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Analytic hierarchy process to assess and optimize distribution network

Mithun J. Sharma [a,*], Ilkyeong Moon [b], Hyerim Bae [b]

[a] *Logistics Information Technology, Pusan National University, Busan 609 735, South Korea*
[b] *Department of Industrial Engineering, Pusan National University, Busan 609 735, South Korea*

Abstract

Effective supply chain distribution network design needs to consider various performance dimensions and product characteristics. Recently, researchers have begun to realize that the decision and integration effort in supply chain design should be driven by a comprehensive set of performance metrics and also product characteristics. In this paper, we relate product characteristics to optimizing supply chain delivery network design and adopt cost and service factor performance metrics as the decision criteria. An analytic hierarchy process (AHP) multi-criteria decision-making methodology is then developed to take into account both qualitative and quantitative factors in the best delivery network design selection. By using AHP methodology we could optimize the selection of delivery network design followed by relevant choices for decision making of Home plus distribution center.

Keywords: Analytic hierarchy process; Distribution network; Supply chain; Multi-criteria decision-making

1. Introduction

A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request. The supply chain not only includes the manufacturer and suppliers, but also transporters, warehouses, retailers, and customers themselves [1]. This chain is traditionally characterized by the flow of materials and information both within and between business entities. Network design decisions are among the most important supply chain decisions as their implications are significant and long lasting. Distribution refers to the steps taken to move and store a product from the supplier stage to a customer stage in the supply chain. Distribution is a key driver of the overall profitability of a firm because it directly impacts both the supply chain cost and the customer experience. Good distribution can be used to achieve a variety of supply chain objectives ranging from low cost to high responsiveness. As a result, companies in the same industry often select very different distribution networks [1]. A network designer needs to consider product characteristics as well as network

* Corresponding author.
E-mail address: mithun@pusan.ac.kr (M.J. Sharma).

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requirements when deciding on the appropriate delivery network. There are various network designs each with their own strengths and weaknesses. Hence choosing the best delivery network design or a combination of design is a major challenge for the decision maker. Research in the design category involves contributions from different disciplines. Design of the supply chain determines its structure, i.e., it focuses on the location of decision spots and the objectives of the design [2–6]. Design of the chain should be able to integrate the various elements of the chain and should strive for the optimization of the chain rather than the entities or group of entities. Information sharing and its control play a vital role in integration of the different elements of the chain and require highly coordinated efforts of both engineers and managers [7–10]. Design needs to focus primarily on the objectives and not just the development of tools used in decision making. This paper primarily deals with the design/selection of an appropriate supply chain configuration to achieve optimal performance, which is measured using a set of metrics.

2. Background

2.1. Performance metrics and product characteristics for network design options

When considering distribution between any other pair of stages, such as supplier to manufacturer, many options pop up. According to Chopra and Meindl [1] there are two key decisions when designing a distribution network:

(a) Will product be delivered to the customer location or picked up from a preordained site?
(b) Will product flow through an intermediary (or intermediate location)?

Based on the choices for the two decisions, there are six distinct distribution network designs that are classified as follows:

1. Manufacturer storage with direct shipping.
2. Manufacturer storage with direct shipping and in-transit merge.
3. Distributor storage with package carrier delivery.
4. Distributor storage with last mile delivery.
5. Manufacturer/distributor storage with customer pickup.
6. Retail storage with customer pickup.

The characteristics of the distribution network are summarized in Table 1.

A network designer needs to consider product characteristics as well as network requirements when deciding on the appropriate delivery network. The various networks have different strengths and weaknesses. The combination used depends on product characteristics and needs of the customer. In order to remain competitive, the performance measure needs to be considered when designing distribution network. At the highest level, performance of a distribution network should be evaluated keeping the companies' objective in mind. In general it can be evaluated along two dimensions:

Table 1
Summary of the characteristics of different distribution network design

Types of distribution network designs	Characteristics
Manufacturer storage with direct shipping	Product is shipped directly from the manufacturer to the customer
Manufacturer storage with direct shipping and in-transit merge	Consolidates the order from different locations to deliver to one customer
Distributor storage with package carrier delivery	Delivery by packaged carriers from distributors/retailers warehouses
Distributor storage with last mile delivery	Delivery by distributor/retailer to customer instead of packaged carrier
Manufacturer/distributor storage with customer pickup	Customers collect their online/phone orders from pickup points
Retail storage with customer pickup	Customers collect their online/phone orders from retail outlets

(a) Customer needs that are met.
(b) Cost of meeting customer needs.

