OR Spectrum (2008) 30:401–430
DOI 10.1007/s00291-007-0120-5

REGULAR ARTICLE

Modeling strategic semiconductor assembly outsourcing decisions based on empirical settings

Jei-Zheng Wu · Chen-Fu Chien

Published online: 12 January 2008

Abstract In semiconductor supply chains, most chip makers focus on core competence of wafer fabrication and utilize assembly outsourcing to reduce operational costs, enhance capital-effectiveness of investments, and diversify the risks among the vendors. Assembly outsourcing decisions involve strategic partnerships with vendors and operational excellence for order allocations subject to production constraints, cost, delivery, and quality. This study aims to develop a decision framework in which preference over vendors at strategic level and order allocations at operational level can be integrated. Focusing on real setting in a semiconductor company, a decision support system embedded with proposed models was developed to evaluate vendor performance, allocate the orders, and generate the associated material requirement planning reports. The results showed practical viability of the proposed framework for modeling manufacturing strategy with the integration of optimized operational decisions.

Keywords Manufacturing strategy · Modeling and analysis for semiconductor manufacturing · Analytic hierarchy process · Mixed integer linear programming · Outsourcing · Vendor selection · Decision analysis

1 Introduction

New technologies and business models have had profound effect on how products and services are created and delivered. One of the most significant paradigm shifts is that businesses no longer compete as individual companies but rather as supply

J.-Z. Wu · C.-F. Chien (✉)
Department of Industrial Engineering and Engineering Management,
National Tsing Hua University, Hsinchu 30013, Taiwan
e-mail: cfchien@mx.nthu.edu.tw

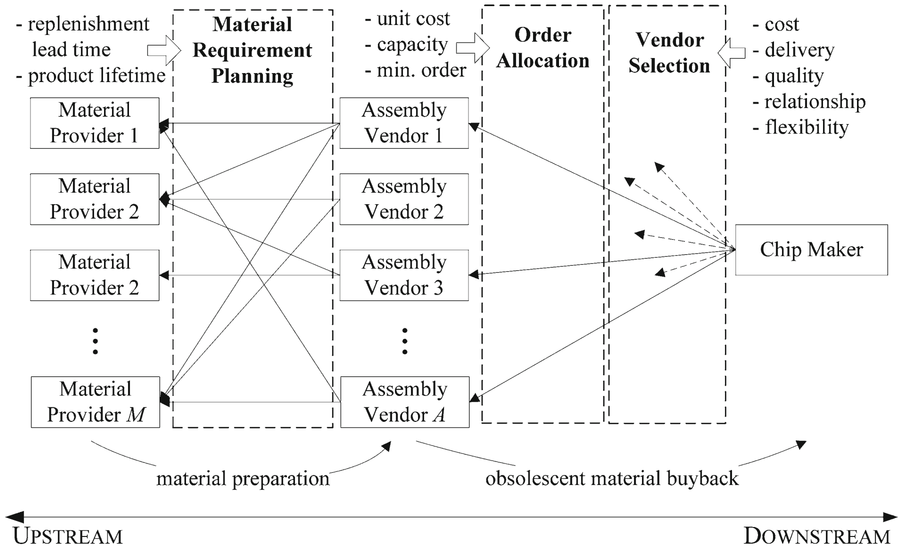

Fig. 1 Semiconductor assembly outsourcing

chains, especially in high-tech industries (Chien 2007). In order to improve capital effectiveness and return of investments, supply chain management of high-tech companies is driven by strategically focusing on core competences and outsourcing other activities to reduce capital investments and providing solutions to targeted segments of customers to pursue higher value proposition in the supply chain. Global competition and shortened product life cycle have forced collaboration and information sharing among partners in supply chains for risk pooling, capital investment effectiveness, and flexibility for quick response (Simchi-Levi et al. 2005). Gaonkar and Viswanadham (2005) modeled the strategic sourcing and collaborative planning, in which vendor selection could be very complicated subject to capacities and capabilities of component suppliers, subassembly manufacturers, and contract manufacturers. Indeed, the success of single company depends on its ability to manage and integrate collaborations with different networks with various partnerships so as to achieve the market advantages of customized products or horizontal specialized manufacturing services with the economies of scale (Chien 2007).

In semiconductor industry, most semiconductor manufacturing companies, namely chip makers, focus on wafer fabrication as their core competence through assembly outsourcing (Chien and Wu 2003; Leachman et al. 2007). However, the vendor selection and associated order allocations for assembly outsourcing are critical as illustrated in Fig. 1 owing to the following factors.

Firstly, decision makers have to tradeoff among multiple quantitative and qualitative attributes including cost, delivery, quality, and flexibility to evaluate the vendors.

