



Multi-Criteria Evaluation of Raw Material Vendors: A Case Study on Paper Supplier Selection using Analytic Hierarchy Process

Hamiden Abd El-Wahed Khalifa¹, Zahra Sobhani², Angeline Harris², Paris Bingham², Robert S. Keyser^{2*}

¹ Department of Mathematics, College of Science, Cairo University, Giza, Egypt

² Department of Industrial and Systems Engineering, Southern Polytechnic College of Engineering and Engineering Technology, Kennesaw State University, Marietta, Georgia, USA

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ABSTRACT

This case study focuses on paper supplier selection for a corrugated box plant using the Analytic Hierarchy Process (AHP). Four criteria were evaluated by top management among three paper suppliers. The two suppliers with the highest overall score were retained as vendors. A consistency index (CI) was compared to a Random Index (RI) value for $n = 4$ criteria to determine the level of consistency in top management's judgments. Results show that Supplier A achieved the highest overall score followed by Supplier B and both were retained as vendors. The consistency ratio, $CR = 0.0113 < 0.05$, indicates very good consistency in top management's preferences.

1. Introduction

Multicriteria decision making involves trade-offs of both intangible and tangible considerations with respect to the objectives of the decision maker, as reported by [1] and [2]. The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty between 1971 and 1975 [3], provides a mathematical framework for incorporating subjective (and personal) preferences of an individual or group in the decision-making process [4,5]. According to [6] and [7], AHP uses pairwise comparisons based on expert judgements to create priority scales that measure intangible factors in relative terms. These comparisons are performed using a scale of absolute judgements that indicate the degree to which one element dominates another with respect to a given attribute. AHP consists of seven pillars developed by [8], that organized into three principles [9] and can be reduced to four steps in the AHP process [6].

Several studies have demonstrated AHP applications in a wide range of industries. Saaty [10] used AHP to select convention sites. Other applications include agricultural decision making in developing countries [11], environmental impact assessment [12], selection of computer operating systems [13],

* Corresponding author.

E-mail address: rkeyser@kennesaw.edu

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and evaluation of marketing mix decisions [14]. Liberatore & Nydick [15] benefited AHP for shared medical and healthcare decision-making between patient and physicians, evaluating and selecting therapies and treatments, and evaluating healthcare technologies and policies [15]. Karimi et al. [16] used AHP to select wastewater treatment process, while Chan & Lynn [17] used it for performance evaluation.

This case study aims to identify the top two paper suppliers for Knox Box, a corrugated box plant, using the AHP methodology while checking for consistency of top management's judgments regarding the criteria under evaluation. This paper is organized as follows. Section 2 introduces the AHP methodology used to analyze the data. Section 3 presents the results, and Section 4 discusses the findings. Finally, the paper concludes with Acknowledgement and Reference sections.

2. Methodology

2.1 The Analytic Hierarchy Process

When applied in decision-making, the application of AHP decomposes a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives [11].

The four steps in the AHP process are as follows [6]:

- (1) Develop the decision hierarchy by defining the problem and determining the knowledge that is desired.
- (2) The overall objective should be stated at the top, followed by evaluation criteria in the middle, and the alternatives at the bottom.
- (3) Create a set of pairwise comparison matrices whereby elements are compared against each other in pairs using a scale from 1 to 9 to indicate how much more important (or preferred) one criterion (or alternative) is when compared to another criterion or alternative.
- (4) Calculate the weights using matrix mathematics to turn the paired comparisons into numerical priority weights for each criterion and alternative. Then, sum up the products of each option after multiplying the weight of each option by the weight of the criteria associated with it. This results in a synthesized total score for each option and provides a means for ranking the options. Select the alternative with the highest or lowest total score depending on the stated objective, i.e., whether the objective function seeks to maximize or minimize the total score, to determine the preferred alternative.

The authors recommend a fifth step – that is, to check a consistency ratio to ensure the pairwise comparison results are not contradictory. However, the most creative task is identifying which factors, or criteria, in step (2) are most important for a given decision [18].

According to Dong and Saaty [19], a team decision-making problem typically consists of a team of experts who express their judgments on a finite set of criteria, sub-criteria, and alternatives. As reported by Chiclana et al. [20] and Herrera-Viedma [21], when a team of experts participate in the AHP process, reaching consensus typically involves multiple rounds of discussion and is moderated by a designated individual [19]. This individual supervises and facilitates the consensus process toward a certain level of agreement (i.e., majority rules) but does not participate in the discussion. A complication in any of the four (or five) AHP steps will likely lead to disruptions in team decision-making.

