A DEA approach for Supplier Selection with AHP and Risk Consideration

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Abstract— **Supplier Selection is a problem that supply chain managers have been facing for many years. Selecting the appropriate suppliers is no longer as simple as choosing only based on the price they offer. There are many criteria, which can be either quantitative or qualitative, to be considered. There is thus a need for an approach that can handle these criteria. Besides, as supply chains are becoming more complex these days, it is also important to incorporate supply risks in the evaluation of the suppliers. This paper offers an approach that mainly focuses on Data Envelopment Analysis (DEA) to analyze and compare the relative efficiencies of the suppliers. Since DEA can only handle quantitative attributes, Analytic Hierarchy Process (AHP) is being utilized to help to analyze qualitative analysis. Risks are also being considered in the evaluation of the suppliers. The proposed approach seeks to offer a holistic approach to tackle the Supplier Selection problem.**

Keywords- Multi-Criteria Decision Making, AHP, DEA, Risk Consideration, Supplier Selection

I. INTRODUCTION

The supplier selection problem is a common issue that numerous companies have faced for many years [1]. Choosing the right supplier can be a real headache – there are many criteria to consider and assessing them is no easy feat [1]. Supplier selection is no longer as simple as picking the suitable ones based on the prices they offer. Also, the decision maker may not be sure on how to choose the right criteria to assess the suppliers [2]. Furthermore, even if the decision maker does have the right criteria in mind, he or she may not know the right tools to assess these criteria and select the ideal supplier(s) [2].

Supplier selection is a process whereby the companies will have to first identify, then assess, and eventually contract with the suppliers [3]. Such process usually requires massive amount of a firm's financial resources and is thus a critical process [3]. It involves a broad comparison of the different suppliers by using the same set of criteria and measures to evaluate their competencies [4]. Furthermore, in today's highly competitive world it is not possible to produce low cost and high quality goods without the proper selection of suppliers [5]. As such, supplier selection is one of the most important components in supply chain management whereby the short and long term success of the companies will be heavily dependent on the right selection of its suppliers [4]. Thus, supplier selection plays an important role in ensuring the survival of the company [6].

Evaluating the supplier selection problem requires both quantitative and qualitative measures to provide a more holistic assessment of the suppliers [2]. Data Envelopment Analysis (DEA), a commonly used decision analysis method, is capable of measuring the efficiencies of the suppliers [7]. However, one downside of DEA is the requirement of data to be in quantitative form [4]. As such, DEA could not involve qualitative attributes in its analysis.

On the other hand, Analytic Hierarchy Process (AHP) can be used to assign values (which are known as weights) to qualitative attributes [4]. This would turn qualitative attributes into quantifiable measures which can then be used in the DEA model. The integration of AHP and DEA would allow the decision maker to compare efficiency of the suppliers based on both quantitative and qualitative attributes. Thus, this paper proposes the use of an AHP-DEA approach to tackle the supplier selection problem.

Besides focusing on the method to select the most appropriate supplier(s), we will also need to identify suitable attributes for us to evaluate the suppliers. On top of usual criteria such as quality and service used for supplier evaluation, this paper also proposes the inclusion of risks, which could stream from potential supply disruptions, as a criterion to evaluate the suppliers. As supply chains are getting more and more complex these days, the issue of risk has always been a main concern of supply chain managers [8] [9]. Thus, risks should also play a role in the evaluation of suppliers so that the decision makers can account for supply risks that could potentially disrupt their operations.

This paper proposes 6 qualitative and 3 quantitative attributes as the criteria for the Supplier Selection. AHP is used to quantify the qualitative attributes. The AHP weights assigned to the qualitative attributes are then used together with the quantitative attributes for the DEA model. In addition, instead of using the basic DEA model, this paper proposes the use of super-efficiency DEA model as it could help to assign scores which could distinguish the suppliers further.

In the next section, a brief literature review will summarize relevant studies to the proposed AHP-DEA approach in this paper. In the 3rd section, the AHP-DEA approach, together with the proposed qualitative and quantitative attributes, will be described in details. An illustrative case will be shown in the following section to provide the reader of a clearer picture of how the approach works. There will be a discussion on the results and the limitations of the approach in the 5th section. Last but not

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least, a conclusion was given to summarize the content of this paper.

II. Brief Literature Review

AHP and DEA are popular decision methods in Supplier Selection problems [1] [2]. Other decision methods for Supplier Selection include Categorical Methods, Cluster Analysis, Case-Based-Reasoning (CBR) systems, Total Cost of Ownership (TCO) models, Mathematical Programming and so on [1] [2]. In this section, we will be reviewing literature that mainly focuses on AHP and DEA in Supplier Selection.

