistent order allocation to evaluation score.

There are some limitations of this paper. First, all parameters are constant and uncertainty of data are not considered. In practice estimation of parameters as constants may not be accurate. Second, the disruption of supply chain issue is handled by only a simple constraint that at least two suppliers must be maintained for each product. Additional mechanisms to handle this issue should be developed. Third, this paper handles the social issue considering only the supplier aspect that the minor supplier should get not too low purchase quantity to ensure that all suppliers are survived and the supply chain is sustained. The social issues should be extended to cover all stakeholders of the supply chain.

To overcome the limitations, further studies in this field are recommended. First, some input parameters which are uncertain should be estimated as fuzzy numbers. As a result, some constraints and objective functions may be fuzzy. Suitable methods to defuzzify the constraints, and handle multiple fuzzy objectives must be developed. A research work [29] presents suitable aggregation operators for multiple objectives considering risk preferences of a decision maker. Moreover, two-phase LP based heuristics [30] may be used to solve big problems instead of the OpenSolver proposed in this paper.

Second, additional method to handle the disruption issue may be done by developing an objective function to minimize the total level of risk associated with all selected suppliers. Third, the social score of suppliers should be determined related to major CSR (corporate social responsibility) activities of suppliers. Then, the total social scores may be maximized by the model. Finally, the purchase quantities may be controlled to be consistent with the supplier evaluation scores using a set of constraints similar to those presented by Suprasongsin et al. [28]. This method allows to handle various aspects of sustainability by multiple objective functions.

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