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ARTICLE *in* EUROPEAN JOURNAL OF OPERATIONAL RESEARCH · MARCH 2002

Impact Factor: 2.36 · DOI: 10.1016/S0377-2217(01)00138-2 · Source: RePEc

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ELSEVIER

European Journal of Operational Research 137 (2002) 336–347

EUROPEAN JOURNAL OF OPERATIONAL RESEARCH

www.elsevier.com/locate/dsw

Case Study

Hub location at Digital Equipment Corporation: A comprehensive analysis of qualitative and quantitative factors

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Received 12 March 1999; accepted 22 November 2000

Abstract

The economic growth of countries in the Asia–Pacific (AP) region has caused many US-based businesses to consider the strategic initiative of setting up facilities therein. In this paper, we describe a study to locate a repair-parts warehouse for Digital Equipment Corporation, a world leader in the computer and electronics market. Digital's management was charged to consider not only the long-term strategic (or qualitative) issues typical of such problems, but they also had to ensure that any facility that is located would also be viable from a freight-cost (or quantitative) perspective. We show how the analytical network process (ANP) model combined with an optimization model can be used to conduct a comprehensive evaluation of these varied issues.

Keywords: Analytical network process; Analytical hierarchy process; Transshipment model; Service operations; Location

1. Introduction

The growth rate of emerging economies has been steadily increasing during the last decade, and is projected to exceed that of the advanced ones during the next decade. To cater to the high level of service demanded by businesses situated in this emerging economic sector, many US-based companies, especially those in the high-technology area, have been decentralizing their operations by setting up facilities internationally (i.e., near these growth regions). The issue of international facility location has, therefore, been gaining in importance as a practical and research topic (Badri, 1996; Hoffman and Schniederjans, 1994; Min, 1994a,b).

Models for the location of manufacturing units, retail outlets, distribution warehouses, and obnoxious facilities (e.g., garbage dumps, water purification plants) have been proposed and extensively studied over a few decades. Typically, the objective of these models is to deliver products/services at a minimum cost. The optimal redesign, determination, development and implementation of a domestic service-parts network considering only tangible factors such as cost is in itself a difficult problem (see Drezner, 1996). Further

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0377-2217/02/$ - see front matter
PII: S0377-2217(01)00138-2

complications associated with international facility location are geopolitical uncertainties and the complexities of international trade. While cost reduction does remain a primary factor in international facility location, the aforementioned strategic factors of the problem necessitate the evaluation of a number of intangible attributes as well. Working somewhat at cross-purposes with this necessity is the pressure on management to arrive at a timely solution that reconciles the varied opinions pertaining to the intangible factors.

Although the location of international facilities is not new any longer, the research literature that considers the unique aspects of such problems is not as extensive as their domestic counterparts. Some of the works in this area include Hoffman and Schniederjans (1994) who propose a two-stage model for international site selection. Their approach relied on goal programming only, and therefore, did not consider a number of qualitative factors relevant to this type of problem. Badri (1999) describes an analytical hierarchy process combined with goal programming for a global facility location problem. In our paper, we describe a combination of models (analytical network process (ANP) and optimization) that were utilized for making a decision to locate a distribution facility (or "hub") that stocks parts for after-market service. Our approach is conceptually similar to Badri's, but is an enhancement in two senses. First, we consider a more comprehensive set of factors. Second, by employing the ANP, we are able to also handle complexities (i.e., feedback) among the factors considered.

This problem considered in our paper arose from Digital Equipment Corporation's (Digital's) evolving service-parts business. Digital, founded in 1957 in MA (USA), is a world leader in implementing and supporting networked business solutions in multivendor environments based on high-performance platforms, and global service and support. The Corporation does business in over 100 countries, deriving more than 65% of its revenue from outside of the US. During the completion of this modeling effort, Digital had approximately 55,000 employees worldwide. Total operating revenues were over $13 billion. The Corporation directly sells, markets, and supports its products and services via multiple locations throughout the world. Arrangements with third parties, including software developers, value added resellers (VARs) and authorized distributors, are an increasingly important part of the Corporation's focus on providing complete solutions to its customers, and on expanding distribution of its products and services through indirect channels. As more of Digital's products and services are distributed through indirect channel partners, service-parts management becomes more critical.

