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Supplier selection of an Indian heavy locomotive manufacturer: An integrated approach using Taguchi loss function, TOPSIS, and AHP

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Abstract Supplier selection is increasingly seen as a strategic issue for any firm. In the literature, a variety of supplier selection criteria and methodologies have been reported. However, in this article, to find the most dependable supplier for an Indian heavy locomotive firm, some of the selection criteria like quality, delivery, price and service are employed. Subsequently, an integrated model is proposed for objective assessment of suppliers by integrating three methods namely, Taguchi loss function, analytical hierarchy process (AHP), and technique for order performance by similarity to ideal solution (TOPSIS). Finally, two cases of the firm under study, along with sensitivity analysis, are considered to demonstrate the credibility of the model.

Introduction

Proficient supplier selection is an imperative and complex issue for any firm, particularly for public firms that operate differently from other business firms. In a public firm, the selection of suppliers is challenged at each step, contrary to business firms where after due diligence is exercised not many questions are posed. A public firm has to function within the boundaries of public procurement rules and regulations, subject to constant scrutiny (e.g., Purchase of goods Act 1930 and its amendments). An incorrect decision at any step may lead to termination of contract or selection of an unsuitable supplier. In both cases, it is a waste of resources for the firm. Moreover, every decision needs to be financially sound and in compliance with the current rules of public procurement, i.e., the awarding manager (or committee) must follow the prescribed procedure and maintain transparency at all stages. There appears to be a fundamental dichotomy between encouraging competitiveness of public firms and limiting the leeway of decision making for managers.

Thus, it is important to select measurable and transparent criteria for supplier selection. In the past, several authors (e.g., Bottani and Rizzi, 2006; Sharma and Balan, 2013; Jain et al., 2016) have suggested numerous criteria and methodologies for the selection of suppliers; however, in the present era characterised by a multitude of options, selection can be daunting. With every passing year, more and more options are available for selection of suppliers. As the nature of products, technology and skill sets, which are

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required to select a supplier varies from one firm to another, selection becomes even more difficult. The selection of a wrong supplier can have expensive consequences and unacceptable quality issues. Furthermore, past studies (e.g., Desanctis and Gallupe, 1987; Khan et al., 2016) suggest that the outcomes of a subjective assessment of suppliers are not only dependent on the selection criteria themselves but also, and perhaps more, on how the factors are evaluated by experts and the use of methodology for supplier evaluation. In other words, the supplier selection criteria used are an important factor which should be considered in understanding the outcomes of supplier selection. Thus, selection of an appropriate supplier involves several factors, and subsequently the use of proper selection methodologies. Moreover, the important issue is the processing of these factors (e.g., how to measure the factors) and methodologies to select the best supplier matching a firm's requirement.

In this article, we have attempted to integrate the relative advantages of multi criteria decision making (MCDM) techniques into a quantifiable supplier evaluation (or selection)model for a public firm that manufactures heavy locomotives in India. The considered firm was established in 1963 by the Government of India. It manufactures heavy locomotives primarily for the Indian Railways and has 6000 employees at present. In the financial year 2014-15, the budget of the firm was more than 32 billion INR. In 1998-99, new generation locomotives known as High Horse Power (HHP) locomotives were initiated that resulted in an increase in purchasing activities, as most of the required components were different from the firm's in-house capabilities. The firm procures raw materials like steel plates, bars, billets, castings, and forgings for the production of HHP locomotives, from different suppliers. The procurement process of the firm is controlled and governed by public procurement rules and guidelines. The areas of concern for supplier selection at present are:

1. Although the Indian regulatory body has prescribed a Supplier Rating formula in 1997, there is no such system currently in use. It is a fairly simple formula, where quality rating has been given 60% weightage and delivery rating has been given 40% weightage. But even this formula is not complete and does not capture the very important aspect of service, assuming the cost to be same for all suppliers.
2. Supplier selection is a formalised system, governed by strict rules and policies, based on the concept of selection of "lowest priced technically suitable offer". But to certify an offer as technically suitable, the methodology is quite subjective.
3. There is a certain lack of objectivity in rating a supplier or selecting a new supplier which leads to complaints and can restrain even good decision makers from taking a chance. As a result, many times unsuitable suppliers are selected.
4. The suppliers are not formally made aware of their bad performance from all points of view and the recording system is not scientific. Each supplier is viewed in isolation. The suppliers are also not aware of each other's performances.

Considering the above issues, this article, in particular, seeks to answer two primary questions: How is a supplier to be selected for the firm under consideration, i.e., how to obtain a preferred supplier from a list of suppliers using a sophisticated model? And based on what criteria, scale of measurement, determination of criteria weights, and selection methodology should this selection be made? Further, this article focusses on objective formulation for the evaluation of suppliers. The idea is to reduce subjectivity, as it may not always be possible to have a foolproof objective assessment.

The supplier selection under multiple criteria and the use of a single technique like weighted average method, which is being practiced by the firm at present, is not sufficient. Given the number of quantitative (or objective) and qualitative (or subjective) supplier selection criteria with different vector of influences — higher is better (enabling) and lower is better (inhibiting) — being used by the firm. That increases the complexity level of decision makers' while assigning weights to individual selection criterion and linking the vector of influences while selecting one supplier over the other, and finally scoring of suppliers, make supplier selection issues challenging. Hence, to handle these issues of the firm, we have proposed a model by integrating three methods, namely, Taguchi loss function, analytical hierarchy process (AHP) and technique for order performance by similarity to ideal solution (TOPSIS) by considering the advantage of these methods. For instance, the Taguchi loss function has the capability of quantifying the criteria and alternatives objectively, AHP is the most popular and widely used method for assigning weights to criteria with consistency check of experts, and TOPSIS is an effective method for finding the most efficient alternative, which has the shortest geometric distance from the positive ideal solution. Thus, an integration of the three techniques has been attempted after considering the advantages of each technique. Finally, on applying the proposed model to two of the real life cases of an Indian manufacturing firm and performing sensitivity analysis, we verified the credibility of the model.