A. Application of AHP to Supplier Selection Problem

AHP, together with a few extensions, was proposed as a decision-making method for supplier selection [10]. 4 criteria namely "Quality", "Price", "Service" and "Delivery" were used in the example [10]. The paper showed the benefits and feasibility of using AHP as an approach for supplier selection [10]. An interactive selection model was introduced to allow the decision maker to determine the buyer-supplier relationship, formulate criteria and finally implement AHP to identify the most suitable suppliers [11]. Fuzzy AHP was also used for evaluating suppliers [12]. They showed the feasibility of applying fuzzy AHP in Supplier Selection problems via the validation of a case study [12]. A voting AHP method was used for the selection of suppliers [13]. Noguchi's voting and ranking was integrated with AHP in the proposed voting AHP method [13]. It was claimed to be a simpler method compared to AHP [13]. Supply chain risks were assessed with the application of AHP for sourcing [14]. A case study was done on a US manufacturing company and it showed potential as a practical methodology for companies. AHP was applied to assess suppliers based on supply risks [15]. The criteria used in were "Supplier Reliability", "Country Risk", "Transportation Reliability" and "Reliability of the supplier's suppliers" [15]. A case study was done on a Midwest Manufacturer and the results showed that AHP was an appropriate methodology that could rank suppliers based on supply risks [15]. AHP was applied to the survey feedbacks that were gathered from interviewing manufacturing firms [16]. 6 criteria were used, namely Supplier Reliability, Product Quality, Lead Time, Product Price, Transportation Ease and Cost, and Supplier Experience [16]. It was found that decision makers placed high importance on 3 criteria, namely Supplier Reliability, Product Quality and Supplier Experience [16]. An exploration on the application of AHP-based approaches to evaluate suppliers was also done [17]. The 4 criteria used in the approaches are "Process and Product Quality", "Service Level", "Management and Innovation" and "Financial Position" [17]. Besides evaluating suppliers using AHP, the paper also highlighted the strengths and weaknesses of supplier selection models for supplier evaluation and the obstacles which could potentially prevent companies from adopting such methods [17].

B. Using the DEA model in Supplier Selection Problem

DEA was used to perform comparison based on suppliers' performances [18]. The results showed that DEA is an effective approach in improving the overall efficiency of suppliers [18]. DEA was proposed to evaluate suppliers based on the normalized survey results gathered [19]. Benchmarking was also done to improve inefficient suppliers [19]. A DEA approach based on Total Cost of Ownership (TCO) was used for supplier selection [20]. It was concluded that management accounting techniques such as TCO should be complemented by evaluation approach such as DEA to provide a holistic analysis for the Supplier Selection problem [20]. A weighted linear optimization model which retains the features of DEA's approach was being proposed [21]. The difference in this model is that it allows the decision maker to rank the relative importance of the criteria used in the model [21]. The model is shown to be practical and useful for Supplier Selection [21]. A hybrid model was formulated with DEA, decision tree and neural network for Supplier Selection [22]. DEA is used to derive the efficiency scores which will then be used to train both the decision tree and the Neural Network [22]. The trained model is then able to predict the performance of new suppliers [22]. Results of the trained model showed potential for application to new suppliers who the decision maker has limited knowledge on [22].

C. Integrating DEA and AHP – Similar Approaches on Supplier Selection

There are some approaches which integrated the two said techniques (DEA and AHP) together for Supplier Selection problem. The following paragraph summarizes work done on the DEA-AHP approach on Supplier Selection. Data Envelopment Analytic Hierarchy Process (DEAHP), which was developed by Ramanathan [23], was applied to a Supplier Selection case study in Turkey [24]. The weights derived from the DEA are then used to aggregate local weights for the AHP and to derive final weights of the alternatives [23]. Though DEAHP is a more cumbersome method, it was shown that it could provide better decisions compared to the AHP approach [24]. A similar decision making model with both DEA and AHP was also developed for Supplier Selection [25]. Basic DEA model is used to generate local weights which are then aggregated by the AHP [25]. It was implemented on a case study and it was shown that rank reversal problem will not occur in their proposed method [25].

There are, however, few works that focus on AHP-DEA approach for Supplier Selection. DEA was integrated with AHP and TOC to tackle the Supplier Selection problem [26]. AHP was used to evaluate the qualitative attributes, namely "Quality", "Technology" and "Service" [26]. TOC was used as the quantitative attribute and was the only input for the DEA model. The DEA computed the relative efficiency scores of the suppliers. This AHP-TCO-DEA framework is said to be extendable to include risk behavior of the suppliers [26]. The integration of Analytical Network Process (ANP), which is a generalized form of AHP, with DEA was proposed to select appropriate suppliers [4]. ANP was used to assess suppliers based on their qualitative attributes. The results of the ANP approach are then used, together with quantitative attributes, in the DEA models [4]. Similarly, there was another work on the integration of ANP with DEA to evaluate suppliers [27]. Weights from the ANP approach were used as criteria weight preferences in DEA model [27]. In addition, green indicators were included in the criteria to account for environmental and sustainability consideration [27].

D. *Qualitative and Quantitative Attributes for Analysis*

Qualitative and quantitative attributes that were used in AHP, DEA or other Multi Criteria Decision Making (MCDM) methods for Supplier Selection in the literature are summarized in the table below. Note that some of the literature defined their criteria as being “Subjective” and “Objective” criteria instead of being “Qualitative” and “Quantitative”. In our classification shown in Table I, “Subjective” criteria are taken to be “Qualitative” while “Objective” criteria are taken to be “Quantitative”. Besides that, only main criteria are listed in Table I. Sub-criteria of the main criteria are not listed as they are of the same nature of the main criteria.