2. Problem statement and modeling approach

2.1. Problem statement

Digital is currently faced with the issue of locating service-parts facilities internationally. Management accorded top priority to this issue, because of increased competition, and the realization of the need to provide cost-effective, quality delivery of service and of service parts to customers across the globe (US, Europe, and Asia–Pacific (AP) regions). From a solution perspective, the location problem is intractable if each and every one of the varied alternatives is to be considered in the decision-making process.

Digital used a four-level, supply-chain network, as shown in Fig. 1, for distributing its repair parts. Vendors, primarily located in the AP region, comprised the first level. They supplied parts to a central warehouse in the US. The US warehouse replenished the inventory of the AP region's stocking points, which met customer demands in their vicinity. This dual shipment of parts (i.e, from AP to US, and back to AP) was considered economical in the past. Demands of AP customers were small. Moreover, the relatively large amount of shipments to the US provided an incentive for businesses to set up good transportation services between AP and US. In fact, it was often economical for an AP vendor to ship to the US, rather than to a stocking point in a neighboring AP country. The growth in the Asian market, notwithstanding the recession that existed at that time, might have ended this anomaly. Digital's

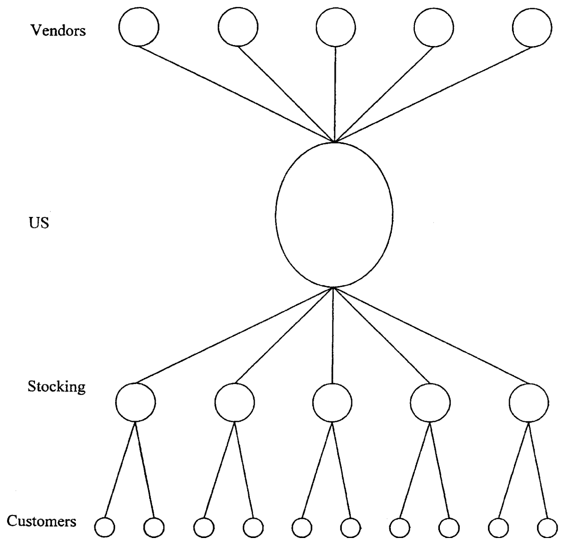

Fig. 1. Four-level supply-chain network for service parts at Digital.

management therefore decided to consider the strategic move of locating a hub for service-parts distribution in the AP region.

2.2. Modeling approach

The hub location problem of Digital was complex. There were 4000 parts and 21 potential site locations. In addition, cost was only one of the factors that needed to be considered, with the others being fiscal and political risk; accessibility; incentives for investments; and labor skills.

Our goal was to quantitatively formulate as many factors as possible, while at the same time ensuring that the resulting model was computationally tractable and also acceptable to Digital's management and its goals. In a presentation of initial issues and modeling approaches scheduled during the early stages of the project, we proposed treating parameters such as location cost, cash flows, taxes, transportation cost, and insurance cost as quantitative parameters that would be evaluated mathematically. Political, environmental, social and labor issues were proposed as qualitative parameters that would be evaluated subjectively.

While a full mathematical model of the aforementioned factors would certainly have been interesting and challenging from a theoretical perspective, it could not be implemented for a number of reasons. Data collection was started based on a rough-cut mathematical model. The data elements included such parameters as country aggregate demand, freight rates, location costs, customs rates, and tax rates. However, at that time, Digital had more than one hundred legacy systems, and this made extraction of data to be very time-consuming and costly. Thus, after a few months, data were available only for a few select countries. In fact, it was also around this time frame that Digital had tried to implement an advanced tool for inventory planning (Enator, 1994), but was not successful, because of the time and resources needed to locate and input data (incidentally, to handle such problems, Digital started implementing an enterprise system). Furthermore, despite the delay in the data collection, senior management did not extend the time to make a decision. Thus, since even the problem of selecting a set of sites that minimizes the sum of location and transportation costs is the NP-complete uncapacitated facility location model (Cornuejols et al., 1990), we knew that there was not enough time to develop effective heuristics to solve the full mathematical model.