Thus, a firm must evaluate the impact of customer service and cost as it compares different distribution network options.

Most decision makers make qualitative analysis such as balanced score card (BSC) to design the distribution network. Through their experience and intuition they select a combination of these network designs. But there is no research so far in optimizing the designs objectively so as to make feasible decisions whether it is a single or combination of selections. To achieve this goal we propose to use multi-criteria decision-making tool known as analytical hierarchy process (AHP) [11].

2.2. Analytic hierarchy process (AHP)

AHP is a decision-making tool that can help describe the general decision operation by decomposing a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives [12]. AHP can be used in making decisions that are complex, unstructured, and contain multiple attributes [13]. The decisions that are described by these criteria do not fit in a linear framework; they contain both physical and psychological elements [14]. AHP provides a method to connect that can quantify the subjective judgment of the decision maker in a way that can be measured. In applying AHP to benchmarking, Partovi [13] describes the process in three broad steps: the description of a complex decision problem as a hierarchy, the prioritization procedure, and the calculation of results. AHP is a method of breaking down a complex, unstructured situation into its components parts, arranging these parts or judgments on the relative importance of each variable, and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation [12]. A problem is put into a hierarchical structure with level-I reflecting the overall goal or focus of the decision. Level-II contains factors or criteria for the decision, level-III contains sub-factors, and level-IV contains the decision options. The prioritization process is accomplished by assigning a number from a scale developed by Saaty [12] to represent the importance of the criteria. A matrix with pair-wise comparisons of these attributes provides the means for calculation.

3. Method application and results

More and more researchers are realizing that AHP is an important generic method and are applying it to various manufacturing areas [15–19]. In addition to the wide application of AHP in manufacturing areas, recent research and industrial activities of applying AHP on other selection problems are also quite active [20–23]. AHP has thus been successfully applied to a diverse array of problems. The process proposed in this study is for selecting the optimal distribution network design in terms of performance metrics and product characteristics. The importance of decisions in the role of distribution within a supply chain helps us to identify factors that are vital when designing a distribution network. Distribution refers to the steps taken to move and store a product from a supplier stage to a customer stage in a supply chain. Distribution is key driver of the overall profitability of a firm because it affects both supply chain cost and customer experience. Therefore, appropriate distribution network can be used to achieve a variety of supply chain objectives ranging from low cost to high responsiveness [1]. In this project, we have conducted a case study for Home plus Distribution center. Home plus is a retail mart in South Korea with two distribution centers, one located in north western part and the other in south eastern part. Home plus distributes directly to these two large distribution centers while obligating small distributors to buy from these two large distributors. Products move directly to these two distribution chains, but move through an additional stage when going to smaller markets. Home plus decision makers want to re-engineer the distribution network and want to select the best distribution network from a set of network design options. Furthermore, they need justification for the selections. Usually firms can make many different choices when designing their distribution network. A poor distribution network can hurt the level of service that customer receives while increasing the cost. An inappropriate network can have significant negative effect on the profitability of the firm and can even lead to failure. The appropriate choice of

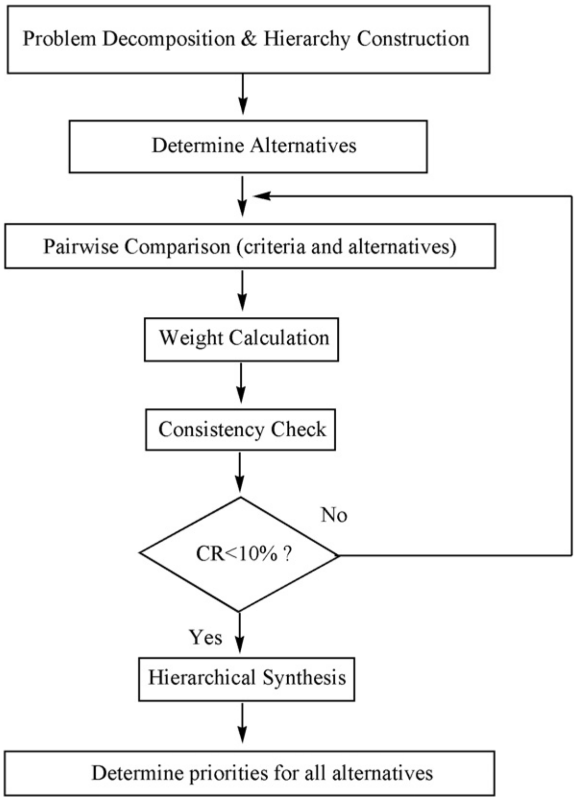

Fig. 1. Schematic representation of the methodology.