Secondly, a number of orders for hundreds of products will be subsequently allocated to qualified and preferred vendors subject to the constraints such as production capability, capacity, the minimum order quantity, and delivery while considering different costs imposed by each vendor.

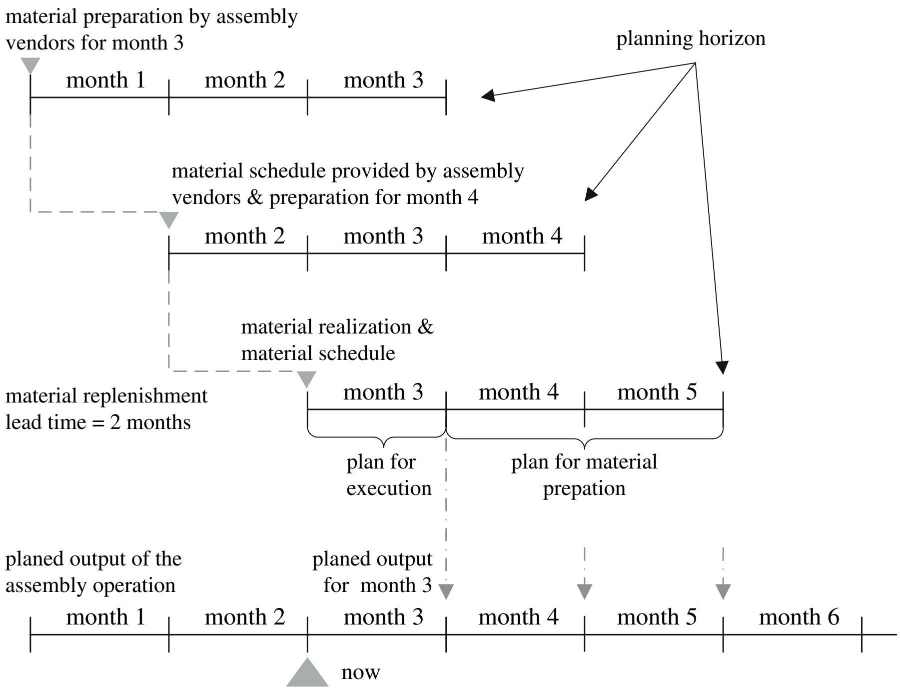

Fig. 2 Semiconductor assembly outsourcing

Thirdly, each outsourcing order requires specific assembly material such as lead frame or substrate, which in average takes 1- to 2-month replenishment lead time. In average, assembly materials accounted for 39.13% of total material costs that represents 13.82% of the semiconductor revenue for 2002 whereas gross margin of chip makers in North America were about 31% (Jones 2005). To avoid capacity or material shortage, chip makers have to provide their vendors with forecasted allocation plans for the following months. Therefore, the contingent allocation plan is rolling-based for revision according to a master plan of assembly scheduled output. For example, Fig. 2 shows that, at the beginning of third month, one vendor would receive a 3-month allocation plan that comprises the first month plan frozen for execution and the others as reference for material preparation. Then, for a material with 2-month replenishment lead time, the material schedule can be adjusted 1-month before the material preparation is realized. Nevertheless, the master plan for a near quarter is robust and the forecast quality of assembly within a quarter is fairly good, since most jobs forecasted to be done in the quarter for assembly have been ordered and released in the wafer fabrication facilities (fabs), in which they are fairly under control of the chip maker.

Fourthly, to reduce the influence of inflated orders and reduce the risks of material shortage, chip makers have to buy back unused materials that will obsolesce after stocked more than a period of time. On one hand, material shortage would lead to production delay and loss due to unmet demand. On the other hand, stocking materials would be uneconomical to vendors since one assembly vendor might deal with hundred types of materials at the same time. Thus, buy-back contracts are compromised solutions to maintain the partnership between chip makers and assembly vendors to ensure the vendors order needed materials based on forecasted allocation plans whereas chip makers take the responsibility to cover the expenses owing to over-optimistic plans. Indeed, the collaborative ways among supply chain entities to deal with demand uncertainty including buyback, risk sharing, order flexibility, and sales rebate would determine the qualifications of vendors and the corresponding relationships (Simchi-Levi et al. 2005).

Finally, because of equipment configuration variations, different assembly orders may consume the same type of material in one vendor, while consuming different materials in another vendor. Thus, the levels of material requirement were dedicated to individual vendors. To support shop-floor control in practice, MRP with finite capacity restriction (Taal and Wortmann 1997; Wuttipornpun and Yenradee 2004) should be incorporated in the proposed solution. Indeed, the present problem shows common characteristics that are not only relevant for the semiconductor industry. Yet, focusing a real setting of assembly outsourcing process allows in-depth investigation.