Literature review

Supplier selection criteria

The important aspects of any supplier selection decision are selection of proper criteria, the possibility of quantifying them, and availability of data for such assessments. The most prevalent criteria for supplier selection have been identified by researchers and practitioners (Sarkar and Mohapatra, 2006; Padhi and Mohapatra, 2010; Ho et al., 2010). For instance, Sarkar and Mohapatra (2006) have considered 23 criteria for supplier selection, such as price, capability and quality. Ho et al. (2010) have analysed research articles from the year 2000 to 2008 in the field of supplier evaluation and selection, and found that the most popular supplier evaluation criteria are quality, delivery and price/cost. Padhi and Mohapatra (2010) have addressed the contractor selection issue in an Indian public firm using four factors viz, price, experience, resources, and financial status of contractors. Based on European public procurement rules and regulations, Falagario et al. (2012) have addressed the issues of supplier selection using two criteria – lowest price and the most economically advantageous tender. Moreover, several applications have been reported in the literature on supplier selection criteria for different industries such as logistics firms (Büyüközkan et al. 2012; Hassan et al., 2013); Original Equipment Manufacturer (OEM) manufacturing firms (Buyurgan and Saygin, 2008; Durán, 2011; Aguilar-Lasserre et al., 2009); automobile firm (Li and Kuo, 2008); glass manufacturing firm (Barla, 2003); telecommunication firm (Önüt et al., 2009); public firm (Igarashi et al., 2015); retail firm (Chiu et al., 2013); and food industry (Amorim et al., 2016).

It is observed that each industry is different from the other and so also the supplier selection criteria. Hence, obtaining a typical set of selection criteria is difficult. More specific to this article is to find out the supplier selection criteria used by the case study firm. Hence, we have selected a few firms that have been supplying different products to the case study firm, these being, BHEL, SAIL, Coal India Limited and Rail Coach Factory (enumerated in Table 1). These firms were considered to maintain uniformity with the case study firm's supplier selection criteria, and also historical records of these supplying firms are available (for the last five years) for objective assessment.

The above firms were analysed to obtain the patterns of similarity so that a generic model could be evolved. Generally, quality is considered the most important criterion for the selection of suppliers. But in most cases, rather than quality, it is the purchase price that is the decisive factor. Some attributes like service quality are difficult to quantify, but play an important role in decision on suppliers. But as the number of criteria increases, so does the complexity and simple rules do not work. Discretion will always be used by managers but their opinion may be influenced by instinct, and this can lead to inaccurate decisions. Additionally, Table 1 shows that the criteria for supplier evaluation are more or less common across the firms. The four factors namely, quality, delivery, price and service are the criteria for assessing supplier performance in most of the aforementioned firms. Furthermore, the Bureau of Indian Standards has issued a comprehensive standard IS 12040:2001 on guidelines for development of supplier rating system. As per these standards, the suppliers can be rated based on any or all of the factors, namely, (1) quality, (2) delivery, (3) price, (4) service and (5) system.

Based on past research, with the evaluation of criteria applicable and manageable in the present context of increasing perceived fairness and transparency, the four salient criteria which are identified as important in supplier evaluation and selection are: (1) quality, (2) delivery, (3) price, and (4) service. System factor of the IS 12040:2001specification has been avoided as it again leads to subjectivity. Moreover, we are trying to devise a method for rating the existing supplier, who is already in business with the manufacturer.

Supplier selection methods

A review of supplier selection methods that covers most of the relevant literature up to the early 2000s by Degraeve et al. (2000), de Boer et al., (2001), and Ho et al. (2010) has categorised the decision models into five groups namely, (1) linear weighting models, (2) total cost of ownership (TCO) models, (3) mathematical programming models, (4) statistical models, and (5) artificial intelligence (AI)-based models. Recently, Chai et al., 2013 have provided a very extensive and systematic review of the relevant literature from 2008 to 2012 to summarise the various methods used for supplier selection, which are: (1) multicriteria decision making

Table 1 Summary of supplier selection/evaluation of Indian firms

Firm	Criteria	Weighted Score (in %)	Remarks
BHEL, India	Quality, Delivery, Service	Q (60), D (30), S (10)	Score used for rating, categorised into 5 categories
ABB, India	Quality, Delivery, Cooperation	D (40-60), Q (20-40)	3 categories of suppliers, evaluation both formal and informal
General Dynamics	Delivery, Quality, Financial stability, and Compliance	D (40), Q (30), FS (10), C (20)	Within each category the weights are further assigned
Ordnance Factories Board (OFB), India	Quality, Delivery, Price, Service	Q (60), D (25), P (10), S (5)	Within each category the weights are further assigned
Rail Coach Factory (RCF), India	Delivery, Quality	D (40), Q (60)	Warranty claim also related to Quality Rating
Coal India Limited (CIL), India	Quality, Delivery, Price	Q (40), D (20), P (40)	Suppliers classified into groups
SAIL, India	Quality, Delivery, Price	Q (50), D (35), P (15)	Vendor is scored for each order. Vendors divided into classes after getting average scores
United Technologies Corporation	Quality, Delivery, Lean, Customer Satisfaction	Specific to suppliers type	Suppliers are categorised
Bureau of Indian Standards, New Delhi	Quality, Delivery, Price, Service, System	Not defined	Only advisory
Indian Locomotive (Case study Firm)	Quality, Delivery, Price, Service	Q (50), D (20), P (20), S (10)	Within each category the weights are further assigned

Source: Respective Firm's Supplier Manual/Documents.

techniques (2) mathematical programming (MP) techniques, and (3) artificial intelligence (AI) techniques.

Of all these methods, the most widely used and dominant methods for supplier selection are integrated methods— in particular, the integrated MCDM methods. Moreover, the integrated method using analytic hierarchy process (AHP) is very popular in literature, because of its simplicity, ease of use, check of consistency, and great flexibility (Ho et al., 2010). Recently, Chai et al., 2013 have reviewed the research work on decision making techniques in supplier selection from the year 2008 to 2012, selecting about 123 articles. They have observed that the AHP technique was the most used technique by itself or in integration with other techniques.