As an alternative, we recommended the following multistaged evaluation, which was approved by management (see Fig. 2). A measured judgmental approach was used to select a site. First, a majority of the 21 potential sites were rated by managers to be deficient (i.e., below a threshold satisfying level) on one or more of the factors described above, and were, therefore, eliminated from the candidate set of sites (we were not privy

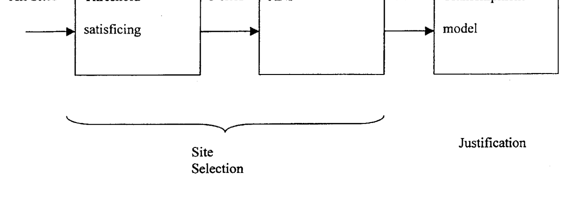

Fig. 2. Overview of multistaged modeling approach.

to this discussion). No formal model was used in this elimination process, because the decisions concerning them were so definitive that the effort in implementing a formal model was not justifiable. This process resulted in three sites that needed more rigorous evaluation. The ANP technique was then used to evaluate the qualitative factors with respect to these three sites. In ANP, pairwise comparisons (PWCs) among varying levels of factors and attributes are used to evaluate their relative importance with respect to the final decision. ANP is similar to the analytical hierarchy process technique, that has been used in the facility-location literature (Badri, 1999; Carlsson and Walden, 1995; Min, 1994a,b; Min and Melachrinoudis, 1999), but it has the advantage of being able to deal with interdependencies among factors, both within and among levels (feedback). Following this selection, a transshipment-like model was used to justify the viability of the chosen site from an operational (i.e., freight-cost) perspective. The remainder of the paper details the two models as well as the results and recommendations submitted to Digital.

3. Assessing qualitative and strategic factors

The qualitative evaluation of the factors was completed using the ANP methodology. ANP is a multiattribute, decision-making approach based on the reasoning, knowledge, experience, and perceptions of experts in the field. Even though it does not provide an optimal solution (from a cost perspective), it is valuable for decision-making involving intangible attributes that are associated with strategic factors present in this case study. ANP relies on the process of eliciting managerial inputs, which by itself allows for a structured communication of information among decision makers. In the ANP approach, the factors affecting the decision are cast into a multilevel (or hierarchical) decision *network*. Relationships (or interdependencies) can exist among factors, both within a level as well as among levels. Once modeled in a network, these interdependencies are then evaluated using a "supermatrix" approach, as outlined below (see Saaty, 1996, for details).

3.1. Applying the ANP approach

The crucial step in applying the ANP approach involves the construction of the hierarchical *decision network*. This network, in our case, has four levels. At the top level is the decision itself, while the bottom level consists of the three decision alternatives, which include the two AP locations (named AP1 and AP2) and one US location. The *factors* affecting the decision comprise the middle two levels, consisting of *clusters* and various *components* within each cluster. An initial list of factors was first adapted from the previous literature and models (e.g., Ady and Conlan, 1993; Ballou, 1992; Haug, 1985; Min, 1994a; Pietlock, 1992). Then, with the aid of managers at Digital, a regrouping and development of additional specific clusters and components was completed. For example, a financial metric such as *taxation* was one of the factors that was included in the model. This factor could have been included under the *costs* cluster, but was put under the *regulatory* cluster after regrouping. Finally, in order to keep the number of PWCs at a manageable level (see Step 1 below), the number of factors was winnowed down to those that were viewed as most important to the decision at hand. For example, for the *political risk* component, Haug (1985) provides a number of subfactors which we kept out of the ANP model, in order to limit the number of comparisons.

This type of regrouping and reduction of factors was completed through group meetings between the analysts and some of the managers. Those managers who were unavailable for attendance were sent copies of the various factors and their definitions. During the process of providing definitions, a consensus was reached on which factors to include, using face-to-face meetings, e-mail, and returned comments from managers. A number of iterations (approximately 4 to 5) was needed to make sure all the factors that needed to be included were included and that the appropriate clusters were defined. It should be pointed out that tools such as affinity diagrams and quality function deployment that are often recommended for such groupings do not lend themselves to our particular situation, because of the dispersal of the concerned managers across a wide geographic region.

This process yielded seven clusters (cost, accessibility, time, risk, regulatory, strategic, and labor clusters), and varying numbers of components within each cluster, as shown in Table 1.

