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ScienceDirect
Int. J. Production Economics 105 (2007) 510–523
international journal of production economics
www.elsevier.com/locate/ijpe

Comprehensive and configurable metrics for supplier selection

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Received 1 January 2005; accepted 1 April 2006
Available online 11 July 2006

Abstract

As firms are increasingly becoming outsourcing oriented, supplier selection has become a major strategic decision for original equipment manufacturers (OEMs). Hundreds of publications can be found in the literature that deal with supplier selection. Researchers from business school often emphasize philosophical issues and focus on developing qualitative principles to guide management decision making. On the other hand, engineering researchers mostly treat supplier selection as an optimization problem. While strategic thinking cannot provide quantitative solutions, a mathematically optimal solution has no meaning if it does not match a firm's business strategy. Therefore, there is a need to integrate strategic thinking with quantitative optimization in order to make sound and effective decisions on supplier selection. This paper presents an integration mechanism in terms of a set of comprehensive and configurable metrics arranged hierarchically that takes into account product type, supplier type, and OEM/supplier integration level. Based on a firm's business strategy, the management configures an appropriate set of metrics used to measure supplier performance. An optimal supplier selection decision is then made based on this chosen set of metrics, achieving a strategic fit between the firm's business model and its supply chain strategy.

Keywords: Supplier selection; Decision making; Metrics; Multi-attribute utility theory

1. Introduction

Due to global competition, original equipment manufacturers (OEMs) are increasingly becoming outsourcing-oriented in order to lower manufacturing costs. According to Krajewski and Ritzman (2001), the percentage of sales revenues spent on purchased materials varies from more than 80 percent in the petroleum refining industry to 25 percent in the pharmaceutical industry. Therefore, the selection of appropriate suppliers has become an important decision for OEMs. OEMs must choose those suppliers that can deliver required raw materials and components at a high-quality level with low cost to satisfy customer demand. In addition, because of shortened product life cycle, OEMs and suppliers need to develop strategic partnerships so they can quickly adapt to a rapidly changing market. Furthermore, with rising consumerism and the concern about the environment, more and more OEMs are consciously building a consumer and environment friendly image.

Partnering with the right suppliers has become a key factor to the success of an OEM (Ellram et al., 2002).

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doi:10.1016/j.ijpe.2006.04.020

As such, many researchers devoted their efforts to developing supplier selection methodologies. Researchers form business school often emphasize philosophical issues and focus on developing qualitative principles to guide management decision making. This is typified by the philosophy of matching business strategy with supply chain strategy, first articulated by Fisher (1997) and later formalized by Chopra and Meindl (2003). On the other hand, engineering researchers mostly treat supplier selection as an optimization problem and attempt to develop mathematical models to generate optimal solutions. We believe these two paradigms are complementary rather than competitive. While strategic thinking cannot provide quantitative solutions, a mathematically optimal solution has no meaning if it does not match a firm's business strategy. The missing link is a set of comprehensive metrics that can be configured based on a firm's business strategy to serve as a basis for formulating an objective function to be optimized quantitatively.

Although some metrics have been proposed in the literature to measure supplier performance, they are not developed specifically to integrate strategic decision making with quantitative optimization. The number of metrics also varies, ranging from 13 to 60 in different publications. The issue of configurability is often ignored. In this paper, we present a comprehensive set of metrics that are configurable based on a firm's business strategy. These metrics are arranged hierarchically to take into account product type (i.e., make to stock, make to order, or engineer to order), supplier type (i.e., local or global), and OEM/supplier integration level (i.e., no integration, operational integration, or strategic partnership). After briefly reviewing relevant literature in Section 2, the metrics development methodology is presented in Section 3. Section 4 discusses how the metrics can be configured for supplier selection. This is followed by an illustrative example in Section 5. Section 6 concludes the paper.

2. Literature review

2.1. Supplier selection

Research on supplier selection can be traced back to the early 1960s when it was called vendor selection. These early research activities are summarized in a literature review by Weber et al. (1991). Ghodsypour and O'Brien (1998) also provided a short but insightful overview of supplier selection research. Supplier selection is a decision-making problem. While some researchers emphasize strategic decision making (Davidrajuh, 2003; Huang et al., 2002; Fisher, 1997), the majority treat it as an optimization problem. Different solution methodologies have been proposed, ranging from linear programming to non-linear programming. Table 1 lists a few representative methodologies.

Treating supplier selection as an optimization problem requires the formulation of an objective function, typically cost minimization. Some researchers focus on overall purchasing costs (Roodhooft and Konings, 1996); others consider total inventory costs that take into account quality, flexibility and responsiveness (Youssef et al., 1996). Ghodsypour and O'Brien (1998) argued that an optimization approach can only handle quantitative criteria, but qualitative considerations are abundant in real-world supplier selection. They proposed an integrated method that uses the Analytical Hierarchy Process (AHP) and linear programming to deal with both qualitative and quantitative criteria. This philosophy was adopted by Wang et al. (2004), where strategic fit between product characteristics and supplier performance is emphasized. Fuzzy set theory has also been used to deal with real-world supplier selection problems

Table 1
Optimization methodologies for supplier selection

Method	References
Linear Programming	Pan (1989), Kingsman (1986), Anthony and Buffa (1977) and Moore and Fearon (1973)
Mixed Integer Programming	Kasilingam (1996), Rosenthal et al. (1995), Chaudhry et al. (1993), Turner (1988), Narasimhan and Stoynoff (1986), Bender et al. (1985) and Gaballa (1974)
Goal Programming	Karpak et al. (1999), Sharma et al. (1989) and Buffa and Jackson (1983)
Multi-objective Programming	Liu et al. (2000) and Weber and Current (1993)
Non-linear Programming	Hong and Hayya (1992) and Benton (1991)

(Chan and Qi, 2003). These research works reflect the recognition that supplier selection is a multi criteria decision-making process. This was pointed out in the survey paper by Weber et al. (1991), where the authors concluded that the problem is highly complicated because of conflicting nature of criteria and conflicting performance of suppliers on these criteria.