There are several approaches for supplier selection, using single methodologies like AHP. For instance, Yadav and Sharma (2016) have used an AHP methodology using six supplier selection criteria — quality, price, delivery, service, relationship, and flexibility — for the Indian automobile industry. Similarly, Dweiri et al (2016) have applied an integrated AHP model to assist managers in solving complex selection problems of the automobile industry. However, several authors propose to combine different methodologies in order to obtain more accurate results (Zeydan et al. 2013, Demirtas and Üstün 2008).

Studies like Xia and Wu (2007) have used an integrated approach of AHP by employing rough sets theory and multi-objective mixed integer programming to determine the optimal number of suppliers. Jain et al (2016) have studied the selection of headlamp suppliers using integrated fuzzy AHP and TOPSIS. Dey et al. (2016) have introduced a novel MCDM approach to solve decision problems in a supply chain. The proposed algorithm multi objective performance analysis is demonstrated with six real life decision problems. The result is compared with other MCDM methods like TOPSIS and Viekriterijumsko Kompromisno Rangiranje (VIKOR) for validation purpose. Nag and Helal (2016) have considered the case of a pharmaceutical set-up where a large number of global suppliers are involved. A range of alternative suppliers were evaluated based on a fuzzy-TOPSIS method considering seven criteria for supplier selection process. They have concluded that the Fuzzy TOPSIS model can be effectively put into practice in uncertain environments. Boranet al. (2009) have combined the TOPSIS method with fuzzy set to evaluate suppliers. Chan et al. (2008) have discussed a fuzzy-AHP methodology to efficiently tackle both quantitative and qualitative decision factors involved in the selection of global suppliers for a manufacturing industry. Chen et al. (2011) have proposed the fuzzy preference ranking organisation method for enrichment evaluation (PROMETHEE) to evaluate four potential suppliers using seven criteria and four decision-makers for a case study firm. Chou et al. (2008) have envisaged a fuzzy Simple Multi-Attribute Ranking Technique (SMART) and applied it to evaluate alternative suppliers, which deals with the ratings of both qualitative and quantitative criteria. Ho et al. (2011) have combined quality function deployment (QFD) with AHP for evaluation of multiple supplier selection factors and determining the importance of evaluating factors and preference of suppliers with respect to selection criteria. Similarly, Khan et al. (2016) have deployed the same integrated methodologies for an automotive parts manufacturing company of Pakistan to determine the importance of selection criteria and ranking of suppliers with respect to each criterion like delivery, price, quality, and service.

Liao et al. (2011) have considered both tangible and intangible criteria, and proposed an integrated fuzzy TOPSIS and multi-choice goal programming (MCGP) approach to solve the supplier selection problem. The advantage of this method is that it allows decision makers to set multiple aspiration levels for supplier selection problems. Ordoobadi (2010) has used an integrated approach of Taguchi loss function and AHP for the inclusion of intangible criteria in the selection of suppliers and determination of weights for the criteria, respectively. Liao et al. (2010) have integrated the Taguchi loss function, AHP and MCGP model for solving the supplier selection problem. The advantage of this method is that it allows decision makers to set multiple aspiration levels for the decision criteria. Pi et al.(2006) have presented an evaluation of suppliers using a combined approach of Taguchi loss function and AHP using four supplier selection criteria — quality, on-time delivery, price, and service. Following the same procedure, Sharma and Balan (2013) have applied an integrative approach considering Taguchi loss function, TOPSIS, and multi criteria goal programming to deal with supplier selection issues and compared the proposed model outputs with data envelopment analysis (DEA) to check the model credibility.

Thus, more relevant to our study is the focus on objective assessment of suppliers through integrating Taguchi loss function (Liao and Kao, 2010), TOPSIS (Behzadian et al., 2012) and AHP (Durán, 2011) approaches to multicriteria supplier selection. The supplier selection criteria, namely, quality (Ayers, 2006; Chase et al., 2014), price (Stevenson, 2009; Chase et al., 2014), delivery (Dawson, 2002; Stevenson, 2009), and service (Dawson, 2002; Ayers, 2006; Stevenson, 2009) should be weighed using a suitable methodology, which is adopted based on its relevance to its usability.

Integrated model for supplier selection

The Taguchi loss function is a method to evaluate loss to an organisation due to deficient quality standards of products (Taguchi, 2004). Traditionally, the product is accepted if a product measurement falls within the specification limit; otherwise, the product is rejected. Taguchi suggests a stricter view of quality by indicating that any deviation from the target value results in a loss. If a measurement is the same as the target value, the loss is zero. Otherwise, the loss can be measured by using aquadratic function, after which actions are initiated to bring back the system close to the target value.

After obtaining the objective measure for suppliers against each criterion using the Taguchi loss function, the TOPSIS method is used. The TOPSIS method was introduced by Hwang and Yoon (1981). Behzadian et al. (2012) have found that it has been applied to many applications ranging from manufacturing to purchasing, health, safety, energy, human resource management, chemical engineering, water resources management and other areas. Tavana and Marbini (2011) have identified it as one of the best MCDM methods in addressing the rank reversal issue. Another advantage of this technique is its simplicity and ease of calculation. The

TOPSIS method has found wide application as it not only seeks to maximise the benefits, but also avoids risk as much as possible. It takes full advantage of attribute information and provides a cardinal ranking of alternatives. The method finds the solution closest to ideal and farthest from the worst scenario.

While determining the suppliers, ranking the weightage of each criterion is an important issue. Thus, we have used the most widely used method i.e., AHP for the evaluation of selection criteria. It is a simple, effective method for the determination of weights of each criterion by pair wise comparison. It is easy for the opinion maker to adjudge the criteria with respect to one another. It has an inbuilt system for checking the decision makers' inconsistency. However, some researchers opine that it fails to address the problem of ranking inconsistency. If the number of attributes increases then the number of judgments to be made increases phenomenally. Despite these shortcomings, AHP is still the most widely accepted method for pairwise comparison of alternatives or criteria.

The Taguchi loss method is very convenient to calculate loss due to failure on the part of supplier, as explained earlier. The AHP is a well-established method for finding the weights of all the supplier selection criteria. Thus an integrated method employing Taguchi loss method, AHP for pair wise comparison and TOPSIS for final ranking would suffice for the requirement of the study i.e., to find an objective, acceptable and simple procedure for supplier evaluation. Figure 1 gives the flow chart of the proposed integrated model.