To obtain the dependencies among the network's components and to provide more accurate descriptions to managers, definitions of the various factors (i.e., of the clusters and the components within each cluster) were circulated among management. Management decided that interdependencies did exist among the clusters, but that they could be ignored among the components. This determination was made because the amount of effort required for eliciting preferences for interdependency evaluation at the component level would be excessive for its benefit in adjusting the weights (see below for number of PWCs required for the current model). This development yielded the decision network shown in Fig. 3. The major difference between this network and a standard AHP hierarchy is the introduction of interdependencies among the clusters. These interdependencies are represented by arcs, shown in Fig. 3, that link the various clusters.

Table 1
Clusters and components used for the ANP model

COST	REGULATORY
Initial costs (IC)	Tax structure (TXS)
The cost of capital (TCC)	Government incentives (GI)
Operations and administrative costs (OAC)	Government restrictions (GR)
Labor cost (LC)	Trade policy (TP)
Freight rate (FR)	Repatriation allowances (RA)
ACCESSIBILITY	LABOR
Supplier accessibility (SA)	Skilled workforce (SW)
Customer accessibility (CA)	Education system (ES)
Infrastructure (IS)	Unionization (UN)
Transport services (TS)	Training support (TRS)
TIME	STRATEGIC ISSUES
Replenishment time (RT)	Competition (CO)
Delivery time (DT)	Current facilities (CF)
Start-up time (SUT)	Market size and penetration (MSP)
	Expansion capabilities (EC)
RISK	
Foreign exchange risk (FER)	
Government intervention (GI)	
Political risk (PI)	
Economic risk (ER)	
Legal risk (LR)	

The next major phase in this methodology, after the development of the network, is the evaluation of the impact of the factors on the decision. The steps in this phase are summarized as follows:
1. elicit PWCs among the entities of the network;
2. calculate relative importance of the factors ("weights");
3. form a supermatrix from the weights;
4. calculate long-term ("stable") weights from the supermatrix.

The details of these steps are given below.

Step 1: Elicit preferences. As mentioned previously, managerial input is central to the ANP decision-making process. The managers involved in our study included the Director of the AP region's field services, two key operations managers from AP, and one from headquarters. These managers were asked to make PWCs of the elements of the network (i.e., its clusters, components, and alternatives), using a nine-point scale suggested by Saaty (1980). In this scale, a value of one between two elements i and j indicates that both are equally important, whereas a score of nine indicates an overwhelming importance of i over j. Weaker importance scores are in the range 1/2–1/9 (which indicates overwhelmingly weak). Thus, given the score for an (i, j)-pair, the corresponding (j, i)-score is simply the reciprocal. The preference information was acquired by use of a survey instrument. A group face-to-face elicitation of preference weights was suggested, but scheduling difficulties made this approach infeasible. The following PWCs were made for this case study:

(i) PWCs to assess the importance of the clusters to the decision. An example question would be: "with respect to the overall decision, how much more important is Cost when compared to Strategic Issues?"

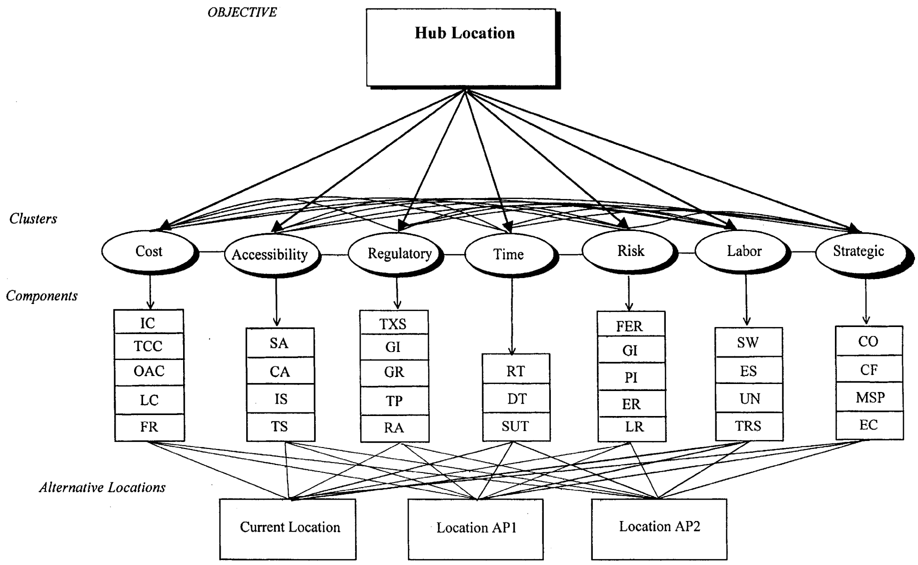

Fig. 3. The ANP network.