distribution network results in customer needs satisfied at the lowest possible cost. The decision makers of Home plus pointed out a couple of distribution network designs such as 'manufacture storage with in-transit merge', 'manufacture storage with pickup', and 'retail storage with customer pickup'. The characteristics of these distribution networks are supplied in Table 1. The decision makers want to prioritize performance metrics based on cost and service factor for evaluation of the optimal network design. For cost factor we consider inventory, transportation and facilities and handling. Therefore, at this evaluation criterion focus should be on reducing cost while keeping the service factor constant. Next for customer demand, to satisfy customers, response time and product variety becomes priority. Based on the two priorities – cost factor and service factor, Home plus wants to design the best distribution network among the provided options. A ranking of these designs can help the decision maker to choose easily the best design or a combination of designs instead of picking a wrong design (often obtained from subjective analysis) that may lead to inefficiency and loss. A schematic representation of the methodology is given in Fig. 1. At first we consider the evaluation in terms of performance metrics followed by product characteristics. The process proposed for selecting the optimal network comprises the following steps:

Step 1: Define the evaluative criteria used to select the optimal distribution network
Administrators and managers from Home Plus mart were interviewed in which two evaluation criteria and five evaluation sub-criteria were incorporated. Each criterion was defined in terms of performance (Table 2). Fig. 2 schematically illustrates the developed AHP model for performance metrics hierarchy.

Step 2: Establish each factor of the pair-wise comparison matrix
In this step, the elements of a particular level are compared pair-wise, with respect to a specific element in the immediate upper level. A judgment matrix is formed and used for computing the priorities of the corresponding elements. First, a criterion is compared pair-wise with respect to the goal. The judgment

matrix, denoted as A, will be formed using the comparison. Let $A_1, A_2, \ldots, A_n$ be the set of stimuli. The quantified judgments on pairs of stimuli A_i, A_j are represented by

$$A = [a_{ij}], \quad i,\ j = 1, 2 \ldots, n. \tag{1}$$

The comparison of any two criteria C_i and C_j with respect to the goal is made using the questions of the type: of the two criteria C_i and C_j which is more important and how much. Saaty [11] suggests the use of a nine-point scale to transform the verbal judgments into numerical quantities representing the values of a_{ij}. Table 3 lists the definition of nine-point scale. Larger number assigned to the pair-wise comparisons means larger differences between criteria levels. The entries a_{ij} are governed by the following rules:

$$a_{ij} > 0, \quad a_{ji} = 1/a_{ij}, \quad a_{ii} = 1 \text{ for all } i. \tag{2}$$

This scale can be applied with ease to criteria that can be defined numerically as well as to those cannot be defined numerically. Relative importance scale is presented. The decision maker is supposed to specify their judgments of the relative importance of each contribution of criteria towards achieving the overall goal.

Table 2
Performance type for defining criteria and sub-criteria type

	Code name	Performance definition
Criteria		
Cost factor	C_f	Cost of meeting customer needs
Service factor	C_s	Customer needs that are met
Sub-criteria		
Inventory	C_i	To decrease cost
Transportation	C_t	To decrease cost
Facilities and handling	C_{fh}	To decrease cost
Response time	C_r	Customer satisfaction
Product variety	C_p	Customer satisfaction