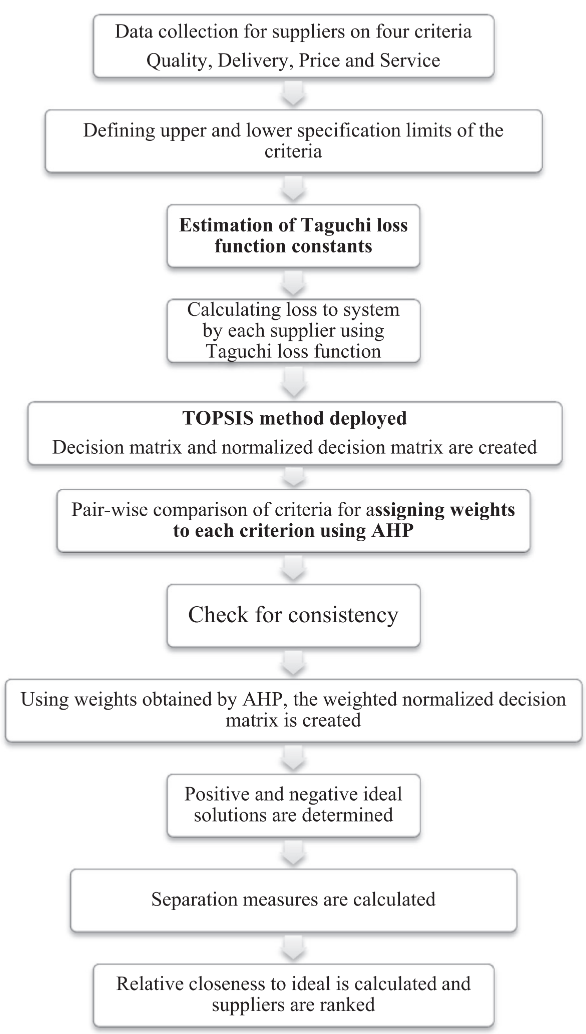

Figure 1 Integrated model for supplier selection.

Case studies to build the two-step model

The above steps, in the context of supplier selection problem, are elaborated through two case studies of an Indian heavy locomotive manufacturer. In the considered cases, suppliers of a product compete with each other to obtain the contract, by quoting attractive offers against each supplier selection criterion fixed by the firm. That is, competition primarily takes place on the price, quality, delivery and services offered by the suppliers.

The total value of purchase of the firm in 2010-11 was 22.13 billion INR, and 7.26 billion INR worth of imported material was used to produce mainly four variants of HHP locomotives. The purchase process is extensive. For instance, to produce 200 HHPs, in the year 2011-12 there were 951 advertised tenders, 241 global tenders, and 5301 limited tenders released, involving 6766 numbers of suppliers in the tendering process. Significant effort of the firm is wasted in pursuing the suppliers for items. The Material Control Organization had been created in the firm with a pool of about 100 officials whose sole purpose was to coordinate with suppliers on delivery issues. An overview of the entire process has revealed that there are different types of items required by the firm for its smooth functioning, such as 224 types of bolts to 12 types of bars, for which there are 9 and 7 registered suppliers respectively. In this article we have used the cases of a particular type of pipe and ball bearing with four potential suppliers in each case.

Initially, we have taken the following three steps to get acquainted with the past and current supplier selection criteria and supplier specific data: (1) Browsing the Websites of the case study firm (e.g., http://www.irfca.org/faq/faq-loco2d.html#wdm-2dated September 18, 2013) and studying the details regarding the types of diesel locomotives and other heavy locomotive engines manufactured in different parts of the country; (2) Gathering detailed information on the supplier selection criteria pertaining to individual suppliers that participated in different tendering processes, by interviewing firm's officials involved in decision making for more than 15 years in purchasing, technical, quality, and service facilities; and also by conducting semi structured interviews of experts to check our results and processing of suppliers and criteria specific information. (3) Collecting the past records and relevant data from the supplier selection criteria used by the firm and its aligned firms' log-books and records.

With the data thus obtained, we have demonstrated the proposed model in detail in the following two subsections. We incrementally build the model and follow the practical application of the respective steps as outlined in the previous section.

Quantifying the loss using Taguchi loss function

Three types of loss functions are used in the Taguchi loss function: first, the nominal value (or the best value), where the proper function depends on the magnitude of variation with variations being allowed in both directions from the target value (Figure 2). The expression for this type of loss function is given by equation (1):

$$L(y) = k(y-m)^2 \quad (1)$$

Where $L(y)$ is the loss associated with a particular value of quality character y;m is the nominal value of the specification; and k is the loss coefficient, whose values are constant depending on the cost limits and the range of the specification.

The other two functions are the one-sided minimum-specification limit, called smaller-is-better (Figure 3A) and the one-sided maximum-specification limit function, called higher-is-better (Figure 3B). Respective loss functions are given in equations (2) and (3):

$$L(y) = k(y)^2 \quad (2)$$

$$L(y) = k/y^2 \quad (3)$$

Hence, for the cases under consideration, a committee of five managers from various departmental functions like service operation, purchasing, and quality control of the firm have objectively rated the suppliers based on historical data on the four supplier selection criteria for both the cases. Then, these objective values were incorporated into the Taguchi loss function for the assessment of suppliers. The four selection criteria have been tabulated with their recommended target value, range and specification limit in Table 2. For instance, a delay in delivery by 15 days is a practical upper limit. The target value is the ideal condition of no delay at all i.e., 0 day. Similarly for quality, 5% of total quantity supplied is an acceptable limit for rejection or non-conformance. The target value is thus 0%.

The calculations of the loss coefficient k, for all the criteria are shown in Table 3. Here, we can observe that the Taguchi function for service criterion is different from the other criteria because of its enabling nature i.e., higher the service level the better it is (enabling criterion).