AHP reflects the natural tendency of human mind to sort elements of a system into different levels and to group like elements in each level. It is favored by many as a generic multi criteria decision-making methodology. More and more researchers are now using AHP for supplier selection, e.g., Chan (2003) and Tam and Tummala (2001). However, several researchers have concerns about the mathematical rigor of AHP (Dyer, 1990a, b; Belton and Gear, 1984). Some other researchers chose to apply multi-attribute utility theory (MAUT), a well-established and mathematically sound decision-making method, to supplier selection (Holt et al., 1994; Min, 1994). To a lesser extent, outranking method is also used to select suppliers (de Boer et al., 1998). Whether AHP, MAUT, or outranking is applied, one must determine the criteria used to measure supplier performance. The criteria used must reflect the OEM's business strategy. As different OEMs have different business strategies for different products, it is impossible to create a universally applicable decision-making model with a fixed set of criteria. Therefore, the prerequisite for effective supplier selection is to determine appropriate performance metrics based on a specific business strategy. This notion appeared in a recent paper by Masella and Rangone (2000), where the authors proposed four configurations (i.e., short-term logistic, long-term logistic, short-term strategic and long-term strategic) for choosing supplier selection metrics.

2.2. *Supplier performance metrics*

Although publications on supplier selection methods are abundant, few researchers devote their efforts to developing metrics for supplier performance measure. In the few publications that we found, the number and types of metrics proposed varied significantly (Table 2). Cost and quality have been the most dominant factors, along with on-time delivery and flexibility. Literature in the late 1970s and early 1980s showed heavy emphasis on cost. In the early 1990s, cycle time and customer responsiveness were added. In the late 1990s, researchers realized the importance of flexibility. In recent years, environmental safety became a key issue among the industrialized nations. This gives rise to the concept of green supply chain. Performance in this area is measured using various metrics depending on product properties, recycling, waste/hazardous emission, and resource usage. The trend is shifting towards developing more exhaustive and detailed performance metrics in a systematic way.

Table 2
Publications on suppler performance metrics

References	Number of metrics
Roa and Kiser (1980)	60
Ellram (1990)	18
Stamm and Golhar (1993)	13
Dickson (1966)	23

Holmberg (2000) took a holistic view of the measurement system for total supply chain management and identified problems due to insufficient "system thinking." The author argued that lack of synchronization between measurement system and overall objectives can result in a number of isolated and incompatible measures. In addition, biased emphasis on financial measures provides insufficient input to the management about the weak links in their supply chains. Beamon (1999) indicated that metrics should satisfy four characteristics, namely, inclusiveness (measurement of all pertinent aspects), universality (comparison under various operating conditions), measurability (measurable data), and consistency (consistent with organizational goal).

Remko (1998) proposed a framework of a 3×3 matrix with contribution of a particular link to supply chain competitiveness on the Y-axis and the stage of logistics as a part of the whole supply chain on the X-axis. van Amstel and D'hert (1996) indicated that the type of performance metrics used for measuring supply chain performance differs, depending on the level at which measurement is done (e.g., at activity level, functional area level, between functions, or between organizations). The study on buyer-seller relationships by Cannon and Perreault (1999) indicated that different performance metrics are needed in different situations. Harland (1997) argued that the role and contribution of a particular link towards the final supply chain goal can be a major factor in assigning performance metrics. This adds one more layer to the complexity in standardizing a performance measurement framework.

Apart from academic research, there is an industry effort to standardize supply chain modeling spearheaded by the Supply Chain Council (SCC). SCC constructed a descriptive framework called the supply chain operations reference (SCOR) model. The SCOR model aims to enable companies to communicate supply chain issues, measure their performance objectively, identify performance improvement objectives, and influence future SCM software development (Stephens, 2001). It is developed around 5 main management processes, namely, Plan, Source, Make, Deliver, and Return. It is a hierarchical process model with four levels. Level I provides basic definitions of the 5 types of management processes. Level II decomposes the process types into 26 core process categories which can be used for configuring the supply chain. Level III describes detailed process elements for each process category along with diagnostics metrics, benchmarks, best practices and software capabilities required. Level IV is the implementation level where each organization can customize their practices and hence not defined in the SCOR Model. The SCOR Model is evolving. Currently, it includes 13 Level I metrics in five categories—delivery reliability, responsiveness, flexibility, costs, and asset management efficiency.

3. Development of comprehensive and configurable metrics

Lehmann and O'Shaughnessy (1982) stated that to develop a set of metrics one must first classify various criteria into an exhaustive and mutually exclusive list of categories. The authors proposed five categories; namely, performance, economic, integrative, adaptive, and legalistic. Wilson (1994) indicated that the first four categories can be roughly equated to quality, price, service, and delivery. It was shown that importance of these criteria changes over time. We thus infer that the categories themselves may also evolve overtime. This is supported by the fact that the widely accepted SCOR model has different categories. Because the SCOR model is intended to be an industrial standard, our metrics development follows its basic structure with two additional categories, namely, safety and environmental. In addition, we organize these seven categories into three tracks, i.e., product related, supplier related, and society related, for easier user configuration. Metrics belong to the five categories related to product type and supplier type are further partitioned to match OEM/supplier integration level. The hierarchy is shown in Fig. 1. The definition of metric categories is shown in Table 3.

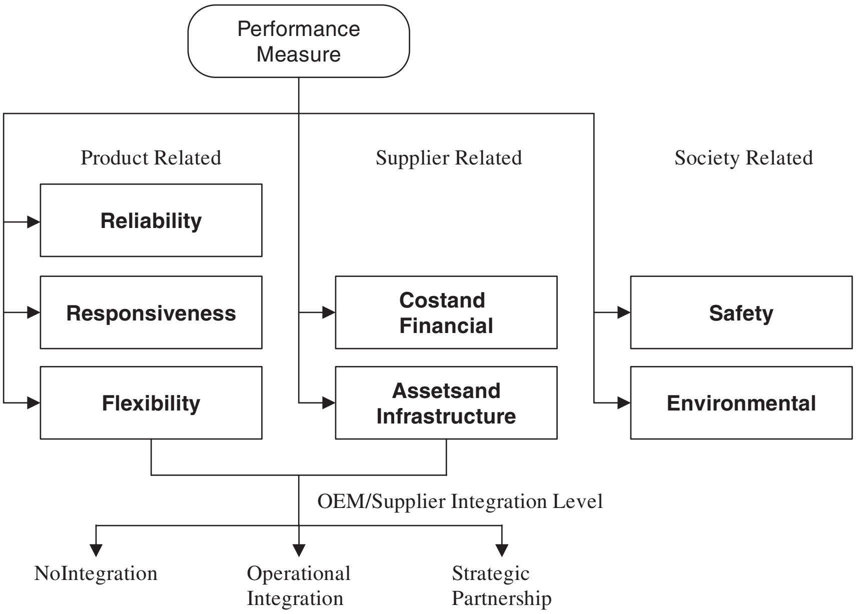

Fig. 1. Hierarchy of supplier selection metrics.