The case study focuses on a corrugated box plant that is based in Tennessee. This plant is known as a “sheet plant,” which means the box plant purchases custom sheet stock to make corrugated shipping containers from three regional paper suppliers. Top management, consisting of the General Manager, Sales Manager, and Production Manager, wanted to reduce the number of paper suppliers

from three to two, to realize improved economies of scale on higher volume sheet stock purchases. At the same time, they try to receive more consistent incoming sheet stock board quality, which has a direct effect on productivity on all machine centers (i.e., the flatter the sheet stock, the better it runs through machines). The three paper suppliers are Supplier A, Supplier B, and Supplier C.

Four key criteria including cost, service, quality, and reliability were identified through a series of top management meetings. **Cost** refers to the price of various grades of sheet stock (\$/square foot). The corrugated box industry is a very competitive industry. As such, although slight differences exist, the overall pricing levels of all three sheet stock paper suppliers are comparable based on their price lists. **Quality** refers to many factors: sheets are cut to correct dimensions with correct scoring profiles, the paper combination matches the type of sheet stock ordered, and the incoming sheet stock is flat (i.e. within +/- 1/16" of perfectly flat), rather than warped. **Service** refers to how well customer/sales service is provided by both the manufacturer's representative and the customer service representatives. This takes into consideration the friendliness and professionalism exhibited by the suppliers' reps, timely responses, order status updates, alerts to potential delivery issues, provision of alternatives to issues that arise, etc. **Reliability** refers to how well each supplier does what is expected (i.e., consistent on-time delivery of orders, the receipt of in-spec sheet stock in the required quantities, and receipt of correct invoices).

Pairwise comparisons are employed in matrix A to rank criteria, or alternatives, by asking top management decision-makers to judge the relative importance of head-to-head evaluations of two items at a time (i.e., which is more important and by how much). Dividing each entry in column i of matrix A by the sum of the entries in column i yields a new matrix A_{norm} , for which the sum of column entries is 1. To compute w_{max} , which is used as an estimate of w , the top management decision-makers' weights, w_i , is estimated as the average of the entries in row i of A_{norm} . Next, we determine an overall score for each decision and select the decision with the highest score as the best decision. To check for consistency, we compute Aw^T and apply this result in tabulating the consistency index (CI), which is a measure of how far the matrix deviates from total consistency. The ratio of the consistency index (CI) to a random index (RI), the average CI of a randomly generated reciprocal matrix of the same size, determines the consistency ratio (CR), a measure of how logical and consistent the pairwise comparisons are. When interpreting the value of CR, if $CR \leq 0.10$, the degree of consistency is satisfactory and if $CR \geq 0.10$, the degree of consistency is too high, and may not yield meaningful results [22]. In this case, a review and revision of pairwise comparisons may be needed to trust the results.

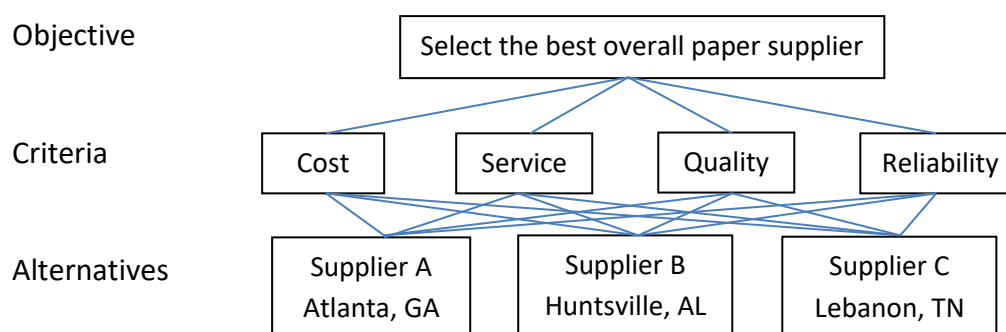


Fig. 1. AHP hierarchy design of best paper supplier

For the i th criteria, AHP generates a weight w_i . Knox Box's weights, calculated as described below, are shown in Table 1.

Completing the analysis for Criterion:

Table 1

Weights for the four criteria.

	Criterion	Cost	Service	Quality	Reliability
A =	Cost	1	1	1/2	1/3
	Service	1	1	1/3	1/4
	Quality	2	3	1	1/2
	Reliability	3	4	2	1
	Criterion	Cost	Service	Quality	Reliability
A_{norm} =	Cost	0.143	0.111	0.130	0.160
	Service	0.143	0.111	0.087	0.120
	Quality	0.286	0.333	0.261	0.240
	Reliability	0.429	0.444	0.522	0.480

For example, in matrix **A**, the management team believes that Quality is two times as important as Cost, and Reliability is four times as important as Service. Therefore, Cost is one-half as important as Quality and Service is one-fourth as important as Reliability.