TABLE I. SUMMARY TABLE OF ATTRIBUTES

Paper	Attributes Used for Analysis
Liu et. al. (2000) [18]	Quantitative: “Supply Variety”, “Quality”, “Price Index”, “Delivery Performance”, “Distance Factor”.
Narasimhan et. al. (2001) [19]	Qualitative: “Quality Management Practices and Systems”, “Documentation and Self-Audit”, “Process/Manufacturing Capability”, “Management of the Firm”, “Design and Development Capabilities”, “Cost Reduction Capability”, “Quality”, “Price”, “Delivery”, “Cost Reduction Performance” and “Other”
Chan (2003) [11]	Qualitative: “Manufacturing Capability”, “Technical Capability”, “Technological Capability”, “Management Capability”, “Degree of Cooperation”, “Degree of Closeness” , “Performance History” and “Financial Performance”; Quantitative: “Cost”, “Quality” and “Design Capability”.
Liu and Hai (2005) [13]	Qualitative: “Discipline” and “Management”; Quantitative: “Quality”, “Delivery”, “Responsiveness”, “Technical Capability”, “Facility” and “Financial”.
Garfamy (2006) [20]	Quantitative: “Manufacturing Cost”, “Quality Cost”, “Technology Cost”, “After Sales Service Cost”, “Price” and “Item Unit”.
Haq and Kannan (2006) [12]	Qualitative: “Quality”, “Production Capability”, “Service”, “Engineering/Technical Capability” and Business Structure”; Quantitative: “Delivery” and “Price”.
Ramanathan (2007) [26]	Qualitative: “Quality”, “Technology” and “Service”; Quantitative: “Total Cost of Ownership”.
Hasan et. al. (2008) [4]	Qualitative: “Ability to modify product/process”, “Schedule Reaction”, “Human Factors” and “Agility Enhancing Factors”; Quantitative: “Net Price”, “Lead Time”, “Service Level” and “Quality”.
Ha and Krishnan (2008) [28]	Qualitative: “Quality” (Production Facilities, Quality Management Intention) and “Management and Organization” (Organization Control, Business Plans, Customer Communication); Quantitative: “Quality” (Quality System Outcome, Claims, Quality Improvement), “Delivery” and “Management and Organization” (Internal Audit, Data Administration).
Ng (2008) [21]	Quantitative: “Supply Variety”, “Quality”, “Distance”, “Delivery” and “Price Index”.
Levary (2008) [15]	Qualitative: “Supplier Reliability”, “Country Risk”, “Transportation Risk” and “Reliability of Supplier’s Suppliers”.
Wu (2009) [22]	Quantitative: “Quality Management Practices and Systems”, “Documentation and Self-Audit”, “Process/Manufacturing Capability”, “Management of the Firm”, “Design and Development Capabilities”, “Cost Reduction Capability”, “Quality”, “Price”, “Delivery”, “Cost Reduction Performance” and “Other”.
Veni et. al. (2012) [25]	Qualitative: “Supplier Profile”, “Risk Management”, “Long Term Relationship” and “Service”; Quantitative: “Cost”.
Shahroodi et. al. (2012) [16]	Qualitative/Quantitative: “Transportation Ease and Cost”, “Experience of the Supplier”, “Lead Time”, “Reliability of the Supplier”, “Price of Product” and “Quality of Product”
Kuo and Lin (2012) [27]	Qualitative: “Organization Structure and Manufacturing”, “Supplier’s Implementation Capability”, “Quality System” and “Environmental Issues”.
Karsak and Dursun (2015) [29]	Qualitative: “Product Volume”, “Delivery”, “Payment Method”, “Supply Variety”, “Reliability”, “Experience in the Sector”, “Earlier Business Relationship”, “Management” and “Geographical Location”.
Krishnadevarajan et. al. (2015) [30]	Qualitative: “Convenience” (Services and Technical Support); Quantitative: “Convenience” (Online Ordering), “Customer Service”, “Financial (Profitability)”, “Growth”, “Innovation”, “Inventory”, “Quality” and “Risk”.
Lee et. al. (2015) [31]	Qualitative: “Purchasing Management”, “Process Management”, “Quality Control”, “Operation Management”, “Cost Management”.

In addition, a review done by Ho et. al. (2010) found that the three most popular criteria for supplier evaluation used are “Quality”, “Delivery” and “Price/Cost” [2]. It was also concluded that the traditional approach of selecting suppliers solely based on the lowest cost bidding is no longer an effective way in modern supply chain management [2].