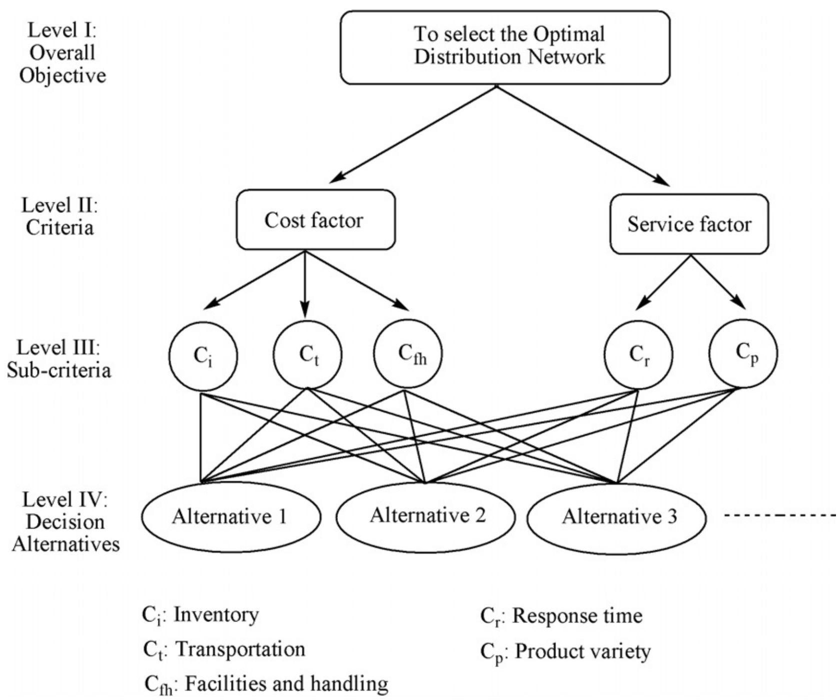

Fig. 2. Proposed AHP model for performance metrics hierarchy.

Table 3
Pair-wise comparison scale [11]

Intensity of importance	Definition
1	Equal importance of both elements
3	Weak importance one element over another
5	Essential or strong importance one element over another
7	Demonstrated importance one element over another
9	Absolute importance one element over another
2, 4, 6, 8	Intermediate valued between two adjacent judgments

Step 3: Calculate the eigenvalue and eigenvector

Having recorded the numerical judgments a_{ij} in the matrix A, the problem now is to recover the numerical weights $(W_1, W_2, \ldots, W_n)$ of the alternatives from this matrix. In order to do so, consider the following equation:

$$\begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ldots & \vdots \\ \vdots & \vdots & \ldots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix} \cong \begin{bmatrix} W_1/W_1 & W_1/W_2 & \ldots & W_1/W_n \\ W_1/W_1 & W_1/W_2 & \ldots & W_1/W_n \\ \vdots & \vdots & \ldots & \vdots \\ \vdots & \vdots & \ldots & \vdots \\ W_n/W_1 & W_n/W_2 & \ldots & W_n/W_n \end{bmatrix} \tag{3}$$

Moreover, let us multiply both matrices in Eq. (3) on the right with the weights vector $W = (W_1, W_2, \ldots, W_n)$, where W is a column vector. The result of the multiplication of the matrix of pair-wise ratios with W is nW, hence it follows:

$$AW = nW. \tag{4}$$

This is a system of homogenous linear equations. It has a non-trivial solution if and only if the determinant of $A - nI$ vanishes, that is, n is an eigenvalue of A. I is an $n \times n$ identity matrix. Saaty's method computes W as the principal right eigenvector of the matrix A; that is,

$$AW = \lambda_{\max} W, \tag{5}$$

where $\lambda_{\max}$ is the principal eigenvalue of the matrix A. If matrix A is a positive reciprocal one then $\lambda_{\max} \geqslant n$ [12]. If A is a consistency matrix, eigenvector X can be calculated by

$$A - (\lambda_{\max} I)X = 0. \tag{6}$$

Here, using the comparison matrix, the eigenvectors were calculated by Eqs. (5) and (6).
Table 4 summarizes the results of the eigenvectors for criteria, sub-criteria, and distribution network design. Besides, the results for each level relative weight of the elements are shown in Table 4.