(ii) PWCs to assess the impact on a cluster from the other clusters (interdependencies among clusters). For example, a question to be asked could be: "how much more important is the impact of Labor on Cost when compared to the impact of Strategic Issues on Cost?"

(iii) PWCs regarding the impact of the components on its cluster. For example, "with respect to Cost, how much more important is Initial Cost when compared to Labor Cost?"

(iv) PWCs regarding the impact of the alternatives on the components (e.g., "with respect to Initial Cost, how much better is API when compared to AP2?")

Note that question set (ii) is what distinguishes the newer ANP approach from traditional AHP. Further, as can be seen, the number of PWCs may increase geometrically, depending on the assumptions made about interdependencies that exist between and within levels. In this case, if J represents the set of clusters, K_j $(j \in J)$ the set of components within cluster j, and L represents the set of alternatives, then the number of PWCs is:

$$\begin{aligned} &|J|(|J|-1)/2 + |J|(|J|-1)(|J|-2)/2 \\ &\quad + \sum_{j\in J}(|K_j|(|K_j|-1))/2 \\ &\quad + \sum_{j\in J}\sum_{k\in K_j}(|L|(|L|-1))/2. \end{aligned} \tag{1}$$

Step 2: Obtain relative importance weights

PWC matrices are formed from each set of questions. For our case study, there are a total of $1 + 2|J| + \sum_j |K_j|$ matrices. The relative weights are then computed as the unique solutions to the following eigenvalue problems:

$$\begin{aligned} &\alpha^{J,\text{decision}}\mathbf{w}^{J,\text{decision}} = \lambda^{J,\text{decision}}\mathbf{w}^{J,\text{decision}}, \\ &\alpha^{J-\{j\},j}\mathbf{w}^{J-\{j\},j} = \lambda^{J-\{j\},j}\mathbf{w}^{J-\{j\},j} \quad \text{for all } j \in J, \\ &\alpha^{K_j,j}\mathbf{w}^{K_j,j} = \lambda^{K_j,j}\mathbf{w}^{K_j,j} \quad \text{for all } j \in J, \\ &\alpha^{L,k}\mathbf{w}^{L,k} = \lambda^{L,k}\mathbf{w}^{L,k} \quad \text{for all } k \in K_j,\ j \in J, \end{aligned} \tag{2}$$

where $\alpha^{J,\text{decision}}$, $\alpha^{J-\{j\},j}$ $(j \in J)$ (the influence of a cluster on itself is ignored), $\alpha^{K_j,j}$ $(j \in J)$ and $\alpha^{L,k}$ $(k \in K_j,\ j \in J)$ are, respectively, the PWC matrices obtained from (i)–(iv) above, $\mathbf{w}$'s are the corresponding weight vectors (eigenvectors) and λ's are the corresponding largest eigenvalues.

Step 3: Supermatrix formation

Each row and respective column of the supermatrix represent an element of the decision network. The first row (and column) represents the objective or "decision" element. The next J rows (and columns) represent the clusters, the next $\sum_j |K_j|$ rows (and columns) represent the components of the clusters and the last L rows (and columns) represent the alternatives. The supermatrix is then composed of the weight vectors determined in Step 2 (see Fig. 4). Finally, to facilitate convergence (Step 4 below), Saaty recommends the addition of the interdependence of each alternative on itself. Thus an $|L| \times |L|$ identity matrix is included in the supermatrix.