An example of computations for the **Cost row** in matrix A_{norm} is as follows:

$$\text{Cost criterion} = \frac{1}{(1 + 1 + 2 + 3)} = 0.143$$

$$\text{Service criterion} = \frac{1}{(1 + 1 + 3 + 4)} = 0.111$$

$$\text{Quality criterion} = \frac{1/2}{(1/2 + 1/3 + 1 + 2)} = 0.130$$

$$\text{Reliability criterion} = \frac{1/3}{(1/3 + 1/4 + 1/2 + 1)} = 0.480$$

Computing w_{max} for Criterion:

$$w_1 = \frac{0.143 + 0.111 + 0.130 + 0.160}{4} = 0.136$$

$$w_2 = \frac{0.143 + 0.111 + 0.087 + 0.120}{4} = 0.115$$

$$w_3 = \frac{0.286 + 0.333 + 0.261 + 0.240}{4} = 0.280$$

$$w_4 = \frac{0.429 + 0.444 + 0.522 + 0.480}{4} = 0.469$$

$\therefore w^T$ = The priority vector for **Criterion** is: [0.136 0.115 0.280 0.469]

The next step is to perform pairwise comparisons of suppliers with respect to each criterion, beginning with Cost, as shown in Table 2. These comparisons result in a priority vector (w^c) and consistency ratio (CR) for the Cost criterion. The CR evaluates the consistency of the pairwise comparisons by comparing the consistency index with a random index

For Cost:

Table 2

Pairwise comparisons related to Cost.

	Cost	Supplier A	Supplier B	Supplier C
A =	Supplier A	1	2	3
	Supplier B	1/2	1	2
	Supplier C	1/3	1/2	1
	Cost	Supplier A	Supplier B	Supplier C
A_{norm} =	Supplier A	0.545	0.571	0.500
	Supplier B	0.273	0.286	0.333
	Supplier C	0.182	0.143	0.167

For example, the management team believes that Supplier A is two times as important as Supplier B in terms of Cost. In turn, Supplier B is deemed one-half as important as Supplier A.

Computing w_{max} for **Cost**:

$$w_1 = \frac{0.545 + 0.571 + 0.500}{3} = 0.539$$

$$w_2 = \frac{0.273 + 0.286 + 0.333}{3} = 0.297$$

$$w_3 = \frac{0.182 + 0.143 + 0.167}{3} = 0.164$$

$\therefore$ The priority vector for **Cost** (w^c) is: [0.539 0.297 0.164], with CR = 0.0052, indicating very good consistency in top management's judgments of all three suppliers in terms of paper cost. CR computations can be found in the Appendix.

Pairwise comparisons of each supplier with respect to Service are displayed in Table 3:

Table 3

Pairwise comparisons related to Service.

	Service	Supplier A	Supplier B	Supplier C
A =	Supplier A	1	2	4
	Supplier B	1/2	1	3
	Supplier C	1/4	1/3	1
	Service	Supplier A	Supplier B	Supplier C
A_{norm} =	Supplier A	0.571	0.600	0.500
	Supplier B	0.286	0.300	0.375
	Supplier C	0.143	0.100	0.125

For example, the management team believes Supplier A is four times as preferable as Supplier C in terms of Service criterion. Conversely, Supplier C is considered one-fourth as preferable as Supplier A.

Computing w_{max} for **Service**:

$$w_1 = \frac{0.571 + 0.600 + 0.500}{3} = 0.557$$

$$w_2 = \frac{0.286 + 0.300 + 0.375}{3} = 0.320$$

$$w_3 = \frac{0.143 + 0.100 + 0.125}{3} = 0.123$$

∴ The priority vector for **Service** (w^s) is: [0.557 0.320 0.123], with CR = 0.0156, indicating very good consistency in top management's judgments of all three suppliers with respect to service criterion.

Pairwise comparisons of each supplier with respect to Quality is given in Table 4:

Table 4

Pairwise comparisons related to Quality.

	Quality	Supplier A	Supplier B	Supplier C
A =	Supplier A	1	1	3
	Supplier B	1	1	2
	Supplier C	1/3	1/2	1
	Quality	Supplier A	Supplier B	Supplier C
A_{norm} =	Supplier A	0.429	0.400	0.500
	Supplier B	0.429	0.400	0.333
	Supplier C	0.142	0.200	0.167

As an example, in terms of Quality, top management believes that Supplier A is three times as preferable as Supplier C. Accordingly, Supplier C is one-third as preferable as Supplier A.