However, most existing studies focus only on specific problems such as vendor evaluation or order allocation (De Boer et al. 2001; Weber et al. 1991) and thus fall far behind to respond the needs in industry. From the perspective of advanced planning and plant coordination (Fleischmann et al. 2000; Grunow et al. 2003), semiconductor assembly outsourcing can be characterized by integral planning, optimization, and hierarchical production planning. That is, vendor selection and order allocation should be planned as an integral, with associated MRP, in which the interdependencies among the entities can be modeled accordingly and the optimal alternatives can be chosen to achieve overall objectives. In addition, hierarchical production planning that avoids thorough modeling of all tasks is practicable to implement. Owing to the inconsistency between strategic priorities and operational optimization, there is a gap between the perception and actual practice of vendor selection (Verma and Pullman 1998). The difficulty can be traced at least in part to the lack of a decision analysis framework in which the interrelation between the preferences among the vendors at strategic level and order allocations at the operational level can be structured and then be integrated for solving the present problem as a whole. Furthermore, planning tasks can be illustrated in the two dimensions of “planning horizon” and “supply chain process” (Fleischmann et al. 2000). Figure 3 shows the supply chain planning matrix of semiconductor assembly outsourcing in which flows of goods and information are specified. This study focuses on coordination and integration of long-term plans on vendor selection and cooperation and mid-term plans on order allocation and corresponding MRP based on the input of master planning. The short-term planning tasks that are aligned to output of mid-term plans will be discussed in another research.

Indeed, vendor selection strategy and vendor evaluation are semi-structured decision problems that require subjective judgments of decision makers to tradeoff among various performance levels of different attributes, while order allocation and MRP problems are structured decision problems in which the decision elements and their interrelations can be thoroughly structured. To fill the gaps, this study aims to construct a decision analysis framework that integrates strategic vendor evaluation based on decision analysis model, i.e., analytic hierarchy process (AHP), and optimal order

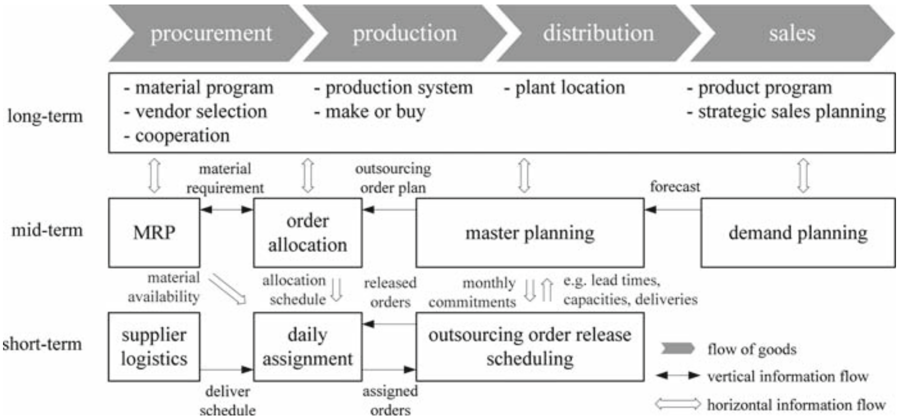

Fig. 3 The supply chain planning matrix of semiconductor assembly outsourcing

allocations based on mixed integer linear programming (MILP) with the associated MRP for assembly outsourcing. The proposed framework explicitly defines the decision elements and structures the interrelationship among them, while the embedded MRP minimizes potential material obsolescence costs. Furthermore, a strategic outsourcing decision support system (SODSS) embedded with proposed models was developed to analyze outsourcing planning decisions in real setting. For validation, an empirical study that also dealt with multiple deals and inventory management over time was conducted in Taiwan. The results showed practical viability of the proposed approach compared to a reference model and existing practice based on domain experts.

The remainder of this paper is organized as follows. Section 2 reviews related studies. Section 3 proposes a decision analysis framework that integrates vendor evaluation and planning models, describes the developed SODSS embedded with proposed models for solving the problem in real setting, and discusses theoretical implications of alternative modeling. Section 4 presents a study in real setting for validation. Section 5 concludes with discussions and future research directions.

2 Vendor selection

2.1 Vendor selection criteria

Many studies have discussed vendor selection criteria. In particular, Dickson (1966) suggested 23 criteria, among which quality was the most important. Weber et al. (1991) reviewed 74 related articles from 1966 to 1991 and identified the five most important criteria including net price, delivery, quality, production facilities and capacity, and geographic location. Stamm and Golhar (1993) suggested quality, reliable delivery, and frequent delivery as the three most critical criteria. Choi and Hartley (1996) clustered 24 criteria into 8 categorical criteria including finances, consistency, relationship, flexibility, technological capability, service, reliability, and price by principle component analysis. Sarkis and Talluri (2002) clustered vendor evaluation criteria into strategic performance metrics and organizational factors including cost, quality, time, flexibility, culture, technology, and relationship.