Step 4: Convergence of supermatrix

Here, we first normalize the supermatrix – divide each element by its column sum – so that each column adds to one (making the supermatrix "column stochastic"). The normalized supermatrix is then raised to a significantly large power. This execution provides the converged (or stable) weights of the elements of the network on one another. The numbers of interest in the resulting supermatrix are weights of the alternatives on the decision – the last $|L|$ rows of the first column.

$$\begin{array}{c} \\ \text{Decision} \\ J \\ K_1 \\ \vdots \\ K_j \\ \vdots \\ K_{|J|} \\ L \end{array}
\begin{array}{c} \begin{array}{cccc} \text{Decision} & J & K_1 \ldots K_j \ldots K_{|J|} & L \end{array} \\
\left[\begin{array}{cccc} & & & \\ \mathbf{w}^{J,\text{decision}} & \mathbf{W}^{J-\{j\},J} & & \\ & \mathbf{W}^{K,J} & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & \mathbf{W}^{L,K} & \mathbf{I} \end{array}\right] \end{array}$$

Notes.
1. Blanks denote 0's, and **I** denotes identity.
2. $\mathbf{W}^{J-\{j\},J}$ is the submatrix $(\mathbf{w}^{J-\{1\},1}, \ldots, \mathbf{w}^{J-\{|J|\},|J|})$
3. $\mathbf{W}^{K,J}$ is a $\Sigma_j|K_j| \times |J|$ matrix whose diagonal elements are $\mathbf{w}^{K_1,1}, \ldots, \mathbf{w}^{K_{|J|},|J|}$, and whose other elements are zero
4. $\mathbf{W}^{L,K}$ is the submatrix $(\mathbf{w}^{L,k})$ for $k \in K_j$, $j \in J$

Fig. 4. The ANP supermatrix used for analyzing intangible factors.

4. ANP results

The supermatrix resulting from one of the managers is shown in Table 2. Convergence (at 10^{-4} level) occurred after raising this matrix to the 16th power. After applying this approach for the other managers, simple averaging of the weights was completed for the final evaluation, since it was assumed that the importance (i.e., knowledge, expertise, perceptions, etc.) of all managers was equal. In the case of unequal importance, instead of a simple average, a weighted average may be used. This would require the determination of the importance levels for each manager, again using the approach outlined in the previous section.

In our case study, the final results showed little variation among the three managers (see Table 3), with the average final scores being (0.409, 0.331, 0.260). These results suggest that AP1 is the preferred location.

5. Assessing impact of location on operational costs

Optimization models for site location have been proposed and studied for over three decades (e.g., [Current et al., 1990; Cornuejols et al., 1990; Drezner, 1996] give details). Typically, by minimizing the sum of the fixed costs of locating sites and the transportation costs of moving goods among sites, these models determine:

(a) the number of sites;
(b) the locations of the sites;
(c) the quantities of goods that must be transported among the sites.

In our case, however, the ANP model recommended that a facility be located in AP1; i.e., the ANP model determined (a) and (b) above. Management decided to locate a facility at AP1, as long as this decision was viable in terms of freight costs. Management also wanted to determine the proportion of the delivery to the various demand centers from the current site (US warehouse) and from the new one (question (c) above). A transshipment model was formulated to make these assessments.

Table 2
Supermatrix corresponding to one of the managers

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.056	0	0.086	0.083	0.02	0.054	0.151	0.176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.284	0.129	0	0.083	0.068	0.092	0.107	0.131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.062	0.035	0.026	0	0.07	0.096	0.09	0.035	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.141	0.034	0.042	0.083	0	0.1	0.052	0.025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.139	0.068	0.08	0.083	0.185	0	0.046	0.116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.066	0.048	0.051	0.083	0.07	0.105	0	0.016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.252	0.187	0.214	0.083	0.085	0.054	0.055	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.062	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.022	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.084	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.048	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.061	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.126	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.066	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.243	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.033	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.061	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.272	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.032	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0.262	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0.312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0.081	0.258	0.258	0.637	0.467	0.649	0.29	0.429	0.429	0.143	0.429	0.429	0.333	0.333	0.429	0.333	0.714	0.714	0.6	0.455	0.455	0.455	0.333	0.333	0.455	0.143	0.637	0.637	0.455	0.188	1	0	0
0	0	0	0	0	0	0	0	0.188	0.105	0.637	0.258	0.467	0.279	0.655	0.143	0.429	0.143	0.429	0.143	0.333	0.333	0.429	0.333	0.143	0.143	0.2	0.455	0.455	0.455	0.333	0.333	0.091	0.714	0.105	0.258	0.455	0.081	0	1	0
0	0	0	0	0	0	0	0	0.731	0.637	0.105	0.105	0.067	0.072	0.055	0.429	0.143	0.714	0.143	0.429	0.333	0.333	0.143	0.333	0.143	0.143	0.2	0.091	0.091	0.091	0.333	0.333	0.455	0.143	0.258	0.105	0.091	0.731	0	0	1