From the review, it could be seen that attributes such as “Quality”, “Service” and “Reliability” appear often as criteria for supplier selection throughout the years. Attributes such as “Environment” and/or “Risks” are less seen and regularly neglected despite the growing trend for increasing demand for the manufacturing sector to be green [32], and also for the increasing complexity in supply chain which leads to the high occurrence of supply chain risks and disruptions [8] [9]. As mentioned earlier in section I, the management of supply chain risks is highly important to a company as disruptions arising from the risks would adversely affect its operations and as such, risks should be considered as a main criterion in the evaluation of suppliers.

III. THE AHP-DEA APPROACH IN SUPPLIER SELECTION

A. Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) was introduced by Saaty [33] [34] as a powerful tool for decision making. AHP allows the decision maker to make comparisons of choices based on various criteria through his or her own personal judgment. These criteria may or may not have to be quantifiable. The decision maker will do pair-wise comparison in a matrix based the on the following scale introduced by Saaty [34] [35]:

TABLE II. SAATY'S INTENSITY OF IMPORTANCE SCALE

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one activity over another
5	Strong Importance	Experience and judgment strongly favor one activity over another
7	Very Strong Importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is required
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	-

The corresponding pair-wise comparison (n-by-n) matrix will look like the following:

$$\begin{pmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{n1} & \cdots & 1 \end{pmatrix}$$

where
$a_{ii} = 1$ for $i = 1, \dots, n$; and
$a_{ij} = \frac{1}{a_{ji}}$ for $i, j = 1, \dots, n$ with $i \neq j$.

As humans are unable to make perfect judgments, some degree of inconsistency in these comparisons may occur. There is a need to perform consistency verification to ensure that judgments stay within acceptable range of inconsistency [35]. The Consistency Index (CI), that Saaty proposed, needs to be first calculated as [35]:

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

where
n is the size of the matrix; and
λ_{max} is the real dominant eigenvalue.

Using the CI, the Consistency Ratio (CR) can be then be derived [35]:

$$CR = \frac{CI\ of\ A}{RI\ for\ size\ n} \qquad (2)$$

where RI is the Random Index which can acquired from the Table III [35]:

TABLE III. RANDOM INDICES FOR MATRICES OF DIFFERENT SIZES

Size of Matrix (n)	Random Index (RI)
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

The rule of thumb is to have the value of CR to be under 0.1, which equates to a 10% inconsistency [35].

B. Data Envelopment Analysis (DEA)

Data Envelopment Analysis (DEA) measures and relatively evaluates the efficiencies of alternatives known as Decision Making Units (DMUs) [36]. DEA is a useful decision making tool as it is capable of analyzing various types of data – regardless of their units of measurement. The measurement for efficiency is based on the concept of constructing an efficient frontier. Interested readers may refer to Seiford's work [37] for more information on frontier analysis in DEA.

Efficiency is defined as a ratio of weighted output to weighted input [7] [26]. The general efficiency ratio for a DMU, relative to a 'test' DMU, can be expressed as [4] [7]:

$$E_{ab} = \frac{\sum_y O_{by} v_{ay}}{\sum_x I_{bx} u_{ax}} \qquad (3)$$

where
E_{ab} is the efficiency of a DMU b, using the weights of the 'test' DMU a;
O_{by} is the output *y* of DMU *b*;
v_{ay} is the weight for 'test' DMU *a* for output *y*;
I_{bx} is the input *x* of DMU *b*; and
u_{ax} is the weight for 'test' DMU *a* for input *x*.

The basic DEA model was first introduced by Charnes, Cooper and Rhodes in 1978 [38]. Also known as basic CCR model, the formulation of the model for a DMU is as follows [39]:

$$\max E_{aa} = \frac{\sum_y O_{ay} v_{ay}}{\sum_x I_{ax} u_{ax}} \qquad (4)$$

such that

$$E_{ab} \leq 1\ \forall b$$
$$u_{ax}, v_{ay} \geq 0$$

in which E_{ab} is the same as the term in equation (3). The decision variables of model (4) are u_{ax} and v_{ay}.

The formulation in (4) which accounts for the efficiency of DMU a, is non-linear. The following formulation in (5) is the equivalent linear programming of (4):

$$\max \textstyle\sum_y O_{ay} v_{ay} \quad (5)$$

such that

$$\sum_y O_{by} v_{ay} \leq \sum_x I_{bx} u_{ax} \;\forall b$$

$$\sum_x I_{ax} u_{ax} = 1$$

$$u_{ax}, v_{ay} \geq 0$$

The transformation to a linear programming problem is done by restricting the denominator to be equal to 1, which is represented by the constraint $\sum_x I_{ax} u_{ax} = 1$.

The optimal efficiency value obtained from the basic CCR model is at most equal to 1 [26]. What this means is that there is a possibility that a handful of DMUs may end up having the same maximum value of 1. This happens when these DMUs lie on the optimal frontier and is not dominated by any other DMUs [4]. This would result in the decision maker having a tough time trying to decide on the rankings of the most efficient DMUs.