Based on literature review and domain knowledge, this study summarized the vendor selection criteria into hierarchy from strategic objectives, fundamental objectives, to the associated attributes as listed in Table 1. Structuring the hierarchy and thus specifying the attributes on which alternative vendor performances can be characterized and measured are crucial for vendor evaluation. Although constructing objective hierarchy is based on the preference structures of decision makers and also context-dependent, the decision makers may select appropriate subsets from Table 1 as a basis for specific vendor selection problems. The selected attributes should be complete, decomposable, measurable, non-redundant, and minimal to enhance construct validity of developed model (Keeney and Raiffa 1993).

However, the interrelationships between the criteria at strategic level and the criteria at operational level are complicated. For example, some criteria such as flexibility to adapting order changes (Bevilacqua and Petroni 2002; Simon 1973) are critical at strategic level but they are not easy to be directly and thus explicitly linked with order allocation decisions, though the needs for vendors to flexibly adapt order change often come from poor order allocations.

2.2 Vendor selection approaches

Many approaches have been developed for vendor selection including cost analysis, decision models, mathematical programming (MP), and decision support systems. However, many existing studies narrowed their scopes only for vendor evaluation models that are complex due to the inherent nature of tradeoffs among various qualitative and quantitative criteria (Jayaraman et al. 1999; Narasimhan et al. 2001; Weber and Current 1993). A vendor selection model applying the compensatory decision rule allows the decision makers to compensate a low rating on one criterion with a high rating on another criterion, while non-compensatory models specify different minimum acceptable thresholds for the criteria. In practice, both decision rules may be employed in a quasi-compensatory model (De Boer et al. 1998).

In particular, total cost of ownership (TCO) models considered many purchase-related costs to comprehend and manage the costs (Degraeve et al. 2000; Ellram 1995). Roodhooft and Konings (1997) applied activity based costing (ABC) approach for vendor selection to analyze the involved activities and determine the corresponding cost drivers. Alternatively, decision models including multi-attribute utility/value models (Min 1994), data envelopment analysis (DEA) (Narasimhan et al. 2001; Weber 1996), and AHP (Narasimhan 1983; Tam and Tummala 2001) have been employed for vendor evaluation and selection. In particular, AHP is a decision analysis technique by using linear multi-attribute weighting and is capable of dealing with both qualitative and quantitative criteria (Saaty 1980). DEA can valuate relative efficiency of decision making units (i.e. vendors) based on multiple input and output criteria without predetermining their relative weights (Chien et al. 2003), in which the efficient vendors are those positioning on a frontier with relative efficiency values equal to one. Since there

Table 1 Vendor selection criteria

Strategic objective	Fundamental objective	Attributes
Cost	Product cost	Net price (cost)
		Discounts
	Miscellaneous cost	Quality cost
		Freight charges
		Foreign exchange rate and custom
		After-sales service cost
		Purchase-related costs
	Cost activity	Compliance with cost analysis system
		Cost reduction activities
Quality and reliability	Quality assessment	Conformance quality
		Shipment quality
		Product reliability
	Quality assurance system	Statistical process control (SPC)
		ISO quality system
		Quality philosophy
		Product improvement
		Quality staff
Delivery	Delivery capability	Consistent/Reliable delivery
		Frequent delivery
		Delivery lead time
		Product development time
		Partnership formation time
		Exact quantity
		Small quantity
	Delivery condition	Freight terms
		Production facilities and capacity
		Geographical location
Technology	Manufacturing capability	Technical capability/expertise
		Operating controls
		Packaging ability
		Technological compatibility
		Current manufacturing facilities/capabilities
		Assessment of future manufacturing capabilities
	Design capability	Product design involvement
		Design capability
		Product development
		Supplier's speed in development
Support	Flexibility	Quota flexibility
		Short setup time
		Responsiveness to customer needs
		Response to changes and process flexibility

Table 1 continued

		Flexibility in changing the order
		Flexibility of response to customer's requirements
		Conflict resolution
	Service	Warranties and claims policies
		Repair service
		Training aids
		Service capability
		After sales support
		Supplier representative's competence
Management and Contest	Finance	Financial position
		Financial records disclosure
		Financial stability
		Capital investment
		Profitability
	Company Status	Performance awards and history
		Management and organization
		Labor relations record
		Top management compatibility
		Compatibility among levels and functions
		Strategic fit
	Environment	Political stability
		Green environment issues
Partnership	Business relationship	Communication system
		Reciprocal arrangements
		Amount of past business
		Co-operative relationship
		Proximity and closeness
		Long-term relationship
	Credit	Procedural compliance
		Reputation and position in industry
		Desire for business
		Attitude
		Impression
		Feeling of trust

are often multiple vendors with relative efficiency value all equal to one, it remains a decision problem for order allocation among the efficient vendors with efficiency all equal to one and other vendors with different efficiency values.