Table 3
Definition of metric categoris

Category	Definition
Reliability	Criteria regarding the performance of a supplier in delivering the ordered components to the right place, at the agreed upon time, in the required condition and packaging, and in the required quantity
Responsiveness	Criteria related to the velocity at which a supplier provides products to the customer
Flexibility	Criteria regarding the agility of a supplier in responding to OEM demand changes
Cost and Financial	Criteria regarding cost and financial aspects of procuring from supplier
Assets and Infrastructure	Criteria regarding the effectiveness of supplier in managing assets to support OEM demand
Safety	Criteria regarding occupational safety at the supplier's facility
Environment	Criteria regarding a supplier's effort in pursuing environmentally conscious production

The procedure for detailed metrics development is shown as follows:

1. *Metrics Collection and Definition*: A comprehensive list of supply chain metrics is put together through extensive literature review including web based information sources. Each metric is defined so that its meaning and measures are clearly understood.
2. *Metrics Evaluation and Categorization*: Each metric is evaluated based on its characteristics, such as qualitative or quantitative, strategic or operational, and whether uncertainty is involved. They are then categorized based on the hierarchy shown in Fig. 1.
3. *Relevancy and Repetition Check*: Each category is reviewed to ensure that all the metrics are relevant. Redundant ones are eliminated.
4. *Structure Development*: Within each category, relationships among the metrics are established using interpretive structural modeling (ISM). Levels created in ISM are used to partition the metrics into three levels (A–C) that match the three types of OEM/supplier integration mechanism (no integration, operational integration, and strategic partnership).

While the first three steps are easy to understand, the fourth step requires some explanation. The step uses ISM, which is a technique developed by Warfield (1974) to structure complex issues to form interpretable pattern. Here we use the development of reliability metrics as an example. Referring to Table 4, a total of 19 metrics related to reliability are collected and defined. Note that reliability metrics are product related and products are of three types, namely, make to stock (MTS), make to order (MTO), and engineering to order (ETO). Some metrics are applicable to all three product types, others are only applicable to one or two product types, as indicated in the configuration column. The level of OEM/supplier integration shown in the last column is derived based on ISM. First, a reachability matrix **M** is established with the metrics as the row and column. If metric i leads to metric j, then the element m_{ij} is defined as 1; otherwise, m_{ij} is 0. Note that m_{ii} is defined as 1 since a metric leads to itself. Summations of rows of **M** indicate driving power of the metrics, while summations of column indicate dependence. Higher dependence and lower driving power indicates dependency, whereas lower dependence and higher driving power indicate autonomy. From the matrix **M**, the reachability set and antecedent set are derived for each metric. The reachability set contains the metric itself and other metrics to which it may reach (if A leads to B and B leads to C, then A can reach C). The antecedent set contains the metric itself and other metrics that may reach to it. Depending on intersection of these two sets, the metrics are partitioned in hierarchical levels. A graphic representation is then formed as shown in Fig. 2, which is called a diagraph. From Fig. 2, it can be seen that level 1 metrics can be measured when the OEM receives the ordered components and hence no OEM/supplier integration is needed. Levels 2 and 3 metrics are measured at the supplier's facility, so operational integration between OEM/supplier is required. Levels 4 and 5 metrics may be considered as proprietary and are only obtained when the OEM and the supplier have formed a strategic partnership.

The development of responsiveness, flexibility, cost and financial, and assets and infrastructure metrics follows similar steps. These metrics are

Table 4
Reliability metrics

No.	Metrics	Definition	Configuration	Level
1	% Orders received damage free	Number of orders received damage free divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
2	% Orders received complete	Number of orders received complete divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
3	% Orders received on time to commit date	Number of orders received on time to commit date divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
4	% Orders received on time to required date	Number of orders received on time to required date divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
5	% Orders received defect free	Number of orders received defect free divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
6	% Orders received with correct shipping docs	Number of orders received with correct shipping docs divided by total number of orders processed in measurement time	MTS/MTO/ETO	A
7	% Short to manufacturing schedule	Number of orders produced exceeding the manufacturing schedule divided by total number of orders produced in measurement time	MTS/ETO	B
8	Fill rate	The percentage of ship-from-stock orders shipped within 24 h of order receipt	MTS	B
9	Ratio of actual to theoretical cycle time	Ratio of measured time required for completion of set of tasks divided by sum of the time required to complete each task based on rated efficiency of the machinery and labor operations	MTS/MTO	B
10	Scrap expenses	Expense incurred from material failing outside of specifications and processing characteristics that make rework impractical as percentage of total production cost	MTS/MTO/ETO	A
11	In process failure rate	The percentage of time work-in-process is not completed, i.e., 1 minus the percentage of completed work-in-process units	MTS/MTO/ETO	C
12	Yields during manufacturing	Ratio of usable output from a process to its input	MTS/MTO/ETO	B
13	% Errors during release of finished product	Number of errors in release of finished products divided by total number of products released during measurement period	MTS/MTO	B
14	Incoming material quality control	Quality assurance procedures, control over quality of incoming material at supplier and quality improvement perspective towards supplier's suppliers	MTS/MTO/ETO	C
15	Inventory accuracy	The absolute value of the sum of the variance between physical inventory and perpetual inventory	MTS/MTO	B
16	% Faultless installations	Number of faultless installations divided by total number of units installed	MTS/MTO/ETO	A
17	Order consolidation profile	The activities associated with filling a customer order by bringing together in one physical place all of the line items ordered by the customer	MTS/MTO/ETO	B
18	% Orders scheduled to customer request date	Percentage of orders whose delivery is scheduled within an agreed time frame of the customer's requested delivery date	MTO/ETO	A
19	Average days per engineering change	Total number of days each engineering change impacts the delivery date divided by the total number of changes	ETO	B

shown in Tables 5–8. Note that for cost and financial and assets and infrastructure metrics, the Configuration column indicates whether the metric is applicable to local or global suppliers. Safety and environmental metrics are society related and not considered proprietary. Therefore, they are not partitioned into different levels, as shown in Tables 9 and 10.