Using these values we calculate the Taguchi loss for each supplier in each case. The data on each criterion for every supplier of a particular item is tabulated in Table 4. This is used for calculating the loss for system from the supplier's failure to perform to the required level.

The Taguchi loss values for each supplier against each criterion is calculated in Table 5 (for both the cases) by multiplying the square of values in Table 4 with the Taguchi constant for the respective criterion (e.g., Quality of Supplier A = 40000 $\times 0.03^2 = 36$).Then, the estimated loss matrix (Table 5)is used as input decision matrix for the TOPSIS method to determine the preferred supplier.

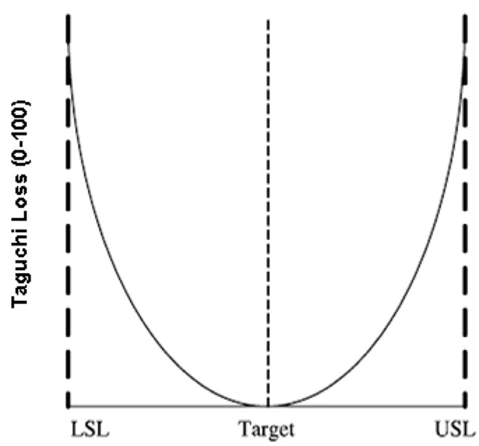

Figure 2 Two-sided equal-specification. Taguchi loss function.

Combining TOPSIS and AHP methods

The principle behind using this step is to estimate an alternative which is closest to the ideal and farthest from the worst solution. Hence, we construct a matrix with n suppliers and m criteria, where each value of the matrix is denoted by $x_{ij,}$ $\forall i$ =1, 2, ..., m and j = 1, 2, ..., n.

For the two cases under consideration, a decision matrix is created (same as Table 5). Next, the normalised decision matrix r_{ij} is calculated, where, $r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$, $\forall i$ =1, 2, ..., m and j = 1, 2, ..., n. Table 6 gives the normalised decision matrix.

To determine the weightage of the selection criteria we have used the AHP method that begins by determining the relative importance of the criteria in meeting the goals (Saaty, 1990). The experts' consolidated opinions are taken

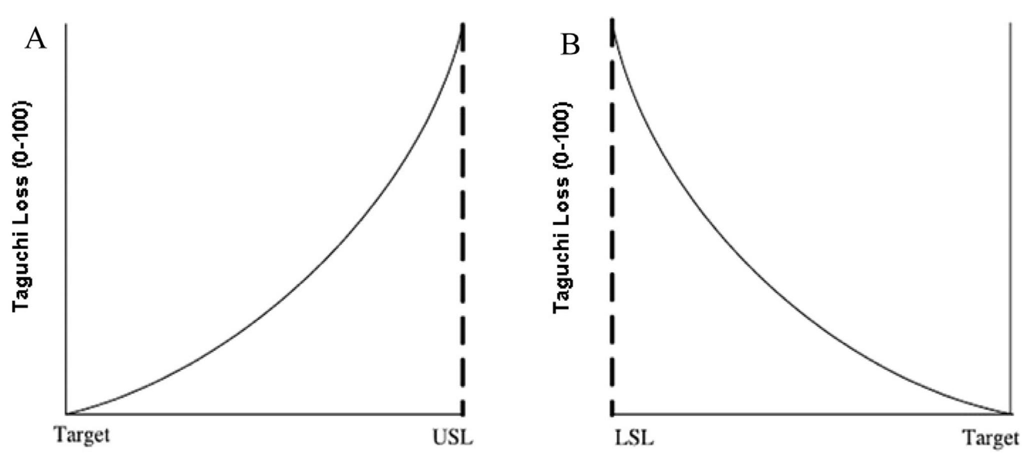

Figure 3 One-sided minimum – (A) and maximum – (B). Specification limit function.

Table 2 Target value of losses and specification limits

Criteria	Target value	Range	Specification limit	Remark
Quality	0%	0-5%	5% rejection	Lower the better
Delivery	0	0-15	15 days	Lower the better
Price	Lowest	0-10%	10% higher	Lower the better
Service	100%	100%-50%	50% lower	Higher the better

Table 3 Calculation of Taguchi loss coefficient

Criteria	Taguchi function	Specification limit	Loss (assuming 100% loss at specification limit)	Value of k
Quality	ky^2	5% rejection	$100 = k \times (0.05)^2$	40000
Delivery	ky^2	15 days	$100 = k \times (15)^2$	0.4444
Price	ky^2	10% higher	$100 = k \times (0.10)^2$	10000
Service	k/y^2	50% lower	$100 = k / (0.50)^2$	25

Table 4 Data for suppliers of particular item

Case	Supplier	Quality % rejection	Delivery delay in days	Price compared to lowest	Service level opinion
Case 1 (Pipe Suppliers)	A	3%	5	0%	85%
	B	3%	6	6.50%	75%
	C	2%	7	8.40%	80%
	D	4%	2	4.20%	65%
Case 2 (Ball bearing suppliers)	E	1%	10	7.50%	70%
	F	2%	7	5.00%	80%
	G	4%	9	10.00%	55%
	H	2%	5	8.75%	60%

Table 5 Calculation of loss by each supplier for each criterion

Case	Supplier (x_{ij})	Quality (Q)	Delivery (D)	Price (P)	Service (S)
Case 1 (Pipe Suppliers)	A	36.00	11.11	0.00	34.60
	B	36.00	16.00	42.25	44.44
	C	16.00	21.78	70.56	39.06
	D	64.00	1.78	17.64	59.17
Case 2 (Ball bearing Suppliers)	E	4.00	44.44	56.25	51.02
	F	16.00	21.78	25.00	39.06
	G	64.00	36.00	100.00	82.64
	H	16.00	11.11	76.56	69.44

in terms of pairwise comparisons of the selected criteria. The pairwise comparisons are done using Saaty's nine point scale (1, 3, 5, 7, and 9 points in the scale represents Equally-, Moderately-, Strongly-, Very strongly-, and Extremely- important and 2, 4, 6, and 8 points are used for intermediate values).The AHP method allows some small inconsistency in opinion because humans are not always consistent. The ratio scales are derived from the principal Eigen vectors and the consistency index is derived from the principal Eigen value.