Step 4: Perform the consistency test

The eigenvector method yields a natural measure of consistency. Saaty [12] defined the consistency index (CI) as

Table 4
Weights of criteria, sub-criteria, and choices

Criteria	Weights	Sub-criteria	Weights	Manufacture storage with in-transit merge	Manufacture storage with customer pickup	Retail storage with customer pickup
C_f	0.667	C_i	0.151	0.280	0.584	0.135
		C_t	0.796	0.415	0.779	0.180
		C_{fh}	0.051	0.766	0.158	0.758
C_s	0.333	C_r	0.900	0.091	0.909	0.818
		C_p	0.100	0.585	0.280	0.134

Table 5
Comparison matrix of relative weight among alternatives (metrics)

Ranking	Category	Relative weight
1	Manufacture storage with customer pickup	1.000
2	Retail storage with customer pickup	0.702
3	Manufacture storage with in-transit merge	0.240

$$\mathrm{CI} = \lambda_{\max} - n/(n-1), \tag{7}$$

where $\lambda_{\max}$ is the maximum eigenvalue and n is the number of factors in the judgment matrix. Accordingly, Saaty [12] defined the consistency ratio (CR) as

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{8}$$

for each size of matrix n, random matrices were generated and their mean CI value, called the random index (RI). Where RI represents the average consistency index over numerous random entries of same order reciprocal matrices. The consistency ratio CR is a measure of how a given matrix compares to a purely random matrix in terms of their consistency indices. A value of the consistency ratio $\mathrm{CR} \leqslant 0.1$ is considered acceptable. Larger values of CR require the decision-maker to revise his judgments.Results of the consistency test and the CR of the comparison matrix from the available interview and previous data are all $\leqslant 0.1$, indicating 'consistency'.

Step 5: Calculate the overall level hierarchy weight to select the distribution network design

The composite priorities of the alternatives are then determined by aggregating the weights throughout the hierarchy. The composite priorities of the alternatives are shown in Table 5 and Fig. 3. According to Table 5, ''manufacture storage with customer pickup'' is optimal design network selection for the Home plus distribution center in terms of performance metrics.

3.1. Evaluation of distribution network design in terms of product characteristics

Following the same preceding procedure, in this phase we propose to obtain the best distribution network design with respect to product characteristics. In this case we do not have the sub-category as was the case in the previous example. The four criteria we selected are – 'high demand product', 'medium-demand product', 'many product sources', and 'high product variety'. Fig. 4 diagrammatically illustrates the developed AHP model for product characteristics.

The priorities for criteria and alternatives are shown in Table 6. Besides, the results for criteria and alternatives relative weight of the elements are shown in Table 6.

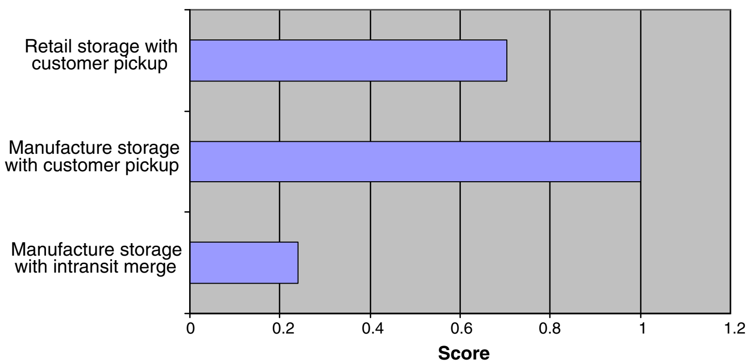

Fig. 3. Score graph for delivery network selection in terms of metrics.

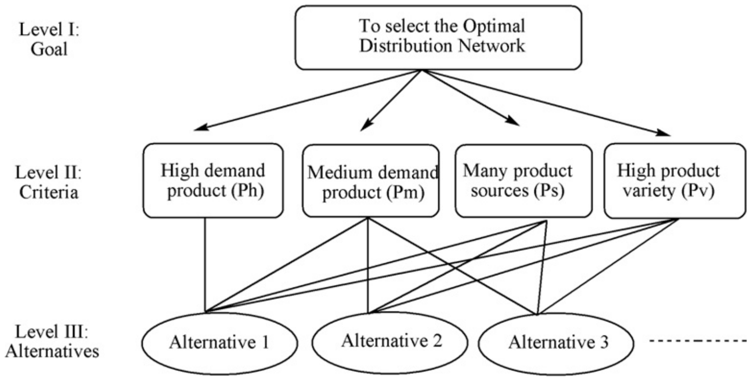

Fig. 4. Proposed AHP model for product characteristics hierarchy.