4. Metric configuration and supplier selection

A total of 101 metrics were collected, categorized, and partitioned for easy configuration. These metrics are intended to be general. A firm should choose only those that are important to its business strategy. The first decision to make is whether to include metrics from all 7 categories. When

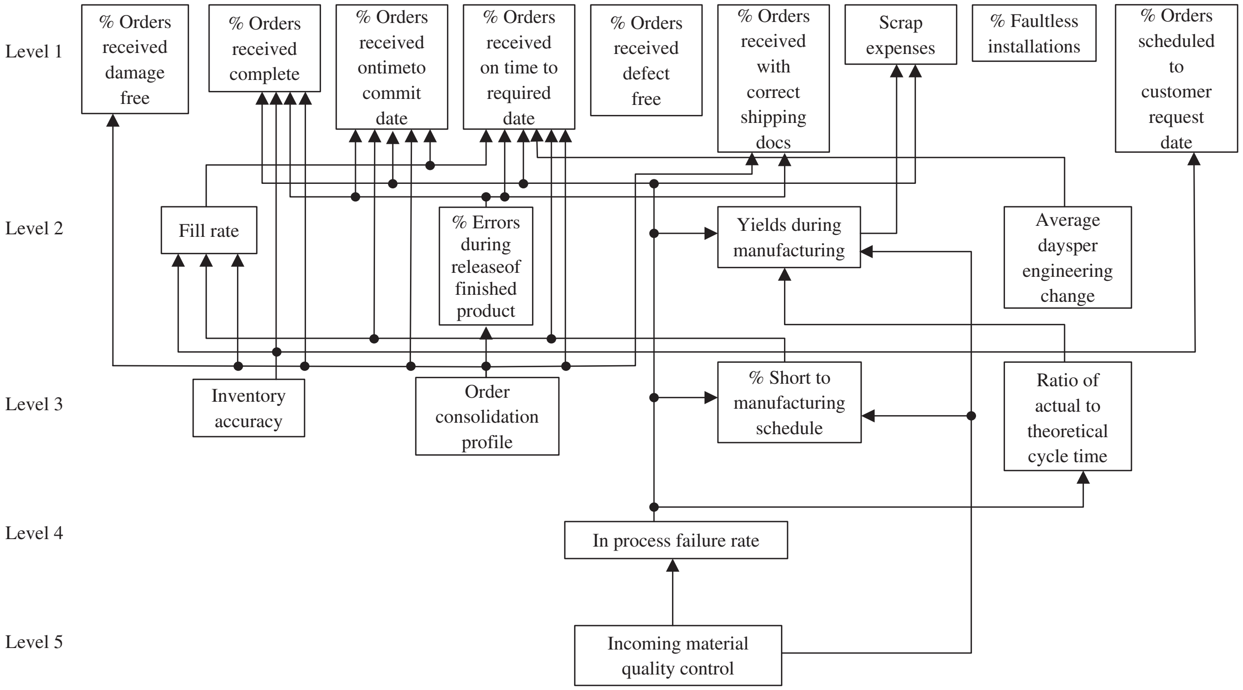

Fig. 2. Diagraph for reliability metrics.

choosing reliability, responsiveness, and flexibility metrics, the type of product (MTS, MTO, or ETO) helps narrow down the applicable ones. Similarly, the type of supplier (local or global) confines the selection of cost and financial and assets and infrastructure metrics. Finally, the level of OEM/supplier integration (A: no integration, B: operational integration, and C: strategic partnership) provides further guidance for choosing desired metrics. Usually, a handful of metrics are sufficient to meet the need of a firm. These metrics should be determined based on the firm's business strategy. Readers may refer to Porter (1980), Treacy and Wiersema (1993), Fisher (1997), Huang et al. 2002, and Chopra and Meindl (2003) for details of how to match a firm's business strategy with its supply chain strategy. Other consideration includes product category and component parts. Readers may refer to Bharadwaj (2004) for more insight.

Once the desired set of metrics is determined, different decision-making methods can be used. When using optimization methods, what each metric measures may be converted to monetary costs to form a single objective function to be minimized; or some sort of preemptive or weighted average optimization can be pursued. The effort needed to formulate an appropriate objective function could be significant. The use of AHP can bypass the challenging task of formulating an appropriate objective function but requires an expert to make pair-wise comparison among suppliers using 1–9 scales with respect to the selected metrics. An example for supplier selection based on SCOR metrics can be found in Wang et al. (2004). Note that 1–9 scales is a qualitative measure and its effectiveness is disputed (Dyer, 1990a). Since a majority of the metrics is quantitative and quite a few of them involve probability, we believe MAUT may be a better method for decision making.

5. Illustrative example

Ultracomp Inc. is a personal computer (PC) manufacturer with a business model based on modularization and postponement for product differentiation. It purchases most of the components from suppliers and assembles the final product prior to delivering to the customer. These components are MTS products and both local and global suppliers are used. The company has recently developed a new model based on a high performance memory chip. Initial forecast shows that introduction of this new model will generate heavy demand. Because the product is innovative and in

Table 5
Responsiveness metrics

No.	Metrics	Definition	Configuration	Level
1	Published delivery cycle time	Typical standard lead time after receipt of order currently published to customers by the sales organization	MTS/MTO/ETO	A
2	Order fulfillment lead time	The average actual lead times consistently achieved, from customer signature/authorization to order receipt, order receipt to order entry complete, order entry complete to start-build, start-build to order ready for shipment, order ready for shipment to customer receipt of order, and customer receipt of order to installation complete	MTS/MTO/ETO	A
3	Return product velocity	Average time required for process of returning the defective, incomplete or damaged orders and reshipping of the order to customer	MTS/MTO/ETO	A
4	Average release cycle of changes	Cycle time for implementing change notices divided by total number of changes	MTS/MTO/ETO	B
5	Total build cycle time	Total build time is the average time for build-to-stock or configure-to-order products from when production begins on the released work order until the build is completed and unit deemed shippable	MTS/MTO/ETO	B
6	Package cycle time	The total time required to perform a series of activities that containerize completed products for storage or sale to end-users	MTS/MTO/ETO	B
7	Product release process cycle time	Total time required to perform post-production documentation, testing, or certification required prior to delivery of finished product to customer	MTS/MTO/ETO	B
8	Installation cycle time	Total time required to prepare and install the product at customer site with full functional commencement	MTS/MTO/ETO	B
9	Sourced/in process product requisition cycle time	The time required to provide manufacturing with a needed component, service, or additive from the time of requisition to the time of delivery	MTS/MTO/ETO	C
10	Product/grade change over time	Average time required to change from one product or grade to another product or grade	MTS/MTO/ETO	C
11	Intra production re-plan cycle time	Time between the acceptance of a regenerated forecast is by the end-product producing location and the reflection of the revised plan in the master production schedule of all the affected plants, excluding external vendors	MTS/MTO/ETO	C
12	Quarantine/hold time	Average time for setting aside of items from availability for use or sale until all required quality tests have been performed and conformance certified	MTS/MTO/ETO	C
13	Production engineering cycle time	Average time required for generation and delivery of final drawings, specifications, formulas, part programs, etc. In general, preliminary engineering work done as part of the quotation process	ETO	C