We construct a pairwise comparison matrix using the Saaty's nine point scale. Considering n criteria, the pairwise comparison of criterion i with criterion j yields a square matrix A where, a_{ij} denotes the comparative importance of criterion i with respect to criterion j. In the matrix, $a_{ij} = 1$, when $i = j$ and $a_{ji} = 1/\ a_{ij}$.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

For the two cases under consideration, a group of five managers involved in the purchase process of the locomotive manufacturer were invited to give their opinions on the relative

Table 6 Normalised decision matrix

Case 1 (Pipe suppliers)					Case 1 (Ball-Bearing suppliers)				
r_{ij}	Q	D	P	S	r_{ij}	Q	D	P	S
A	0.43	0.38	0.00	0.38	E	0.06	0.71	0.40	0.41
B	0.43	0.55	0.50	0.49	F	0.24	0.35	0.18	0.31
C	0.19	0.74	0.84	0.43	G	0.94	0.58	0.71	0.66
D	0.77	0.06	0.21	0.65	H	0.24	0.18	0.55	0.55

Table 7 Relative importance matrix

	Quality	Delivery	Price	Service
Quality	1	3	7	9
Delivery	1/3	1	3	5
Price	1/7	1/3	1	1/3
Service	1/9	1/5	3	1

importance of the criteria and the highest frequency of opinions were considered for evaluation. Their opinion/relative importance grading was used to form the square matrix (A). The matrix with relative importance as derived from their opinion is shown in Table 7.

We calculate the normalised matrix A_n by summation of each column and then dividing each element by the respective column total, where, element c_{ij} is the normalised element, $c_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$ and $A_n = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix}$.

Next, we calculate the mean of each row to obtain the normalised principal Eigen vector i.e., $\begin{bmatrix} \frac{1}{n}\sum c_{1j} \\ \vdots \\ \frac{1}{n}\sum c_{nj} \end{bmatrix}$ for $j= 1,2,\ldots, n$. Here, several iterations are done by squaring the normalised matrix till the difference in principal Eigen vectors in previous and iterated matrix becomes almost zero or negative. This final iterated matrix gives the principal Eigen vector (or priority vector), which is the weight of each criterion. The principal Eigen value of the matrix A has to be calculated, and it is called λ_{max}. It is calculated by multiplying the column sums of matrix A with the principal Eigen vector (e) i.e., $\lambda_{max} = \left[\sum_{i=1}^{n} a_{i1} \quad \ldots \quad \sum_{i=1}^{n} a_{in}\right] \times \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix}$.

We calculate the consistency index (CI) = ($\lambda_{\max}$ - n) / (n-1) and also obtain the Random Index (RI), for the number of criteria used in decision making, which is four (n = 4) for the case under consideration and the respective value of RI = 0.9. Finally, we calculate the consistency ratio (CR) = CI / RI. Usually, a CR of 0.10 (10%) or less is considered acceptable.

For the two cases under consideration, by following the above procedure we obtain the criteria priority weights and we also undertook a consistency check of the decision makers. The stepwise calculations have not been shown as AHP is now a standard procedure. The results are shown in Table 8.

From Table 8, it is observed that the consistency ratio is within limits i.e., less than 10% and the relative weight of each criterion is also estimated i.e., quality (62%), delivery (22%), price (8%), and service (8%). It can be observed that price has not been given priority over other factors. From a holistic view, if the quality, delivery and service of a supplier are not as per specifications or within range, it can cause loss and irreparable damage to the organisation. Even when the loss can be directly attributed to the failure of the supplier, the liability is limited only up to a certain percentage of purchase value in most cases. Moreover, this assessment is possible only after the damage is done. The factors other than price are very important, and this concept can be translated into decision making, if right from the beginning, the process and method are clear to all the stakeholders.

We calculate the weighted normalised value (v_{ij}) i.e., $v_{ij} = r_{ij} \times w_j$, $\forall i$ =1, 2,..., m and j = 1, 2, ..., n., where w_j is the weight of the j^{th} criterion or attribute and $\sum_{j=1}^{n} w_j = 1$.

For the two cases under consideration, the weights as determined above (Table 8) are deployed in Table 9 to get the weighted normalised decision matrix.

The ideal solution (A^*) and negative ideal solution (A^-) are determined. They are calculated for each criterion separately using the below formulas.

$A^* = (v_1^*, v_2^*, \ldots, v_n^*) = \{(\max_i\{v_{ij}\}|j\epsilon C^*), (\min_i\{v_{ij}\}|j\epsilon C^-)\}$ and
$A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \{(\min_i\{v_{ij}\}|j\epsilon C^*), (\max_i\{v_{ij}\}|j\epsilon C^-)\}$,
where, C^* is associated with enabling attribute and $C^-$with inhibiting attribute.

For the two cases under consideration, we have computed the positive and negative ideal solutions against each criterion separately as given below.

case	*Ideal*	Q	D	P	S	
Case 1	v^-	0.4762	0.1637	0.0671	0.0523	Negative ideal
	v^*	0.1190	0.0134	0.0000	0.0306	Positive ideal (lesser loss)
Case 2	v^-	0.5828	0.1562	0.0568	0.0528	Negative ideal
	v^*	0.0372	0.0396	0.0144	0.0248	Positive ideal (lesser loss)

Table 8 Normalised matrix and calculation of weights

	Normalised matrix				Normalised principal Eigen vector	
Quality	0.63	0.66176	0.5	0.58696	62%	
Delivery	0.21	0.22059	0.21429	0.32609	22%	
Price	0.09	0.07353	0.07143	0.02174	8%	
Service	0.07	0.04412	0.21429	0.06522	8%	
Lambda	0.9896	1.0039	1.1161	1.1563	**4.266**	**Principal Eigen value**
n	**4**			CI	0.089	
				CR	**9.8%**	**Consistency**

Table 9 Weighted normalised decision matrix

Case	$v_{ij} = r_{ij} \times w_j$	Q	D	P	S
	Weights	0.62	0.22	0.08	0.08
Case 1 (Pipe suppliers)	A	0.2678	0.0835	0	0.0306
	B	0.2678	0.1202	0.0402	0.0393
	C	0.1190	0.1637	0.0671	0.0345
	D	0.4762	0.0134	0.0168	0.0523
Case 2 (Ball bearing suppliers)	E	0.0372	0.1562	0.0320	0.0328
	F	0.1488	0.0770	0.0144	0.0248
	G	0.5828	0.1276	0.0568	0.0528
	H	0.1488	0.0396	0.0440	0.0440

We calculate the separation measures. The separation measures of each alternative from the positive ideal solution and the negative ideal solution, respectively, are as follows:

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2},\ S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2}\ \forall i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n$$

For the two cases under consideration, the separation measures are calculated. Table 10 gives the separation measure for positive ideal solution and Table 11 gives the separation measure for negative ideal solution, respectively.