Table 6
Weights of criteria and alternatives

Criteria	Weights	Manufacture storage with in-transit merge	Manufacture storage with pickup	Retail storage with customer pickup
P_h	0.162	0.091	0.091	0.818
P_v	0.489	0.223	0.321	0.454
P_s	0.190	0.123	0.203	0.673
P_m	0.157	0.148	0.160	0.690

Table 7
Comparison matrix of relative weight among alternatives (product)

Ranking	Category	Relative weight
1	Retail storage with customer pickup	1.000
2	Manufacture storage with customer pickup	0.398
3	Manufacture storage with in-transit merge	0.298

The composite priorities of the alternatives are shown in Table 7 and Fig. 5. "Retail storage with customer pickup" is optimal design network selection for the Home plus distribution center in terms of product demand.

Home plus wants to select the best distribution design based on product characteristics that can provide high availability levels of relatively common but varied demand products. They provided the same distribution network design options with the previous case.

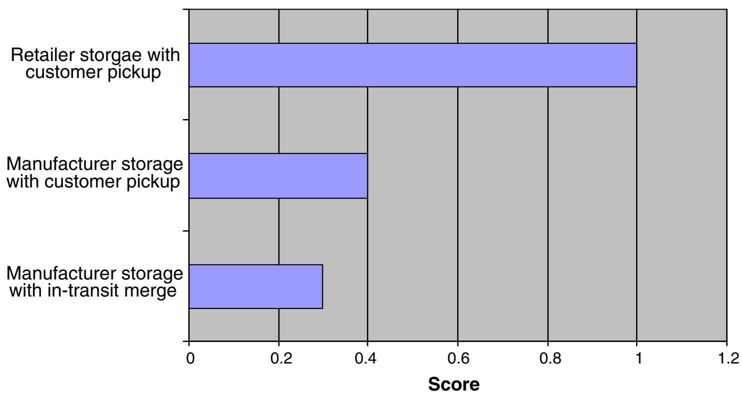

Fig. 5. Score graph for delivery network selection in terms of product.

Table 8
Selection of decision-making results

Results	Distribution network designs	
	AHP rating (weight)	Final decision
Performance metrics		
MS in-transit merge	0.240	Choose MS storage customer pickup
MS storage customer pickup	1.000	
RS customer pickup	0.702	
Product characteristics		
MS in-transit merge	0.298	Choose RS customer pickup
MS storage customer pickup	0.398	
RS customer pickup	1.000	

MS: manufacture storage and RS: retail storages.

Analyses performed using the proposed methodology for the two cases and results obtained, Home plus can now select the distribution network design/s from its given options.

Referencing the analyses results from Table 8, Home plus can opt to use a combination of two distribution network designs (manufacture storage pickup in terms of performance and retail storage customer pickup in terms of product characteristics) to achieve its objectives. According to the given options by the decision makers of Home plus, we provided network that is tailored to match the characteristics of product and performance along with the needs of the customers. From the analysis, fast moving and emergency items can be stocked locally at the small distributors and customers can either pick them up or have them shipped depending on the urgency. Slower moving items can be stocked at the two large distribution centers and shipped to the customer within a day or two. We also see that the performance characteristics of a network with manufacture storage with pickup can lower delivery costs and provide a faster response time than other networks. Thus the hybrid network recommended for Home plus can match the characteristics of product and the needs of customer.

4. Conclusion

The case study presented above illustrated how multiple criteria (e.g. level-I performance metrics) can be included in the AHP approach to permit a more flexible and inclusive use of data in a decision on distribution network design selection. It has also been demonstrated how the AHP weighting can be compared against factors in the distribution network design selection process. The AHP methodology can select the best set of multiple distribution networks to satisfy profitability and customer satisfaction.

As the preceding examples illustrate, firms can make many different choices when designing their distribution network. A poor distribution network can hurt the level of service that customers receive while increasing the cost. An inappropriate network can have significant negative effect on the profitability of the firm. The appropriate choice of distribution network results in customer needs being satisfied at the lowest possible cost.