the introduction and growth stage of its life cycle, management has decided to emphasize flexibility and responsiveness as the demand may fluctuate significantly. In addition, management has decided to select from three global suppliers (S_1, S_2, and S_3) with whom the company has a strategic partnership to support the production of this new PC model. All three suppliers have similar assets and infrastructure. Furthermore, all of them have safe and environmental friendly production facility. Therefore, the management at Ultracomp decided to consider only reliability, responsiveness, flexibility, and cost and financial metrics. A total of 8 metrics are selected as shown in Table 11.

To use MAUT for decision making, utility function for each attribute needs to be established to capture management's preference. There are various techniques for determining utility functions (Keeney and Raiffa, 1976). The most common one is the mid-value splitting technique that involves an analyst (can be a computer program) interviewing the decision maker. Take published delivery cycle time as an example, the analyst will first ask the decision maker what is considered a perfect cycle

Table 6
Flexibility metrics

No.	Metrics	Definition	Configuration	Level
1	Time for expediting delivery and transfer process	Expediting cycle time for delivery and transfer Process compared to the standard cycle time for the delivery and transfer Process	MTS/MTO/ETO	A
2	Cost of expediting delivery and transfer process	Additive cost required by the disconnect to expedite the delivery and transfer process	MTS/MTO/ETO	A
3	Ability to augment return capacity rapidly	Appropriation of return resources and assets to meet anticipated as well as unanticipated return requirements	MTS/MTO/ETO	A
4	Upside order flexibility	Number of days required to achieve an unplanned sustainable 20% increase in orders	MTS/MTO/ETO	A
5	Downside order flexibility	Percentage order reduction sustainable at 30 days prior to shipping with no inventory or cost penalties	MTS/MTO/ETO	A
6	Upside production flexibility	Number of days required to achieve an unplanned sustainable 20% increase in orders	MTS/MTO/ETO	B
7	Downside production flexibility	The percentage order reduction sustainable at 30 days prior to delivery with no inventory or cost penalties	MTS/MTO/ETO	B
8	Upside delivery flexibility	Number of days required to achieve an unplanned sustainable 20% increase in deliveries	MTS/MTO/ETO	B
9	Downside delivery flexibility	Percentage delivery reduction sustainable at 30 days prior to delivery with no inventory or cost penalties	MTS/MTO/ETO	B
10	Upside installation flexibility	Number of days required to achieve an unplanned sustainable 20% increase in installations	MTS/MTO/ETO	B
11	Downside installation flexibility	Percentage installation reduction sustainable at 30 days prior to installing with no inventory or cost penalties	MTS/MTO/ETO	B
12	Upside shipment flexibility	Number of days required to achieve an unplanned sustainable 20% increase in shipments	MTS/MTO/ETO	C
13	Downside shipment flexibility	Percentage shipment reduction sustainable at 30 days prior to shipping with no inventory or cost penalties	MTS/MTO/ETO	C
14	ECO cycle time	The total time required from request for change from customer, engineering, production or quality control to revise a blueprint or design released by engineering, and implement the change within the Make operation	ETO	A

time and what is absolutely unacceptable. Suppose the decision maker answers 4 and 96 h, respectively; then a utility of 1 is assigned to 4 h and a utility of 0 is assigned to 96 h. The analyst then ask "suppose a supplier improves from a 96 h delivery cycle time to $h_{0.5}$ hours and another supplier improves from $h_{0.5}$ hours to 4 h, what would be the value of $h_{0.5}$ so that you think the two suppliers have equal amount of improvement?" Suppose the answer is 54 h, then a utility of 0.5 is assigned to 54 h. The analyst will then ask a similar question—"suppose a supplier improves from a 54 h delivery cycle time to $h_{0.75}$ hours and another supplier improves from $h_{0.75}$ hours to 4 h, what would be the value of $h_{0.75}$ so that you think the two suppliers have equal amount of improvement?" If the supplier answers 36 h, then 36 h is assigned a utility of 0.75. Once a few points (5–7) are obtained, the analyst will fit these points into a curve and ask the decision maker to evaluate and fine tune the curve to obtain a desired utility function. When the utility function is established, it can be used to obtain a utility value for a specific supplier based on its performance. As such, there is no need to do pair-wise comparison as required by AHP, which is advantageous when the number of suppliers to be evaluated is large.

For each metric, a utility function is established using the mid-value splitting technique. The utility values obtained using these utility functions for all three suppliers are shown in Table 11. Also shown in Table 11 is the scale factor for each metric. The scale factor is equivalent to criterion weight in AHP. In MAUT, it is obtained through an interview-based process similar to that used to establish a utility function. It is a rather elaborated process and may be confusing at times. Interested reader can refer to Keeney and Raiffa (1976) for more details. In AHP, criterion weight is obtained using pair-wise comparison of the criteria in a relatively straightforward manner. Since the number of metrics used by a