We determine the relative closeness to the ideal solution. The relative closeness C^*_i of the alternative A^* with respect to A^- is defined as: $C_i^* = \frac{S_i^-}{S_i^* + S_i^-}$ $\forall i$ =1, 2,...,m.

For the two cases under consideration, the final step is the estimation of relative closeness to ideal, for each supplier ranking depends on the closeness of this value to 1. Table 12 depicts the value and ranking of suppliers.

The best alternative is the alternative with C^*_i, closest to 1. The alternatives can also be ranked in the order of their closeness to 1. Thus, minimising the distance measure from the ideal alternative and maximising the distance to the worst or negative ideal best alternative is obtained. Thus, the suppliers are ranked in the order C, A, B and D for case 1; and E, H, F, and G for case 2. The integrated model is found to be a simple, straightforward method. It can be understood by all players in the system. It definitely increases the perceived fairness in the system.

A discussion ensued on what could be the acceptable limit for loss by a supplier, so that a performance evaluation could be carried out and a supplier with loss above that limit would not be allowed to participate in the purchase process. Moreover, the luxury of rejecting a supplier is possible only when there are many suppliers in the fray. This function can only give an objective assessment of the supplier. However, if one of the approved suppliers is very high on loss, he may be warned or rejected. This system will now give the purchase manager

Table 10 Separation measure for positive ideal solution

Case	$(v - v_i^*)^2$	Q	D	P	S	sum	$S_i^* = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^*)^2}$
Case 1 (Pipe suppliers)	A	0.02214	0.00492	0.00000	0.00000	0.02706	0.1645
	B	0.02214	0.01142	0.00161	0.00008	0.03525	0.1878
	C	0.00000	0.02259	0.00450	0.00002	0.02711	0.1647
	D	0.12754	0.00000	0.00028	0.00047	0.12830	0.3582
Case 2 (Ball bearing suppliers)	E	0.0000	0.0136	0.0003	0.0001	0.0140	0.1182
	F	0.0125	0.0014	0.0000	0.0000	0.0139	0.1177
	G	0.2977	0.0077	0.0018	0.0008	0.3080	0.5550
	H	0.0125	0.0000	0.0009	0.0004	0.0137	0.1170

Table 11 Separation measure for negative ideal solution

Case	$(v_i^- - v)^2$	Q	D	P	S	sum	$S_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_j^-)^2}$
Case 1 (Pipe suppliers)	A	0.04340	0.00643	0.00450	0.00047	0.05480	0.2341
	B	0.04340	0.00189	0.00072	0.00017	0.04618	0.2149
	C	0.12754	0.00000	0.00000	0.00032	0.12786	0.3576
	D	0.00000	0.02259	0.00253	0.00000	0.02512	0.1585
Case 2 (Ball bearing suppliers)	E	0.2977	0.0000	0.0006	0.0004	0.2987	0.5465
	F	0.1884	0.0063	0.0018	0.0008	0.1972	0.4441
	G	0.0000	0.0008	0.0000	0.0000	0.0008	0.0286
	H	0.1884	0.0136	0.0002	0.0001	0.2022	0.4497

Table 12 Relative closeness to ideal and final ranking

Case	Suppliers	$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}$	Ranking
Pipe suppliers	A	0.5873	2
	B	0.5336	3
	C	0.6847	1
	D	0.3068	4
Ball bearing suppliers	E	0.8222	1
	F	0.7905	3
	G	0.0490	4
	H	0.7935	2

quantitative information to take action, which is absent currently in the firm's procedure and system.

Sensitivity analysis

To evaluate the effectiveness of a supplier selection methodology, one should be able to compare the results obtained from the methodology with the results obtained from other methodologies. Unfortunately, a sequence of suppliers ranked by one method cannot be compared with a different sequence ranked by a different method due to lack of any criteria as the basis for such evaluation. Hence, with regard to the validity of the method, we have used the defined ranges of each criterion (Table 13) using the target value of losses, and specification limits of Table 2 to generate data using uniform distribution function. In this process, we have generated four scenarios such as ascending values of lower the better criteria and ascending values of higher the better criteria, to descending values of both types of criteria. A sample of the inputs is given in Table 13. In this process of sensitivity analysis we retain the criteria weights obtained from AHP methodology because AHP method takes care of consistency check of decision makers, which is also a strategic decision. Hence, we have avoided redoing the pairwise comparisons as repeating the same study for the same organisation would risk the biases of the previous study and understanding.

Sensitivity analysis of the four sets of input data helps in generating four scenarios (Figure 4). In the top two scenarios — descending (LB) and descending (HB); descending (LB) and ascending (HB) — the composite score of suppliers is showing monotonically increasing functions. This is because majority of the LB criteria data trends are following the same direction as that of the target values of set for each criterion. Additionally, the weight of these (LB) criteria are

Table 13 Sample inputs for scenario analysis

Quality % rejection (LB)*	Delivery delay in days (LB)*	Price compared to lowest (LB)*	Service level opinion (HB)#
0-5%	0-15	0-10%	100%-50%
	Range (Considering uniform distribution)		
Ascending	Ascending	Ascending	Descending
0	0	1%	100%
1	1	2%	95%
1	2	3%	90%
2	4	4%	85%
2	6	5%	80%
3	8	6%	75%
4	9	7%	70%
4	11	8%	65%
5	13	9%	60%
5	15	10%	50%

* LB: lower the better i.e., inhibiting criterion.
\# HB: higher the better i.e., enabling criterion.