This study illustrated the use of a multi-criteria technique, namely AHP. AHP can combine quantitative and qualitative factors to handle different groups of actors, and to combine the opinions of many experts. Selecting a distribution network is extremely complex, and often relies on the subjective assessment of decision makers. Particularly, administrators in some companies lack objective decision-making procedures and clearly defined evaluation criteria. The proposed AHP-based algorithm significantly contributes to optimizing distribution network selection process. Specifically, the proposed algorithm can assist decision makers in solving similar multi-criteria problems by offering an objective and systematic method of selecting the network design in terms of cost and service factors. Finally, the proposed procedure enables managers to adjust a combination of network design to eliminate risk and to enhance service quality and profitability. This study could identify the characteristics and criterion that affect the final result of distribution network design process; therefore, this study could effectively select the best distribution network, results in customer needs being satisfied at the lowest possible cost.

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References

[1] S. Chopra, P. Meindl, Supply Chain Management: Strategy, Planning, Operation, Prentice Hall, NJ, 2001.
[2] B.C. Arntzen, G.G. Brown, T.P. Harrison, L. Trafton, Global supply chain management at digital equipment corporation, Interfaces 25 (1995).
[3] D. Berry, M.M. Naim, Quantifying the relative improvements of redesign strategies in a PC supply chain, Int. J. Prod. Econ. 46–47 (1996).
[4] M. Mourits, J.J. Evers, Distribution network design, Int. J. Phys. Dist. Log. Manage. 25 (1995).
[5] C.S. Revelle, G. Laporte, The plant location problem: new models and research prospects, Oper. Res. 44 (1996).
[6] D.R. Towill, N.M. Naim, J. Wikner, Industrial dynamics simulation models in the design of supply chains, Int. J. Phys. Dist. Log. Manage. 22 (1997).
[7] M.L. Fisher, A. Raman, Reducing the cost of demand uncertainty through accurate response to early sales, Oper. Res. 44 (1996).
[8] H.L. Lee, V. Padmanabhan, S. Whang, Information distortion in a supply chain: the bullwhip effect, Manage. Sci. 43 (1997).
[9] K. Moinzadeh, P.K. Aggarwal, An information based multi-echelon inventory system with emergency orders, Oper. Res. 45 (1997).
[10] K. Srinivasan, S. Kekre, T. Mukhopadhyay, Impact of electronic data interchange technology on JIT shipments, Manage. Sci. 40 (1994).
[11] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, NY, 1980.
[12] T.L. Saaty, Decision Making for Leaders, RWS Publications, PA, 1990.
[13] F.Y. Partovi, Determining what to benchmark: an analytic hierarchy process approach, Int. J. Oper. Proj. Manage. 14 (1994).
[14] S.A. Mian, C.X. Dai, Decision making over the project life cycle: an analytical hierarchy approach, J. Proj. Manage. 30 (1) (1999).
[15] A.A. Andijani, M. Anwarul, Manufacturing blocking discipline: a multi-criterion approach for buffer allocations, Int. J. Prod. Econ. 51 (1997) 3.
[16] F.T.S. Chan, B. Jiang, N.K.H. Tang, Development of intelligent decision support tools to aid the design of flexible manufacturing systems, Int. J. Prod. Econ. 65 (2000) 1.
[17] D. Liu, G. Duan, N. Lei, J.S. Wang, Analytic hierarchy process based decision modeling in CAPP development tools, Int. J. Adv. Manuf. Techol. 15 (1999) 1.
[18] K. Jiang, E.M. Wicks, Integrated investment justification approach for cellular manufacturing systems using activity-based costing and the analytic hierarchy process, J. Eng. Val. Cost Anal. 2 (1999) 4.
[19] Z.C. Lin, C.B. Yang, Evaluation of machine selection by the AHP method, J. Mater. Process. Technol. 57 (1996) 3–4.
[20] M.C.Y. Tam, V.M.R. Tummala, An application of the AHP in vendor selection of a telecommunications system, Omega 29 (1997).
[21] V.S. Lai, R.P. Trueblood, B.K. Wong, Software selection: a case study of the application of the analytical hierarchical process to the selection of a multimedia authoring system, Inform. Manage. 36 (1999) 4.
[22] W.A. El-Wahed, H. Al-Hindi, Applying the analytic hierarchy process to the selection of an expert system shell, Adv. Model. Anal. 40 (1998) 2.
[23] M.J. Schniederjans, T. Garvin, Using the analytic hierarchy process and multi-objective programming for the selection of cost drivers in activity-based costing, Euro. J. Oper. Res. 100 (1997) 1.