In addition, MP models explicitly formulate the decision problems and the objective functions into mathematical forms subject to constraints such as capacities and minimum order quantities (Jayaraman et al. 1999; Weber and Current 1993). For example, Arunkumar et al. (2005) considered minimum order quantities and minimum business allocated for selected vendors to solve the problem with quantity discounts using lexicographic method. Karpak et al. (1999) employed Visual interactive goal programming (VIGP) to interact with decision makers during the model building and solution process based on Pareto Race (Korhonen and Wallenius 1988) for vendor selection. Weber and Current (1993) used multi-objective programming model to simultaneously minimize total monetary cost of purchases, total number of late deliveries, and total number of rejected units to obtain a set of non-dominated order allocation scenarios for decision support. Bevilacqua and Petroni (2002) developed a fuzzy logic-based approach to deal with insufficient, imprecise, or incomplete information for vendor selection. Sadrian and Yoon (1994) implemented a procurement decision support system where the supplier offered discounts on total dollar amount of sales volume.

Furthermore, a number of studies have combined different approaches for solving problems related to vendor selection. In particular, Degraeve and Roodhooft (2000) developed a MILP model to minimize the TCO, while considering inventory management policy based on ABC information. Weber et al. (2000) determined the number of vendors by using MOP for order quantity and evaluated relative efficiency of the vendors by using DEA. Ding et al. (2005) proposed a simulation optimizer for vendor selection by using genetic algorithm (GA) for searching approximations of optimal supplier portfolio and incorporating a discrete-event simulation system for detailed modeling of the dynamic interrelatedness between vendor selection and supply chain performance. Ghodsypour and O'Brien (1998) combined AHP and linear programming (LP) to optimize order allocations by maximizing the total value of purchasing (TVP) that is the sum of order quantities assigned to each vendor weighted by its rating, subject to the constraints of vendors and the quality and service requirements of the buyers. However, the TVP model cannot address the gap between the strategic decision preference and actual allocations when the two decisions involve different levels of information granularity. Table 2 summarizes related methodologies for vendor selection.

Indeed, the present problem involves not only vendor evaluation but also sequential decisions to determine the corresponding orders to outsource and thus allocate among the preferred and qualified vendors in tandem (Jones 2005; Weber and Current 1993). Multiple deals and inventory management over time are increasingly important as the employments of SCM and global logistics (De Boer et al. 2001; Degraeve et al. 2000), in which multiple-deal models have to consider interdependencies among different products across the product groups while single-deal business models considered one product or a group of items at a time. To address the needs in real setting, this study aims to evaluate the performance of vendors and allocate the orders among them in multiple deals based on given demand forecasts subject to vendor performance and constraints, while considering inventory management and material planning over time.

3 Research framework

This study proposes a two-phase framework as shown in Fig. 4 to link preferences over the vendors with operational performance resulting from associated planning models for order allocations and material inventory management. The first phase deals with

Table 2 Vendor selection methodologies

Study	Interrelationship between vendor evaluation and order allocation	Multiple deals and inventory management over time	Problem structure
AHP (Tam and Tummala 2001)			Semi-structured
Outranking (De Boer et al. 1998)			Semi-structured
DEA (Weber 1996)			Semi-structured
VIGP (Karpak et al. 1999)		Explicitly modeled	Semi-structured
TCO (Roodhooft and Konings 1997)	As extended study		Structured
Simulation + GA (Ding et al. 2005)	GA search vendor portfolio as simulation evaluates performance		Structured
MOP + DEA (Weber et al. 2000)	Limit number of selected vendors in MOP		Structured and semi-structured
TCO + MILP (Degraeve and Roodhooft 2000)	If a vendor is selected, at least some products must be bought	Explicitly modeled	Structured
AHP + LP (Ghodsypour and O'Brien 1998)	AHP ratings are used as coefficients in LP	As extended study	Semi-structured and structured