To overcome this, a variation of the basic CCR model, known as Super-Efficiency CCR model, was proposed by Andersen and Petersen in 1993 [40]:

$$\max \textstyle\sum_y O_{ay} v_{ay} \quad (6)$$

such that

$$\sum_y O_{by} v_{ay} \leq \sum_x I_{bx} u_{ax} \;\forall b, b \neq a$$

$$\sum_x I_{ax} u_{ax} = 1$$

$$u_{ax}, v_{ay} \geq 0$$

The model in (6) does not differ much from (5). The only difference is that the second constraint will include all DMUs except for the 'test' DMU (which is DMU a in this case). This model shall be the one of interest in our approach in this paper.

C. *Proposed Attributes*

We have identified 6 qualitative criteria which we propose to be important for supplier selection. These criteria are derived based on the literature review conducted and are believed to be able to cover needs of supply chain managers in supplier evaluation. The criteria we propose for supplier selection are: Quality, Service, Reputation, Management, Environment and Risks. The table below summarizes what each of the criteria means:

TABLE IV. CRITERIA AND THEIR EXPLANATION

Criteria	Explanation
Quality [41]	Standards, including durability and conformance, of the goods produced by the supplier.
Service [42]	Responsiveness - how fast the supplier answers to queries and orders. It also involves flexibility, which refers to the ability of the supplier to accommodate changes, such as coping with sudden change in production capacity due to demand surge or dealing with customization of product designs.
Reputation [43]	The perceived reliability of the supplier and his status as a stronghold in the market. It serves as a basis for the amount of trust that customers have and the level of commitment that customers may have in the supplier.
Management [44]	Organizational structure, such as no. of employees and their level of technical skills and training; and implementations within company, such as production planning system. On the whole, it is the effectiveness of the supplier's operations.
Environment [45]	Efforts of the supplier to go green in product design and to be environmental friendly in their production through the reduction in pollution.
Risks [14] [15]	Risks that could arise potentially from supply chain disruptions. Example of such risks includes logistics risk, order fulfillment risk, natural disasters, accidents, political instability and so on.

From the literature review conducted, we concluded that the criteria "Quality", "Service", "Reputation" and "Management" are important attributes that are commonly used for evaluation. On top of these, we decided to include "Environment" and "Risks" as criteria too since they have been gaining popularity for evaluation in recent years as seen from the literature review.

As global warming has become more and more threatening due to emission of manufacturing waste, it is definitely important that manufacturers put in an effort to go green and reduce greenhouse emissions [32]. As such, supply chain managers should also put in an effort to include environmental performance in the evaluation of the suppliers [45] as it would in turn encourage manufacturers to go green. Besides that, as mentioned earlier in section I, the consideration of risks is essential in the evaluation of suppliers. Accounting for risks is crucial for the company's performance and competitiveness as supply disruptions are common nowadays and could stem from all sorts of sources – be it natural disasters, labor strikes or terrorism and so on [14]. Also, AHP has been shown to be capable of accounting for risks based on decision maker's preferences [46] and also for assessing risks for the supply chain [14]. Thus, the inclusion of "Risks" as a criterion in our approach would allow the decision maker to incorporate the issue of supply risks in the evaluation of suppliers.

The evaluation of the criterion "Risks" in the AHP approach for the suppliers will be similar to what Schoenherr did, in which suppliers are being pair-wise compared based on their performance with respect to risks [14]. For instance, if supplier i is "extremely better" than supplier j in terms of performance with respect to "Risks", supplier i will be assigned a score of '9' over supplier j.

These criteria mentioned in Table IV will be used in AHP for pair-wise comparison. Notice that these criteria are defined to be qualitative attributes and thus the application of AHP will be appropriate.

As for quantitative attributes, we proposed these 3 attributes: Price, Lead-Time and Delivery Charges. The table below summarizes what each of the attribute means:

TABLE V. INPUTS AND THEIR EXPLANATION

Input	Explanation
Price	Quantity of payment given by the customer to the supplier in return for goods and services.
Lead-Time	Time between initiation and completion of the deal. This includes the delivery time of the goods.
Delivery Charges	Cost required for goods to be transported from the supplier to the customer

These 3 quantitative attributes will serve as inputs for the DEA model. Examples on how the inputs are supposed to be like will be shown in the next section.

D. *The AHP-Super Efficiency DEA approach*

AHP will be applied to perform pairwise comparison on the (qualitative) criteria of the suppliers. The weights derived from the AHP for each criterion will be used as outputs for the DEA model. In other words, what this means is that the criteria for supplier selection are actually the outputs of the DEA model. The use of AHP is to make these qualitative attributes quantifiable such that they will then be suitable for the DEA model.

Note that the inputs of the DEA model are quantifiable attributes which become better when their values are smaller. For instance, if the value of the price of the product is lower, it will definitely be better for the customer as that would mean a cheaper cost to the customer. The rationale for having such property for the inputs is that since efficiency is a ratio of output to input, having smaller values of input would actually result in higher efficiency. Similarly, the concept applies to the outputs – the higher the AHP weights are, the better the outputs are. This accounts for why AHP weights are used as outputs in the model. Besides that, to avoid double counting, the outputs and inputs are chosen such that they are mutually exclusive.