Table 7
Cost and financial metrics

No.	Metrics	Definition	Configuration	Level
1	Inventory turns	Total cost of goods sold divided by value of inventory carried throughout the measurement period	Local/global	A
2	Payment terms	Suitability of terms and conditions regarding payment of invoices, open accounts, sight drafts, credit letter and payment schedule	Local/global	A
3	Return policy	Suitability of policies regarding return of the defective, damaged or incomplete orders	Local/global	A
4	Warranty costs	Warranty costs include materials, labor and problem diagnosis for product defects	Local/global	A
5	Landed cost	Final cost including the cost of components/order, shipping cost, duties, broker fees, custom fees, qualification fees etc required to be paid per component/order	Local/global	A
6	Discount rate	Suitability of discount scheme implemented on payment of invoices within time frame	Local/global	A
7	Financial stability	Indicator of excessive asset price volatility, the unusual drying-up of liquidity, interruptions in the operation of payment systems, excessive credit rationing, etc.	Local/global	B
8	Packaging cost	Cost of series of activities that containerize completed products for storage or sale to end-users	Local/global	B
9	Inventory carrying cost	Inventory carrying costs are the sum of opportunity cost, shrinkage, insurance and taxes, total obsolescence for raw material, WIP, and finished goods inventory, channel obsolescence and field sample obsolescence	Local/global	B
10	Order fulfillment costs	Includes costs for processing the order, allocating inventory, ordering from the internal or external supplier, scheduling the shipment, reporting order status and initiating shipment	Local/global	B
11	Freight	Costs of transporting component from supplier facility to customer facility	Local/global	B
12	Value added productivity	Value added per employee is calculated as total product revenue less total material purchases divided by total employment (in full-time equivalents)	Local/global	C
13	Release cost per unit	Cost involved in post-production documentation, testing, or certification required prior to delivery of finished product to customer	Local/global	C
14	Cost reduction trend	Average change in operating costs during the measurement period	Local/global	C
15	Foreign exchange rate fluctuation	Fluctuation in frequency and range fluctuation of the currency exchange rate between the two countries	Global	A
16	Local price control	Suitability of price control and counter trade policies due to country government policies and local government rules and regulations	Global	B
17	Tariffs and custom duties	Custom duties/tariffs imposed by importing country on goods and services imported from particular country	Global	B

firm is typically around 10 or less, managers may find it easier to use the standard AHP method developed by Saaty (1980). With the scale factor and all the utility values determined, the evaluation of suppliers in this case is nothing but a weight sum problem. We found that the overall utility values for suppliers S_1, S_2, and S_3 are 0.90, 0.83, and 0.89, respectively. Thus, S_1 is somewhat favored over S_3, while S_2 is the least desired supplier. Manager can use this information to make a final decision. They may choose a sole supplier, or use the utility values to generate ratioed order shares among all three suppliers as suggested by Gregory (1986).

6. Conclusion

The high correlation between supply chain strategy and business performance has been empirically demonstrated (Carter and Narasimhan, 1996). Firms now realize that their supply chain strategy

Table 8
Assets and Infrastructure metrics

No.	Metrics	Definition	Configuration	Level
1	Labor stability	Labor turn over during period measurement within various employee categories	Local/global	A
2	Asset turns	Total gross product revenue divided by total net assets	Local/global	A
3	Company size	Indicator of various factors such as facility size, area, work force strength, turnover, capacity etc.	Local/global	A
4	Quality system certification/ assessment	Quality certifications acquired and performance on conformance audits during measurement period	Local/global	A
5	Strategic fit	Compatibility of long term planning in regards to expansion plans, area of concentration, interest in collaborating etc.	Local/global	A
6	Negotiability	Negotiation flexibility with regards to cost, payment terms, return policies and similar other terms and conditions in supplier–buyer contract	Local/global	A
7	Legal Claims	Pending or filed legal claims against the supplier	Local/global	A
8	Critical process subcontracting	Percentage of critical process subcontracted by supplier	Local/global	A
9	Inventory days of supply	Total gross value of inventory at standard cost before reserves for excess and obsolescence including inventory on company books only excluding future liabilities	Local/global	B
10	Capacity utilization	A measure of how intensively a resource is being used to produce a good or service. Some factors that should be considered are internal manufacturing capacity, constraining processes, direct labor availability and key components/materials availability	Local/global	B
11	Management outlook and functional compatibility	Degree of alignment in future plans, management policies, competitive strategies and match between various functions across the supplier organization	Local/global	B
12	Ethical standards	Compatibility of ethical standards practiced at supplier end	Local/global	B
13	Designing capabilities	Capabilities regarding conceptualizing, designing, drafting and prototyping of new product requirements	Local/global	C
14	Development capabilities	Capabilities regarding development of manufacturing processes, trial runs, quality assurance for new product design	Local/global	C
15	EDI Capabilities	Capabilities and infrastructure regarding electronic data transfer at supplier facility for effective communication	Local/global	C
16	Manufacturing/ process capabilities	Capabilities in areas of machining, manufacturing, assembly, special purpose machines and equipment etc. in line with product requirements	Local/global	C
17	Customer concentration	Percentage share of sales from the supplier as compared to other buyers	Local/global	C
18	Political stability	Political stability and relations with the exporting country	Global	A
19	Cultural similarity	Cultural and language barriers between buyer and supplier	Global	C

must match their business model in order to be competitive and profitable. A sound business model must be based on market environment and customer demand, which are strongly influenced by product characteristics and its life cycle stage. For example, staples have a nearly constant design and their demand pattern is highly predictable. There is no technical barrier to entry to the staple production business. Therefore, profitability can only be achieved by minimizing cost and employing a level schedule across the entire supply chain. On the other hand, personal computers have a short product life cycle. At the introduction stage of a new model (e.g., IBM PCs in the 1980s), customer demand cannot be accurately forecasted. To maximize profitability, a responsive supply chain is needed that can quickly scale up and down production depending on customer acceptance. At the mature stage, competitive firms allow customers to configure their own computers over the internet

Table 9
Safety metrics

No.	Metrics	Definition
1	Number of lost time accidents	Number of accidents per million working hours resulting in lost time
2	Recordable incident rate	OSHA or equivalent recordable incident rate per 100 employees
3	Dollars spent in worker compensation	Total dollar amount spent in worker compensation due to work related injury during the measurement period
4	Safety training	Procedures and practices regarding safety training and level of awareness
5	Safety audits	Feedback on of safety procedures through review audit