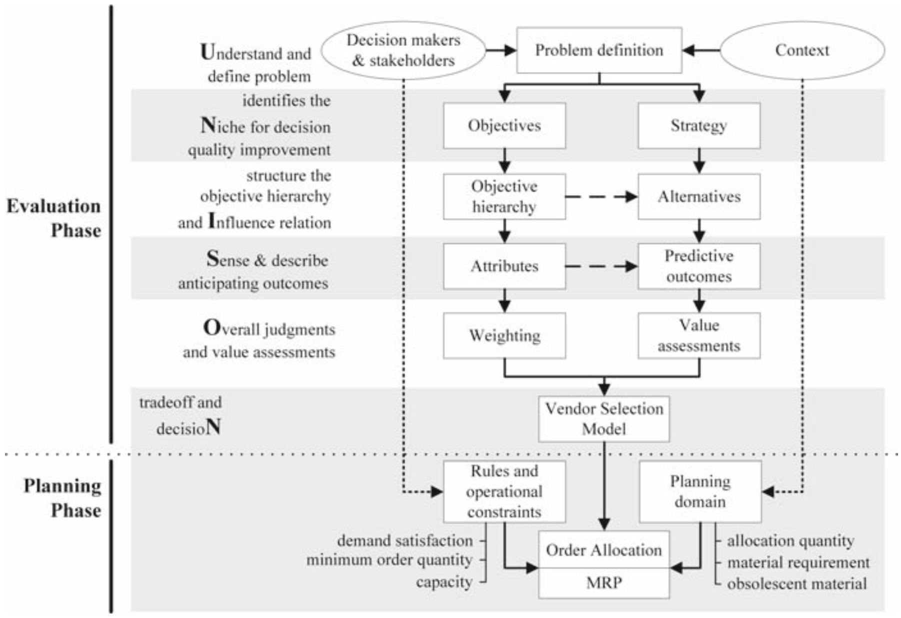

Fig. 4 Conceptual framework

strategic vendor selection and evaluation with respect to multiple attributes that are formulated to link strategic criteria with operational performance to determine the corresponding shares of outsourced business allocated to the preferred vendors. The second phase then optimizes the allocations of various orders to preferred and qualified vendors subject to operational constraints to meet the strategic objectives of business shares among the vendors while minimizing overall costs. The associated plans of required materials can also be derived and specified. In practice, to ensure that the selected vendors will reserve sufficient capacity and prepare corresponding assembly materials for the next months based on the forecasted allocation plans, there are often contracts or commitments between chip makers and vendors to buy back unused materials that will obsolesce after stocked more than 10 months.

3.1 The approach

Based on UNISON framework (Chien 2005; Chien et al. 2007), the first phase consists of six steps for vendor evaluation: (1) understand and define the problem, (2) identify the niche for decision quality improvement, (3) structure the objective hierarchy, generate the alternatives, and clarify influence relationships among uncertain events, (4) sense and describe expected outcomes, (5) overall judgments and value assessments, and (6) tradeoff among the attributes and make the decision.

Step 1: Vendor selection is fairly static authorized by top management, while monthly order allocations are dynamic performed by engineers or planners. There is an inconsistency between strategic priorities over selected vendors and operational optimization to minimize outsourcing costs while considering the operational constraints and delivery requirements.

Step 2: Since most existing studies focusing only on sub-problems of vendor evaluation or order allocation fall far behind to respond the needs in industry, there is a niche to solve the present problem by formulating the problem into two-level decisions to achieve the interrelated objectives at strategic vendor selection and operational order allocation. Furthermore, to minimize potential material obsolescence costs, MRP considering capacity restriction should be incorporated in the proposed solution. Fundamental objectives reflect what the decision makers really want to accomplish. In practice, there are gaps and resolution difference between the considerations involved in the decisions at different levels. For example, vendor performance attributes such as "on-time delivery" and "consistent delivery" are considered for vendor evaluation, yet such attributes cannot be directly incorporated as input factors into planning model for order allocation that will involve complicated interrelationship among criteria, expected outcomes, and constraints. The proposed framework aimed to allow substantially meaningful consideration of such attributes via linking the fundamental objectives of order allocations and the corresponding delivery performances of allocated vendors.

Step 3: Based on vendor selection objectives summarized in Table 1 and the needs for a specific problem, the objectives can be identified and categorized into strategic and operational levels. Top-down decomposition and bottom-up synthesis (Clemen 1996) can be employed to structure the hierarchy of fundamental objectives. Following

Clemen (1996), top-down decomposition asks decision-makers "what do you mean by that upper-level objective?" whereas bottom-up synthesis asks for "of what more general objective is this aspect?" Then, the associated attributes for evaluating the performance of alternative vendors are identified and formulated to link them with the variables in order allocation models constructed in the second phase. Furthermore, the constructed objective hierarchy can reduce complexity of the evaluation process as pair-wise comparisons are employed in AHP (Saaty 1980). A detailed illustration of the approach for structuring the objective hierarchy for ERP system selection can be seen in Wei et al. (2005).
Step 4: The performances of vendors are measured with respect to the attributes based on historical data of performance in light of anticipating outcomes from allocated orders. Indeed, the proposed framework formulate the present problem to allow the linkages between the measurements of the attributes at strategic and operational levels to reduce the conflict of poor vendor performance due to poor order allocations.
Step 5: According to the preference structure of the decision maker, AHP (Saaty 1980) is employed to conduct pair comparisons to determine relative weightings of the attributes and the relative values among the vendors based on their performances with respect to each of the attributes. In addition, alternative multi-attribute decision analysis methodologies may be employed for value assessments.
Step 6: The relative preferences of the vendors can be derived from the aggregated values of the vendor performances based on AHP model. Thus, the corresponding shares of total outsourcing business among the preferred vendors can be determined according to the relative preferences over the vendors, while detailed allocated orders and products will be determined in the next phase. Indeed, vendor selection is also a portfolio selection problem (Chien 2002), in which diversification among the qualified vendors for risk management and maintaining bargain power over the vendors is also a concern. Thus, rather than relying on one or two major vendors, the preferences over the qualified vendors are used as a basis to divide outsourcing business among the vendors so as to drive preferred operations to strengthen desired partnerships.