With those outputs and inputs, the objective values can be derived from the DEA model. Based on the derived objective values, which are the efficiency values for each supplier, the decision maker is then able to rank the suppliers and thus decide on the suitable suppliers.

An exemplary case has been written in the next section to illustrate how this AHP-Super Efficiency DEA approach works for supplier selection.

IV. ILLUSTRATIVE CASE

As mentioned in the literature review, both DEAHP and ANP-DEA are similar approaches for supplier selection. Ramanathan formulated a DEAHP approach which included a small illustrative case to demonstrate a comparison of alternatives [23]. The ANP-DEA approach proposed by Hasan used an illustrative case to demonstrate how the approach works [4]. Similarly, this paper will propose an illustrative case to show how our approach works in supplier selection.

Assume that the company of interest is a small manufacturing company which sources for components to build its products. A supply chain manager, who is also the decision maker, faces a supplier selection problem that involves 6 suppliers in total. Let "S1", "S2", "S3", "S4", "S5" and "S6" denote supplier 1, supplier 2, supplier 3, supplier 4, supplier 5 and supplier 6 respectively.

A. *AHP and the weights*

The hierarchy of the AHP for these 6 suppliers will look like the following:

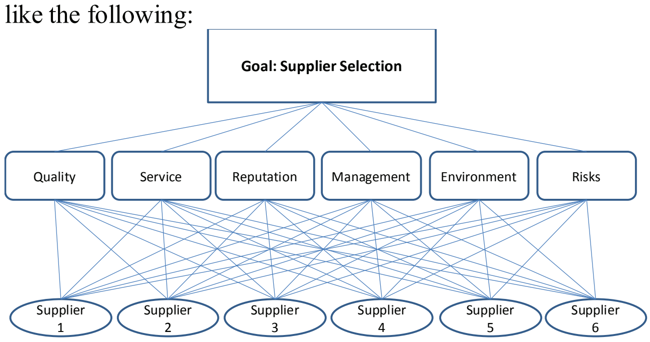

Figure 5: AHP Hierarchy for the 6 suppliers

For each criterion, pairwise comparison was done among the 6 suppliers. Below is an example of the pairwise comparison due for the criterion "Quality":

Quality

$$\begin{array}{c} \\ S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{array} \begin{array}{cccccc} S1 & S2 & S3 & S4 & S5 & S6 \\ \end{array}$$

$$\begin{matrix} S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{matrix} \begin{bmatrix} 1 & 2 & 4 & 1/3 & 1/2 & 2 \\ 1/2 & 1 & 2 & 1/6 & 1/3 & 1/2 \\ 1/4 & 1/2 & 1 & 1/5 & 1/4 & 1/2 \\ 3 & 6 & 5 & 1 & 2 & 4 \\ 2 & 3 & 4 & 1/2 & 1 & 3 \\ 1/2 & 2 & 2 & 1/4 & 1/3 & 1 \end{bmatrix}$$

The eigenvalue for the matrix is 6.134 with CI to be 0.027 and CR to be 0.022. Thus, inconsistency is within 10% and acceptable.

The corresponding weight is then:

$$\begin{matrix} S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{matrix} \begin{pmatrix} 0.154 \\ 0.072 \\ 0.051 \\ 0.391 \\ 0.236 \\ 0.097 \end{pmatrix}$$

Gathering the weights for the 6 suppliers from the 6 criteria, we have the following matrix which will serve as the output for the DEA model:

$$\begin{matrix} & S1 & S2 & S3 & S4 & S5 & S6 \\ Quality & 0.154 & 0.072 & 0.051 & 0.391 & 0.236 & 0.097 \\ Service & 0.032 & 0.427 & 0.047 & 0.099 & 0.283 & 0.113 \\ Reputation & 0.144 & 0.048 & 0.049 & 0.450 & 0.226 & 0.082 \\ Management & 0.034 & 0.126 & 0.104 & 0.457 & 0.242 & 0.036 \\ Environment & 0.038 & 0.229 & 0.421 & 0.046 & 0.093 & 0.172 \\ Risks & 0.101 & 0.050 & 0.179 & 0.032 & 0.380 & 0.258 \end{matrix}$$

B. The Super Efficiency DEA model

The price, lead-time and delivery charges for the 6 suppliers are summarized in the Table VI.

TABLE VI. INPUT DATA FOR THE 6 SUPPLIERS

Supplier / Attribute (Unit)	S1	S2	S3	S4	S5	S6
Price ($ per unit ordered)	1.45	1.20	0.95	1.55	1.65	1.35
Lead Time (Days)	2	5	7	4.5	3	4
Delivery Charges ($ per unit ordered)	3.50	2.85	4.65	2.30	3.80	4.15

These data will serve as the input for the DEA model.