Table 10
Environmental metrics

No.	Metrics	Definition
1	Conventional pollutants released to water	Average volume of conventional pollutants (suspended solids, biological oxygen demand, fecal coliform bacteria, pH, and oil and grease) per day during measurement period
2	Ambient air releases	Average volume in ppmv of ambient air releases per day during measurement period
3	Hazardous/non hazardous waste	Average volume of hazardous/non hazardous waste released per day during measurement period
4	Chemical releases	Average volume of chemical releases per day during measurement period
5	Global warming gases	Average volume in ppmv of global warming gas (carbon dioxide, methane) releases per day during measurement period
6	Ozone depleting chemicals	Average volume of ambient air releases per day during measurement period
7	Bio accumulative pollutants	Average volume of ambient air releases per day during measurement period
8	Indoor environmental releases	Average volume of ambient air releases per day during measurement period
9	Resource consumption (material, energy, water)	Resource consumption in terms of material, energy and water during the measurement period
10	Non renewable resource consumption	Resources not renewable in 200 years (fossil fuels minerals etc) consumed in terms during the measurement period
11	Recycled content	Percentage of materials that can be recovered from the solid waste stream, either during the manufacturing process or after consumer use
12	Product disassembly potential	Ease with which a product can be disassembled for maintenance, replacement or recycling
13	Product durability	Measure of useful life of the product
14	Component reusability	Percentage of reusable components in total number of components in the product and their frequency of reusability

Table 11
Selected metrics and supplier performance data

Category	Metrics	Performance			Utility			Scale factor
		S_1	S_2	S_3	S_1	S_2	S_3	
Reliability	% Orders received defect free	95%	97%	87%	0.91	0.93	0.82	0.15
	Fill rate	97%	95%	91%	0.92	0.89	0.78	0.10
	In process failure rate	93%	97%	95%	0.87	0.94	0.91	0.05
Responsiveness	Published delivery cycle time	28	36	12	0.89	0.75	0.92	0.25
Flexibility	Cost of expediting delivery process	15	22	15	0.92	0.87	0.92	0.25
Cost and Financial	Warranty cost	12	8	9	0.81	0.96	0.94	0.05
	Tariffs and custom duties	20	32	23	0.94	0.88	0.93	0.10
	Inventory carrying cost	40	33	33	0.90	0.93	0.93	0.05

and deliver the customized computers within days (e.g., present day DELL PCs). This requires an agile supply chain that emphasizes low volume high variety production and short lead time. It is obvious that no suppliers can be universally superior to the others under all circumstances. Rather, selection of the best suppliers must be driven by a firm's supply chain strategy, which is a high-level management decision.

Researchers in Engineering schools (including Operations Research) overly emphasized the need of quantitative optimization and overlooked the importance of integration with business strategic thinking when it comes to supplier selection. The result is a large body of literature on different methodologies for supplier selection without a clear rationale for choosing an appropriate objective function to be optimized. It is our view that the large amount of decision-making methodologies presented in the literature is basically variations of optimization methods, AHP-based methods, MAUT-based methods, or outranking methods. Each of these methods has its pros and cons and the effort for improving them is certainly worthwhile. However, the more important issue is how to make sure that these methods are used effectively so decisions made indeed lead to the improvement of a firm's profitability. We believe the answer is a set of comprehensive metrics that can be selectively configured by management based on a firm's business model to guide quantitative optimization, as presented in this paper. The metrics we collected are by no means exhaustive, especially in today's rapidly changing world with continually evolving new business models. To meet their needs, firms may choose to add new metrics to the existing categories or even create new categories if necessary. The key is to configure a set of metrics that truly reflect a firm's business strategy. Firms should then critically evaluate their suppliers along these metrics and remain engaged with high performers to build competitive advantage (Bharadwaj and Matsuno, 2006). This will enable a firm to optimize its order management cycle, leading to improved customer satisfaction, receded interdepartmental problems, and improved financial performance (Shapiro et al., 1992).

References

Anthony, T.F., Buffa, F.P., 1977. Strategic purchasing scheduling. Journal of Purchasing and Material Management, Fall, 27–31.

Beamon, B., 1999. Measuring supply chain performance. International Journal of Operations and Production Management 19 (3), 275–292.

Belton, V., Gear, T., 1984. On the short-coming of Saaty's method of analytic hierarchies. Omega 11 (3), 228–230.

Benton, W.C., 1991. Quantity discount decision under conditions of multiple items, multiple suppliers and resource limitation. International Journal of Production Research 29 (10), 1953–1961.

Bender, P.S., Brown, R.W., Isaac, H., Shapiro, J.F., 1985. Improving purchasing productivity at IBM with a normative decision support system. Interface 15, 106–115.

Bharadwaj, N., 2004. Investigating the decision criteria used in electronics component procurement. Industrial Marketing Management 33, 317–323.

Bharadwaj, N., Matsuno, K., 2006. Investigating the antecedents and outcomes of customer firm transaction cost savings in a supply chain relationship. Journal of Business Research 59, 62–72.

Buffa, F.P., Jackson, W.M., 1983. A goal programming model for purchase planning. Journal of Purchasing and Material Management Fall, 27–34.

Cannon, J.P., Perreault Jr., W.D., 1999. Buyer–seller relationships in business markets. Journal of Marketing Research 36 (4), 439–460.

Carter, J.R., Narasimhan, R., 1996. Is purchasing really strategic? International Journal of Purchasing and Materials Management 32 (1), 20–28.

Chan, F.T.S., 2003. Performance measurement in a supply chain. International Journal of Advanced Manufacturing Technology 21, 534–548.

Chan, F.T.S., Qi, J.H., 2003. An innovative performance measurement method for supply chain management. Supply Chain Management: An International Journal 8 (3), 209–223.

Chaudhry, S.S., Forst, F.G., Zydiak, J.L., 1993. Vendor selection with price breaks. European Journal of Operations Research 70 (1), 52–66.

Chopra, S., Meindl, P., 2003. Supply Chain Management: Strategy, Planning, and Operation, second ed. Prentice-Hall, Upper Saddle River, NJ.

Davidrajuh, R., 2003. Modeling and implementation of supplier selection procedures for E-commerce initiatives. Industrial Management and Data Systems 103 (1), 28–38.

de Boer, L., van der Wegen, L., Telgen, J., 1998. Outranking methods in support of supplier selection. European Journal of Purchasing and Supply Management 4, 109–118.

Dickson, G.W., 1966. An analysis of vendor selection systems and decisions. Journal of Purchasing 2, 5–17.

Dyer, J.S., 1990a. Remarks on the analytic hierarchy process. Management Science 36 (3), 249–258.

Dyer, J.S., 1990b. A clarification of 'Remarks on the Analytic Hierarchy Process'. Management Science 36 (3), 274–275.