Computing w_{max} for **Quality**:

$$w_1 = \frac{0.429 + 0.400 + 0.500}{3} = 0.443$$

$$w_2 = \frac{0.429 + 0.400 + 0.333}{3} = 0.387$$

$$w_3 = \frac{0.142 + 0.200 + 0.167}{3} = 0.170$$

∴ The priority vector for **Quality** (w^Q) is: [0.443 0.387 0.170], with CR = 0.0156, indicating very good consistency in top management's judgments of all three suppliers in terms of quality. Pairwise comparisons of each supplier with respect to Reliability is given in Table 5:

Table 5

Pairwise comparisons related to Reliability.

	Reliability	Supplier A	Supplier B	Supplier C
A =	Supplier A	1	1/2	4
	Supplier B	2	1	4
	Supplier C	1/4	1/4	1
	Reliability	Supplier A	Supplier B	Supplier C
A_{norm} =	Supplier A	0.308	0.286	0.444
	Supplier B	0.615	0.571	0.444
	Supplier C	0.077	0.143	0.112

For example, the management team believes that Supplier B is two times as preferable as Supplier A in terms of Reliability. Conversely, Supplier A is deemed one-half as preferable as Supplier B.

Computing w_{max} for Reliability:

$$w_1 = \frac{0.308 + 0.286 + 0.444}{3} = 0.346$$

$$w_2 = \frac{0.615 + 0.571 + 0.444}{3} = 0.543$$

$$w_3 = \frac{0.077 + 0.143 + 0.112}{3} = 0.111$$

∴ The priority vector for **Reliability** (w^R) is [0.346 0.543 0.111], with CR = 0.0460, indicating very good consistency in top management's judgments of all three suppliers in terms of reliability.

3. Results

3.1 Supplier Scores versus Each Criterion

The AHP "score" for each paper supplier regarding each criterion is shown in Table 6. The values come from the priority vectors for each criterion.

Table 6

AHP Weight Scores of Each Supplier vs. Each Criterion.

Criterion	Supplier A	Supplier B	Supplier C
Cost	0.539	0.297	0.164
Service	0.557	0.320	0.123
Quality	0.443	0.387	0.170
Reliability	0.346	0.543	0.111

By synthesizing objective weights with the scores of each criterion on the overall objective, we obtain:

Supplier A overall score = $0.136(0.539) + 0.115(0.557) + 0.280(0.443) + 0.469(0.346) = 0.424$ (#2)

Supplier B overall score = $0.136(0.297) + 0.115(0.320) + 0.280(0.387) + 0.469(0.543) = 0.440$ (#1)

Supplier C overall score = $0.136(0.164) + 0.115(0.123) + 0.280(0.170) + 0.469(0.111) = 0.136$ (#3)

Based on an overall score of 0.440, Supplier B is selected as the best paper supplier by Knox Box, followed by Supplier A, with an overall score of 0.424. Supplier C was subsequently removed as an approved supplier to Knox Box.

3.2 Checking for Consistency

Checking for overall consistency follows a four-step process, as follows:

Step 1: Compute Aw^T

$$Aw^T = \begin{matrix} & \begin{matrix} A \end{matrix} & \begin{matrix} w^T \end{matrix} & \begin{matrix} Aw^T \end{matrix} \\ \begin{matrix} 1 \\ 1 \\ 2 \\ 3 \end{matrix} & \begin{pmatrix} 1 & 1 & 1/2 & 1/3 \\ 1 & 1 & 1/3 & 1/4 \\ 2 & 3 & 1 & 1/2 \\ 3 & 4 & 2 & 1 \end{pmatrix} & \begin{pmatrix} 0.136 \\ 0.115 \\ 0.280 \\ 0.469 \end{pmatrix} & = & \begin{pmatrix} 0.5472 \\ 0.4615 \\ 1.1315 \\ 1.8970 \end{pmatrix} \end{matrix}$$

Step 2: Compute

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{\text{ith entry in } Aw^T}{\text{ith entry in } w^T}$$

$$\lambda_{max} = \frac{1}{4} \left\{ \frac{0.5472}{0.136} + \frac{0.4615}{0.115} + \frac{1.1315}{0.280} + \frac{1.8970}{0.469} \right\} = 4.0306$$

Step 3: Computing the consistency index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.0306 - 4}{3} = 0.0102$$

Step 4: Compare CI to Random Index (RI) and check whether judgments are consistent.