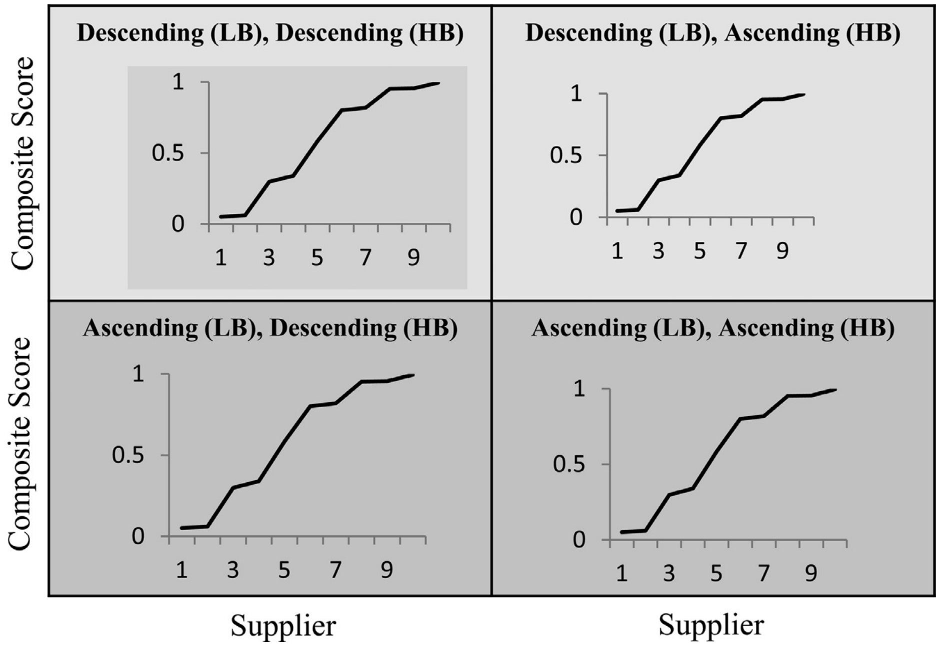

Figure 4 Scenarios and sensitivity analysis.

comparatively high (62% + 22% + 8% = 92%) when compared to that of (HB) criterion weight (8%) obtained from AHP method, which is also pushing the graph in the upward direction irrespective of descending (HB) criterion data. Similarly for the bottom two scenarios — ascending (LB) and descending (HB); ascending (LB) and ascending (HB) — the composite score of suppliers is showing monotonically decreasing functions. This is because majority of the LB criteria data trends are following the opposite direction as that of the target values of set for each criterion. Additionally, the weight of these (LB) criteria is comparatively high (92%) compared to that of (HB) criterion weight (8%) obtained from AHP method, which is also pulling down the graph irrespective of ascending or descending (HB) criterion data. Hence, the outputs obtained from this proposed model help managers to objectively rank suppliers with identically separable scores between two adjacent suppliers. The output obtained through sensitivity approach indicates that superior outcomes can be obtained using this proposed model.

Conclusions

This paper proposes an integrated model through combining advantages of three methods namely: Taguchi loss function, AHP, and TOPSIS, to help managers objectively evaluate suppliers by eliminating bias and subjectivity. The application of the proposed model to an Indian heavy locomotive manufacturer (HLM) is a new application area, with a prolonged history of supplier selection problems. Two real life cases of an Indian heavy locomotive manufacturer have been explained by applying the proposed model along with sensitivity analysis to test the credibility of the proposed model.

The supplier evaluation and selection can be made objective using the suggested model. This will give purchase managers the authority to override an offer which is lowest in price as other criteria will play a significant role in getting the best supplier. The lowest in price criterion is a very serious problem with the current procurement procedure in the public firms. The supplier can (or may) take undue advantage of this position, where only price plays the decisive role. The other advantage of the suggested model is that now suppliers will have a performance report in front of them to make a comparison with other firms in their domain. This will instil positive competition as they will have quantifiable objectives to work upon and improve. The integrated approach institutionalises the advantages of the loss function, AHP and TOPSIS in the system of evaluation. The loss function is perhaps the most objective method to quantify the loss, where it is possible to eliminate subjective discretion. The AHP is a time tested method for pair wise comparison used in finding the weightages of criteria. Finally, combining TOPSIS to find which supplier is closest to best helps making an objective assessment of suppliers and also addresses the rank reversal issue generally incurred in MCDM problems.

Despite this, there may still be the influence of the discretion of managers or officers, but this will be within acceptable limits. In the present state of affairs, the public firm under consideration may find it a little difficult to gather so much data about the supplier's criteria for a large number of items. But if the system of collecting data is put in place for all the items, within 2-3 cycles of procurement enough data on suppliers will be available for this proposed model to display its efficacy. There will be a perceived fairness in the system, which is of great importance in a public procurement scenario.

The methods adopted in this work have tried to take care of necessities of the considered firm. This work has assumed constant delivery time but it may be extended to the case with dynamic lead times. In real life situations there will be dynamic delivery times. Additionally, this study has been confined to a few items in the HLM's master list of material. This serves as a guide and can be extended to all items after grouping. A methodology to estimate the genuine suppliers for a set of products can be evolved; this will help in determining the optimal group of suppliers for a set of products under these selection criteria or similar criteria of comparable products. At present, the price of the product is determined by the market; by analysing the offers received by the suppliers, more effective price targets can be obtained.

In assessing the suppliers' selection, many comprehensive models have been developed, in which every criteria has sub criteria and they are all assigned scores, which are finally added to get a final score. The difficulty of such a comprehensive system is in quantifying all criteria. Even with five or six criteria it gets very difficult to quantify all criteria. This is a potential area of research, wherein some methodology may be found to quantify most of the criteria. Moreover, a method like AHP requires data based on experience, knowledge and opinion which are subjective to each decision-maker. Another disadvantage of this method is that it does not consider risks and uncertainties regarding the supplier's performances.

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