Ellram, L.M., 1990. The supplier selection decision in strategic partnerships. Journal of Purchasing Material Management 26 (4), 8–14.

Ellram, L.M., Zsidisin, G.A., Siferd, S.P., Stanley, M.J., 2002. The impact of purchasing and supply management activities on corporate success. Journal of Supply Chain Management: A Global Review of Purchasing and Supply 38 (1), 4–20.

Fisher, M.L., 1997. What is the right supply chain for your product? Harvard Business Review 75, 105–116.

Gaballa, A.A., 1974. Minimum cost allocation of tenders. Operations Research Quarterly 15 (3), 389–398.

Ghodsypour, S.H., O'Brien, C., 1998. Decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. International Journal of Production Economics 56-57, 199–212.

Gregory, R.E., 1986. Source selection: a matrix approach. Journal of Purchasing and Materials Management 22 (2), 24–29.

Harland, C., 1997. Supply chain operational performance roles. Integrated Manufacturing Systems 8 (2), 70–78.

Holmberg, S., 2000. A systems perspective on supply chain measurements. International Journal of Physical Distribution & Logistics Management 30 (10), 847–868.

Holt, G.D., Olomolaiye, P.O., Harris, F.C., 1994. Applying multi-attribute analysis to contractor selection decisions. European Journal of Purchasing and Supply Management 1 (3), 139–148.

Hong, J.D., Hayya, .C., 1992. Just-in-time purchasing: single or multiple sourcing? International Journal of Production Economic 27, 171–181.

Huang, S.H., Uppal, M., Shi, J., 2002. A product driven approach to manufacturing supply chain selection. Supply Chain Management: An International Journal 7 (3/4), 189–199.

Karpak, B., Kumcu, E., Kasuganti, R., 1999. An application of visual interactive goal programming: a case in vendor selection decisions. Journal of Multi-criteria Decision Analysis 8 (2), 93–105.

Kasilingam, R.G., 1996. Selection of vendors—a mixed integer programming approach. Computers and Industrial Engineering 22 (1/2), 347–350.

Keeney, R.L., Raiffa, H., 1976. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Wiley, New York, NY.

Kingsman, B.G., 1986. Purchasing raw materials with uncertain fluctuating prices. European Journal of Operations Research 25, 358–372.

Krajewski, L.J., Ritzman, L.P., 2001. Operations Management: Strategy and Analysis, sixth ed. Addison-Wesley, Reading, MA.

Lehmann, D.R., O'Shaughnessy, J., 1982. Decision criteria used in buying different categories of products. Journal of Purchasing and Materials Management 18 (1), 9–14.

Liu, J., Ding, F.-Y., Lall, V., 2000. Using data envolopment analysis to compare suppliers for supplier selection and performance improvement. Supply Chain Management: An International Journal 5 (3), 143–150.

Masella, C., Rangone, A., 2000. A contingent approach to the design of vendor selection systems for different types of co-operative customer/supplier relationships. International Journal of Operations & Production Management 20 (1), 70–84.

Min, H., 1994. International supplier selection: a multi-attribute utility approach. International Journal of Physical Distribution and Logistics Management 24 (5), 24–33.

Moore, D.L., Fearon, H.E., 1973. Computer-assisted decision-making in purchasing. Journal of Purchasing 9, 5–25.

Narasimhan, R., Stoynoff, K., 1986. Optimizing aggregate procurement allocation decisions. Journal of Purchasing and Material Management Spring, 23–30.

Pan, A.C., 1989. Allocation of order quantity among suppliers. Journal of Purchasing and Material Management Fall, 36–39.

Porter, M.E., 1980. Competitive Strategy. The Free Press, New York, NY.

Remko, I.V.H., 1998. Measuring the unmeasurable—measuring and improving performance in the supply chain. Supply Chain Management: An International Journal 3 (4), 187–192.

Roa, C.P., Kiser, G.E., 1980. Educational buyer's perception of vendor attributes. Journal of Purchasing Material Management 16, 25–30.

Roodhooft, F., Konings, J., 1996. Vendor selection and evaluation: an activity based costing approach. European Journal of Operations Research 96 (1), 97–102.

Rosenthal, E.C., Zydiak, J.L., Chaudhry, S.S., 1995. Vendor selection with bundling. Decision Science 26 (1), 35–48.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, NY.

Shapiro, B.R., Rangan, V.K., Sviokla, J.J., 1992. Staple yourself to an order. Harvard Business Review 70 (4), 113–122.

Sharma, D., Benton, W.C., Srivastava, R., 1989. Competitive strategy and purchasing decision. Proceedings of the 1989 Annual Conference of the Decision Science Institute, pp. 1088–1090.

Stamm, C.L., Golhar, D.Y., 1993. JIT purchasing attribute classification and literature review. Production Planning Control 4 (3), 273–282.

Stephens, S., 2001. Supply Chain Council and Supply Chain Operations Reference (SCOR) Model Overview. Supply Chain Council, Inc.

Tam, M.C.Y., Tummala, V.M.R., 2001. An application of the AHP in vendor selection of a telecommunications system. Omega 29, 171–182.

Treacy, M., Wiersema, F., 1993. Customer intimacy and other value disciplines. Harvard Business Review 71 (1), 84–93.

Turner, I., 1988. An independent system for the evaluation of contract tenders. Operations Research Society 39 (6), 551–561.

van Amstel, R.P., D'hert, G., 1996. Performance indicators in distribution. The International Journal of Logistics Management 7 (1), 73–82.

Wang, G., Huang, S.H., Dismukes, J.P., 2004. Product driven supply chain selection using integrated multi-criteria decision making methodology. International Journal of Production Economics 91 (1), 1–15.

Warfield, J.N., 1974. Structuring Complex Systems. Battelle Memorial Institute, Columbus, OH.

Weber, C.A., Current, J.R., 1993. A multiple-objective approach to vendor selection. European Journal of Operations Research 68, 173–184.

Weber, C.A., Current, J.R., Benton, W.C., 1991. Vendor selection criteria and methods. European Journal of Operations Research 50, 2–18.

Wilson, E.L., 1994. The relative importance of supplier selection criteria: a review and update. International Journal of Purchasing and Materials Management 30 (3), 35–41.

Youssef, M.A., Zairi, M., Mohanty, B., 1996. Supplier selection in an advanced manufacturing technology environment: an optimization model. Benchmarking for Quality Management & Technology 3 (4), 60–72.