While trying to meet the business shares among the preferred vendors, the second phase is to construct an optimization model for order allocation planning to minimize overall outsourcing costs subject to resource constraints, operation capabilities, and capacity constraints of the vendors. That is, the complex interrelationships among the operational factors will be considered and linked with vendor performance attributes to integrate operational planning and strategic business sharing to provide constructive mechanism to guide the vendors to preferred performance. Furthermore, slack analysis of resource constraints and associated monitoring mechanism are developed in SODSS to identify associated planning of packaging materials required for the vendors. The operational performances of vendors will then be evaluated according to the planning results of order allocations to drive long term favorable relationships and vendor performance.

In sum, this two-phase framework considers the interdependences among the attributes at strategic and operational levels to integrate vendor selection and order allocations so that the optimized order allocations will align with the preferences among the vendors.

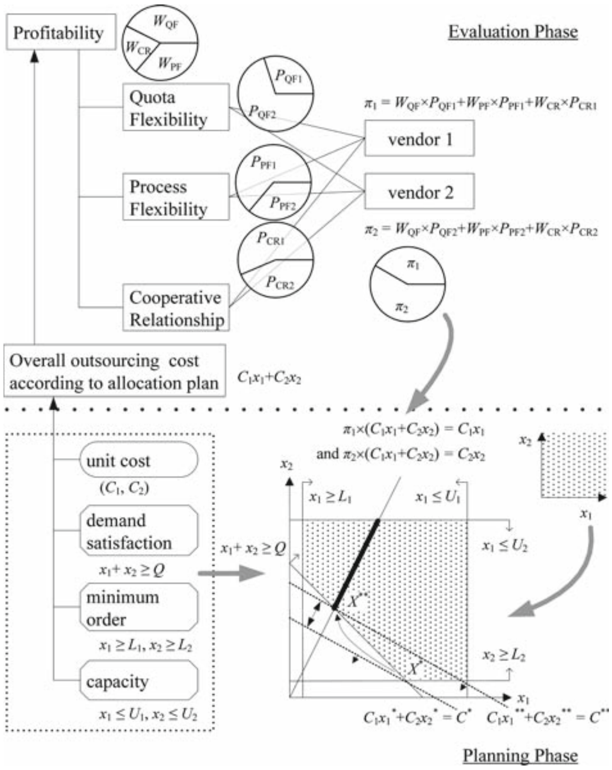

Fig. 5 An illustrative modeling

3.2 Illustrative modeling

To illustrate modeling involved in the proposed framework, an example that simplifies the high-dimensional product and material structure without considering material costs and constraints is used as shown in Fig. 5. A full planning model based on empirical data in real setting will be discussed in Sect. 4. Suppose the decision maker would like to allocate the orders of total amount Q to two qualified vendors. The notations used in this illustration are specified as follows.

C^*	optimal cost exclusive of vendors' relative ratings
C^{**}	optimal cost of the order allocation problem inclusive of vendors' relative ratings
C_v	unit cost of vendor v, $v \in \{1, 2\}$
W_c	relative weight of attribute c, $c \in$ {QF, PF, CR}
L_v	minimum order restricted by vendor v, $v \in \{1, 2\}$
Q	total amount of a batch of divisible orders
x_v	decision variable determining the amount of orders allocated to vendor v, $v \in \{1, 2\}$

x_v^*	optimal amount of orders allocated to vendor v exclusive of vendors' relative ratings, $v \in \{1, 2\}$
X^*	optimal combination of order allocation exclusive of vendors' relative ratings
x_v^{**}	optimal amount of orders allocated to vendor v inclusive of vendors' relative ratings, $v \in \{1, 2\}$
X^{**}	optimal combination of order allocation inclusive of vendors' relative ratings
U_v	capacity limit offered by vendor v, $v \in \{1, 2\}$
P_{cv}	relative preference value of vendor v with respect to attribute $c, c \in \{\text{QF, PF, CR}\}$, $v \in \{1, 2\}$
Π_v	overall relative preference rating of vendor v, $v \in \{1, 2\}$
φ_v	allocation excess variable with respect to vendor v
Y_v	allocation shortage variable with respect to vendor v
Z_v^*	minimum total allocation excesses and shortages with respect to vendor v