Table 3
ANP results for all three managers

	AP1	AP2	US
Manager 1	0.407	0.371	0.222
Manager 2	0.359	0.268	0.270
Manager 3	0.461	0.253	0.287
Average	0.409	0.331	0.260

The freight rates in the transportation model below are dependent on the weights of the parts in a stepwise, discrete manner. In other words, the rate is the same for a range of weights. Therefore, rather than deal with individual parts, parts were classified accordingly into six types. The model can now be given as follows.

Definitions

Let

G = (N, A) be a network with node set N and arc set A;
a_i^+ = set of arcs into node i;
a_i^- = set of arcs going away from node i;
T = set of part types;
d_{it} = demand of part type t at node i ($i \in N$, $t \in T$);
r_t = ratio of demand of part type t that can be supplied from AP;
c_{jt} = freight cost of one unit of part type t on arc j ($i \in A,\ t \in T$);
x_{jt} = number of units of part type t flowing on arc j.

Model M

$$\text{Min} \quad \sum_{t \in T} \sum_{j \in A} c_{jt} x_{jt} \tag{3}$$

subject to:

$$\sum_{j \in a_i^+} x_{jt} = \sum_{j \in a_i^-} x_{jt} + d_{it} \quad \text{for all } i \in N, \tag{4}$$

$$\sum_{j \in a_{\text{AP}}^-} x_{jt} \leqslant r_t \sum_{i \in N} d_{it}, \tag{5}$$

$$x_{jt} \geqslant 0 \quad \text{for all } j, t. \tag{6}$$

The objective in (M) is to minimize the freight costs. Constraint (4) ensures that the supply into a node equals the supply (and demand) out of it. Constraint (5) ensures that the supply of part type t from AP, as a ratio of the total demand, is less than r_t. Because the US warehouse operates on a very large scale, such constraints are not imposed on it.

6. Cost model results

Using data supplied by Digital, we conducted a sensitivity analysis of the r_t parameter on the freight-cost model, (M). This analysis was conducted for two reasons. First, management wanted to determine the potential savings attainable by implementing the recommendations of the model. The second and more important reason arose out of business compulsions. Digital had a number of outstanding contracts with vendors to supply to its US hub. Moreover, transportation services between some AP locations with other AP locations were not as fully developed as those between some AP locations and US locations. Management, therefore, felt that, no matter what the cost model recommended, it was not immediately possible to shut down the supply-chain operation from the US, and completely replace it by one from the AP hub. In other words, according to management, the shifting of operations (from US to AP) should be completed in a phased manner.

Table 4 shows the results of running the cost model for various values of r_t. The data for the model were supplied by Digital. Column 3 gives the total freight cost, column 4 gives the maximum shipment from AP1 (the right-hand side of (5) in model M), while the last two columns give the recommended shipment amounts from the US and AP1 locations, respectively.

To determine how the current practice of making all shipments from the US compares with the recommendations of the model, the cost for $r_t = 0$ is compared with that for $r_t = 1$. Table 5 shows that the cost saving was of the order of about 10%, which works out to \$1.83 million annually. Given that the current vendor base in AP will improve with the economic growth therein, these savings are expected to be higher in the long run.

Another way of looking at the results of the model is to graphically portray the costs. Fig. 5 plots the percentage savings for the different r_t