With $n = 4$ criteria (Cost, Service, Quality, and Reliability), the Random Index value from Table 7 is 0.90.

Table 7

Random Index (RI) Values by Saaty [22]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

$$CR = \frac{CI}{RI} = \frac{0.0102}{0.90} = 0.0113$$

4. Conclusions

The objective of this case study is to select the top two paper suppliers from three available suppliers for a corrugated box company. This is because of economies of scale on future paper purchases (based on higher volume purchases) and more consistent quality sheet stock by eliminating one supplier. Using the AHP process to distinguish the two best paper suppliers, Supplier A (score = 0.425) and Supplier B (score = 0.410) should be retained, while Supplier C (score = 0.165) should be removed as an approved supplier.

The degree of consistency is satisfactory if $CR < 0.10$ and there is very good consistency if $CR < 0.05$ [23]. Conversely, if $CR > 0.10$, this is considered unacceptable consistency, in which the judgments should be reviewed. In our case study, $CR = 0.0113 < 0.05$. Hence, we conclude that top management's judgments have very good consistency with respect to the four criteria determined. In future studies, AHP extensions can be applied [].

Author Contributions

Conceptualization, H.K. and R.K.; methodology, H.K. and R.K.; software, R.K.; validation, H.K., Z.S., A.H., P.B., and R.K.; formal analysis, H.K., Z.S., A.H., P.B., and R.K.; investigation, R.K.; resources, R.K.; data curation, R.K.; writing—original draft preparation, H.K. and R.K.; writing—review and editing, Z.S., A.H., P.B., R.K.; visualization, R.K.; supervision, R.K.; project administration, R.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The dataset generated and analyzed during the current study are available in the FigShare repository, <https://doi.org/10.6084/m9.figshare.33207945>

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Consistency ratio (CR) computations for all four criteria can be found below.

For **Cost**:

	A_c			w^c	$A_c w^c$
Cost	Supplier A	Supplier B	Supplier C		
Supplier A	1	2	3	0.539	1.6250
Supplier B	1/2	1	2	0.297	0.8945
Supplier C	1/3	1/2	1	0.164	0.4920

$$\lambda_{max} = \frac{1}{3} \left\{ \frac{1.6250}{0.539} + \frac{0.8945}{0.297} + \frac{0.4920}{0.164} \right\} = 3.0089$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.0089 - 3}{2} = 0.0030$$

Table 7

Random Index (RI) Values by Saaty [22]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

$$CR = \frac{CI}{RI} = \frac{0.0030}{0.58} = 0.0052$$

For **Service**:

	A_s			w^s	$A_s w^s$
Service	Supplier A	Supplier B	Supplier C		
Supplier A	1	2	4	0.557	1.6890
Supplier B	1/2	1	3	0.320	0.9675
Supplier C	1/4	1/3	1	0.123	0.3688

$$\lambda_{max} = \frac{1}{3} \left\{ \frac{1.6890}{0.557} + \frac{0.9675}{0.320} + \frac{0.3688}{0.123} \right\} = 3.0180$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.0180 - 3}{2} = 0.0090$$

$$CR = \frac{CI}{RI} = \frac{0.0090}{0.58} = 0.0156$$

For Quality:

	A_Q			w^Q		$A_Q w^Q$
Quality	Supplier A	Supplier B	Supplier C			
Supplier A	1	1	3	0.443	=	1.3400
Supplier B	1	1	2	0.387		1.1700
Supplier C	1/3	1/2	1	0.170		0.5110

$$\lambda_{max} = \frac{1}{3} \left\{ \frac{1.3400}{0.443} + \frac{1.1700}{0.387} + \frac{0.5110}{0.170} \right\} = 3.0180$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.0180 - 3}{2} = 0.0090$$

$$CR = \frac{CI}{RI} = \frac{0.0090}{0.58} = 0.0156$$

For Reliability:

	A_R			w^R		$A_R w^R$
Reliability	Supplier A	Supplier B	Supplier C			
Supplier A	1	1/2	4	0.346	=	1.0615
Supplier B	2	1	4	0.543		1.6790
Supplier C	1/4	1/4	1	0.111		0.3333

$$\lambda_{max} = \frac{1}{3} \left\{ \frac{1.0615}{0.346} + \frac{1.6790}{0.543} + \frac{0.3333}{0.111} \right\} = 3.0533$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.0533 - 3}{2} = 0.0267$$

$$CR = \frac{CI}{RI} = \frac{0.0267}{0.58} = 0.0460$$