As mentioned earlier, model (6) will be the DEA model we will be using. The DEA model for the *m-th* supplier will be:

$$\max \textstyle\sum_y O_{my} v_{my} \quad (7)$$

such that

$$\sum_y O_{sy} v_{my} \le \sum_x I_{sx} u_{mx} \; \forall s, s \ne m$$

$$\sum_x I_{mx} u_{mx} = 1$$

$$u_{mx}, v_{my} \ge 0$$

There are 6 criteria for the output and so *y* will be 6. Similarly, there are 3 attributes for the input and so *x* will be 3. Since there are 6 suppliers, there will be 6 such DEA models (model (7) for each supplier). Note that the output O_{sy} will be:

$$\begin{bmatrix} 0.154 & 0.072 & 0.051 & 0.391 & 0.236 & 0.097 \\ 0.032 & 0.427 & 0.047 & 0.099 & 0.283 & 0.113 \\ 0.144 & 0.048 & 0.049 & 0.450 & 0.226 & 0.082 \\ 0.034 & 0.126 & 0.104 & 0.457 & 0.242 & 0.036 \\ 0.038 & 0.229 & 0.421 & 0.046 & 0.093 & 0.172 \\ 0.101 & 0.050 & 0.179 & 0.032 & 0.380 & 0.258 \end{bmatrix};$$

the input I_{sx} will be:

$$\begin{bmatrix} 1.45 & 1.2 & 0.95 & 1.55 & 1.65 & 1.35 \\ 2 & 5 & 7 & 4.5 & 3 & 4 \\ 3.5 & 2.85 & 4.65 & 2.3 & 3.8 & 4.15 \end{bmatrix};$$

the *m-th* output O_{my} will be the *m-th* column of the output O_{sy}; the *m-th* input I_{mx} will be the *m-th* column of the input I_{sx}; and u_{mx}, v_{my} are the decision variables.

We are interested in getting the objective value for the DEA model as it will form the basis for us to do the ranking of the suppliers. Since model (7) is a small linear programming problem, it can be easily solved using Solver in Microsoft Excel. Thus, we derived the results summarized in the Table VII.

TABLE VII. SCORES FOR THE 6 SUPPLIERS IN AHP-DEA APPROACH

Supplier	Score (Objective value derived from Super Efficiency DEA model)
Supplier 1	0.895
Supplier 2	2.321
Supplier 3	2.508
Supplier 4	3.284
Supplier 5	2.712
Supplier 6	0.913

Thus, based on the scores we can rank the suppliers in a descending order: Supplier 4, Supplier 5, Supplier 3, Supplier 2, Supplier 6 and Supplier 1.

V. DISCUSSION

A. Applying AHP only

Let "Q", "S", "R", "M", "E" and "Rk" represent "Quality, "Service", "Reputation", "Management", "Environment" and "Risks" respectively.

If the decision maker were to perform AHP only, he will also have to perform pairwise comparison for the 6 criteria. Suppose he did so and the pairwise comparison matrix is as follows:

$$\begin{matrix} & Q & S & R & M & E & Rk \\ Q & 1 & 3 & 7 & 5 & 3 & 2 \\ S & 1/3 & 1 & 3 & 6 & 1/3 & 1/3 \\ R & 1/7 & 1/3 & 1 & 1/2 & 1/4 & 1/5 \\ M & 1/5 & 1/6 & 2 & 1 & 1/7 & 1/6 \\ E & 1/3 & 3 & 4 & 7 & 1 & 1/4 \\ Rk & 1/2 & 3 & 5 & 6 & 4 & 1 \end{matrix}$$

The eigenvalue for the matrix is 6.604 with CI to be 0.121 and CR to be 0.097. Thus, inconsistency is within 10% and acceptable.

The corresponding weight is then:

$$\begin{matrix} Q \\ S \\ R \\ M \\ E \\ Rk \end{matrix} \begin{pmatrix} 0.342 \\ 0.113 \\ 0.037 \\ 0.042 \\ 0.173 \\ 0.293 \end{pmatrix}$$

Based on all the weights derived, the overall scores for the suppliers will be:

$$\begin{matrix} S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{matrix} \begin{pmatrix} 0.099 \\ 0.134 \\ 0.154 \\ 0.198 \\ 0.259 \\ 0.156 \end{pmatrix}$$

Thus, the ranking for the suppliers in descending order would be: Supplier 5, supplier 4, supplier 6, supplier 3, supplier 2 and Supplier 1.

B. Integrating AHP with Basic CCR model only

If the decision maker were to use the basic CCR model (which is model (5) in section III) for the DEA segment, then the DEA model will become:

$$\max \textstyle\sum_y O_{my} v_{my} \quad (8)$$

such that

$$\sum_y O_{sy} v_{my} \leq \sum_x I_{sx} u_{mx} \; \forall s$$
$$\sum_x I_{mx} u_{mx} = 1$$
$$u_{mx}, v_{my} \geq 0$$

This model (8) only differs from model (7) by one constraint only. Again, using Solver in Microsoft Excel, we could derive the results as summarized in the Table VIII.

TABLE VIII. SCORE FOR THE 6 SUPPLIERS USING AHP WITH BASIC DEA MODEL

Supplier	Score (Objective value derived from basic DEA model)
Supplier 1	0.895
Supplier 2	1.000
Supplier 3	1.000
Supplier 4	1.000
Supplier 5	1.000
Supplier 6	0.913

Suppliers 2, 3, 4 and 5 will tie at the first place, followed by supplier 6 and then supplier 1.