Table 4
Results of the sensitivity analysis of the freight-cost model

Part type	Ratio (r_t)	Total freight cost	Max AP shipment	Actual US shipment	Actual AP shipment
1	1.0	175490	6377	3390	2987
1	0.7	175490	4465	3390	2987
1	0.5	175490	3189	3390	2987
1	0.2	183929	1275	5102	1275
1	0.0	194307	0	6377	0
2	1.0	279735	7871	4831	3040
2	0.7	279735	5510	4785	3086
2	0.5	279735	3936	4831	3040
2	0.2	289303	6297	6197	1574
2	0.0	311934	0	7871	0
3	1.0	148140	4166	2752	1414
3	0.7	148140	2916	2789	1377
3	0.5	148140	2083	2789	1377
3	0.2	151779	833	3333	833
3	0.0	163142	0	4166	0
4	1.0	509753	22843	12202	10641
4	0.7	509753	15990	12281	10562
4	0.5	509753	11422	12202	10641
4	0.2	533121	18274	18274	4568
4	0.0	561883	0	22843	0
5	1.0	8928178	37725	7575	30150
5	0.7	9040740	26408	11318	26407
5	0.5	9331795	18863	18863	18862
5	0.2	9695614	7545	29294	9431
5	0.0	10248864	0	37725	0
6	1.0	3385698	55893	16149	39744
6	0.7	3388764	39125	16768	39125
6	0.5	3459733	27947	27947	39125
6	0.2	3634554	11179	44714	11179
6	0.0	3777175	0	55893	0

values (with respect to $r_t = 0$). Note that the savings for $r_t = 0.7$ are essentially the same as for $r_t = 1$. In other words, the saving on account of the model's recommendations ($r_t = 1$) is essentially the same as the savings when no more than 70% of the shipment can be delivered from AP ($r_t = 0.7$). This means that the significant savings predicted by the model are attainable without having to effect an immediate shift of the entire supply-chain operations to AP, a requirement that management cannot meet for the business reasons mentioned earlier.

Table 5
Cost savings for different part types comparing all shipments from US location with optimal shipments based on model M ($r_t = 1$)

Part type	% Cost savings	Savings in $ (millions)
1	9.7	0.02
2	10.3	0.03
3	9.2	0.02
4	9.3	0.05
5	12.9	1.32
6	11.6	0.39
Total		1.83

7. Conclusions

In this paper, we have considered the problem of locating an international repair-parts hub warehouse for Digital Equipment Corporation.

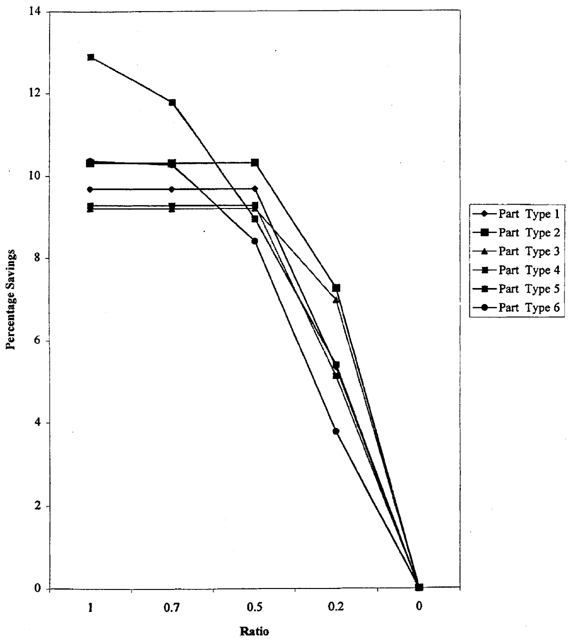

Fig. 5. Cost savings for different supply requirements.

Besides cost, a solution to this problem has to deal with a wide range of issues, including strategic ones such as geopolitical, fiscal and trade uncertainties. Based on the ANP model for addressing the strategic factors and a transshipment-like optimization model for evaluating costs, we concluded that the location of a warehouse in the AP region can yield significant cost savings to Digital, without adversely affecting its current business obligations. This result was presented to the Vice President of the International Services Division in charge of making the final decision.

The contributions of our work are as follows:

1. We have brought out how mathematical, managerial and business-related issues must be considered in choosing the modeling approach that is finally brought to bear on the problem.
2. We have shown how a combination of models can be used to address a wide spectrum of qualitative and quantitative factors affecting facility-location decisions.
3. We have demonstrated that, by a judicious selection of factors affecting the final decision, interdependencies present among them can be effectively evaluated by employing the ANP technique, which has been rarely applied.
4. We also gained management's acceptance of this approach to address a major facility-location decision facing them.

These contributions are significant to the practice of operational research due to the growing trend among companies to locate facilities internationally and to the lack of an extensive research literature (as compared to domestic facility location) in addressing the concerned issues.

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