C. Comparison of Results from the 3 Approaches

We summarize all results in Table IX.

TABLE IX. SUMMARY OF RESULTS FROM 3 DIFFERENT APPROACHES

	AHP	AHP-Basic DEA	AHP-Super Efficiency DEA
Supplier 1	0.099	0.895	0.895
Supplier 2	0.134	1.000	2.321
Supplier 3	0.154	1.000	2.508
Supplier 4	0.198	1.000	3.284
Supplier 5	0.259	1.000	2.712
Supplier 6	0.156	0.913	0.913

Supplier 1 has the least score out of all 6 suppliers in all 3 types of approaches. Since Supplier 1 has a relatively low AHP score and comparable inputs (costs and lead time are on par with others), it is not unexpected that it will continue to have the lowest score in both DEA models. What this suggests is that supplier 1 could be a dominated alternative.

Using the AHP with basic DEA will yield a bunch of suppliers with values of 1, as the maximum of the objective value is restricted to 1. This results in a tie for most suppliers. But with the use of the Super Efficiency DEA model, the restriction no longer exists and thus the tie disappears. It allows the decision maker to have a better distinction among the suppliers.

Comparing the AHP approach with the AHP-Super Efficiency DEA approach, we realized that the rankings for the suppliers changed. For instance, supplier 4 switched places with supplier 5 in AHP-Super Efficiency DEA approach despite supplier 5 having a higher AHP score. What this means is that having a higher AHP does not guarantee a higher DEA score; the DEA score is still dependent on both the outputs (which refer to the AHP scores) and the respective inputs.

However, note that the AHP approach was only applied to the 6 qualitative attributes. If it had been applied to all attributes (the 6 qualitative attributes and the 3 quantitative attributes), the resulting scores might turn out to be different. It could also provide as a fair comparison with the AHP-DEA or AHP-Super Efficiency DEA approach as they both took in the consideration of both quantitative and qualitative attributes. As the scores from applying AHP on both qualitative and quantitative attributes are not of any use in this approach, thus we did not conduct the said AHP analysis.

D. Limitations and Future Work

One well-known disadvantage of the AHP approach would be the “rank-reversal” problem [27] [47]. As the proposed AHP-Super Efficiency DEA approach involves AHP and the AHP is not in ideal-mode, the rank-reversal issue is highly likely to surface too. However, rank-reversal may or may not pose as a real problem as its effect on rational decision making is still highly debatable and the occurrence of rank-reversal is rare in reality [48] [49] [50].

When there are too many suppliers to choose from, the curse of dimensionality will be unavoidable [51]. As the number of suppliers gets larger, the number of pair-wise comparisons to perform can get tremendously huge. Also, since each supplier will have its own DEA model, the number of DEA models to formulate and solve will also increase proportionately to the number of suppliers. So, having a lot of suppliers will mean having a lot of DEA models to solve. The large amount of models might be hard for the decision maker to deal with. However, given the computational power and speed of modern computers, this will not pose as a big problem as computers will be able to deal with the large amount of models effectively [23].

Nevertheless, in future work, we can still explore ways to make AHP more efficient as pairwise comparison can get very tedious when there are more suppliers. For instance, dominated options can be left out and not be considered in the subsequent DEA models. Also, there is a constant need to check for consistency for the matrices in AHP. This will require the decision maker to work on the matrix again and again until the inconsistency is within acceptable range. More work may be done to ensure consistency and eliminate the need for constant checking. Sensitivity analysis, which is not discussed in this paper, should be also implemented to explore how critical certain variables (such as the criteria or inputs) are to the resulting weights of the model. We also seek to work with a real company so as to validate our proposed approach in the near future.

VI. CONCLUSION

The AHP-Super Efficiency DEA approach, together with the proposed quantitative and qualitative attributes, provides a holistic approach for the decision maker to choose the best supplier. In order for the DEA model to work, the inputs and outputs of the model must be in quantitative form. This limitation of DEA can be easily addressed by using AHP to quantify these qualitative factors through the assignment of weights in the analysis process.

We have also defined and proposed the criteria for AHP pairwise-comparison. The outputs and inputs that should be in the DEA model are suggested too. An illustrative case for the proposed approach was also shown in this paper so that the reader can have a better sense of how the AHP-Super Efficiency DEA approach would work. The results of AHP, AHP-basic DEA and AHP-Super Efficiency DEA were also shown and discussed. It was concluded that the proposed AHP-Super Efficiency DEA approach could potentially be the most appropriate supplier selection solution. Limitations for the approach were also discussed and further improvements were suggested for future work. In addition, a large number (or rather, dataset) of suppliers, coupled with the high computation power of modern computers, can be dealt with in this proposed approach. The AHP-Super Efficiency DEA approach, together with the proposed qualitative and quantitative attributes, should be able to help the decision maker to rank the suppliers more effectively and thus select the most appropriate supplier(s) for his or her own company.

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