Following the proposed framework, the strategic objective of maximizing long-term profitability (PR) and the associated attributes including "quota flexibility" (QF), "process flexibility" (PF), and "cooperative relationship" (CR) are considered. Then, AHP is employed to derive relative weights of these attributes W_{QF}, W_{PF}, and W_{CR} with respect to the strategic objective PR, where $W_{\text{QF}} + W_{PF} + W_{\text{CR}} = 1$. Similarly, the relative preference values over Vendor 1 and Vendor 2 with respect to each of the attributes QF, PF, and CR, i.e., P_{QF1}, P_{PF1}, P_{CR1}, P_{QF2}, P_{PF2}, and P_{CR2}, can be derived, where $P_{\text{QF1}} + P_{\text{QF2}} = 1$, $P_{\text{PF1}} + P_{\text{PF2}} = 1$, and $P_{\text{CR1}} + P_{\text{CR2}} = 1$. Thus, the overall relative ratings of Vendor 1 and Vendor 2 can be determined as $\pi_1 = W_{\text{QF}} \times P_{\text{QF1}} + W_{\text{PF}} \times P_{\text{PF1}} + W_{CR} \times P_{\text{CR1}}$ and $\pi_2 = W_{\text{QF}} \times P_{\text{QF2}} + W_{\text{PF}} \times P_{\text{PF2}} + W_{\text{CR}} \times P_{\text{CR2}}$.

In the second phase, an optimal allocation model is constructed, in which the decision variables are the amount of orders allocated to Vendor 1 and Vendor 2, i.e., x_1 and x_2, respectively. Without loss of generality, specific constraints including demand satisfaction, minimum order quantity, and maximum capacity are considered. In particular, the total amount of orders allocated to the two vendors should satisfy demand, i.e. $x_1 + x_2 \geq Q$. The minimum order quantity and maximum capacity of vendor 1 and vendor 2 are denoted as (L_1, U_1) and (L_2, U_2), respectively. The costs of different vendors are denoted as C_1 and C_2, respectively. Thus, the LP model of order allocation can be constructed to minimize total outsourcing cost, i.e. $C_1x_1 + C_2x_2$, to increase profitability. However, there is a gap between the optimal solution $X^* = (x_1^*, x_2^*)$ solved for order allocation and strategic preferences over the vendors, i.e. (π_1, π_2), since vendor selection attributes including QF, PF, and CR are omitted from the LP model. In other words, the performances of QF, PF, and CR of a vendor cannot be specified and linked in terms of order quantities allocated to the corresponding vendor.

To fill the gap, strategic preference over the vendor is used as a proxy attribute denoting corresponding share of outsourced assembly business. Therefore, $\pi_1 = C_1x_1/(C_1x_1 + C_2x_2)$ is derived, implying that the more preferred vendor will get more business. Consequently, the feasible region will be limited to the thick line segment as shown in Fig. 4 and the optimal solution will move from X^* to $X^{**} = (x_1^{**}, x_2^{**})$ with additional cost $C^{**} - C^* > 0$. Then, the relative preference evaluated in the first phase will be integrated with the relative share allocated to the vendor in the second phase. This hierarchical modeling concept conforms to the behavior of decision-making in practice, where the alignment of order allocation and strategic vendor preference will take extra cost as the additional considerations may rule out some alternatives. Indeed, the gaps are mainly owing to information asymmetry between strategic and operational levels and thus more extra cost may be needed to align the two-level decisions in practice.

To deal with potential infeasibility, the lexicographic (preemptive) goal programming (GP) can be applied to iteratively generate solutions when priority orders of goals are predetermined. Combining with GP, the proposed model can minimize the total differences between the intensities of relative importance and the portions of contribution to the ultimate objective and afterward solve the original problem subject to the constraints aligning to the relative ratings. Therefore, GP firstly seeks to minimize the differences from allocation excess or shortage with respect to the relative share of preferred vendors, i.e., $(\varphi_1 + \gamma_1 + \varphi_2 + \gamma_2)$, subject to constraints as shown in Fig. 4. That is, $C_1x_1 = \pi_1(C_1x_1+C_2x_2)+\varphi_1-\gamma_1$ and $C_2x_2 = \pi_2(C_1x_1+C_2x_2)+\varphi_2-\gamma_2$. If the original problem is feasible, GP will obtain minimal difference Z_1^* and Z_2^*. Then, GP minimizes total allocation cost, i.e., $C_1x_1 + C_2x_2$, subject to the above constraints and additional constraints $\varphi_1 + \gamma_1 = Z_1^*$ and $\varphi_2 + \gamma_2 = Z_2^*$.

3.3 Strategic outsourcing decision support system

To deal with the present problem efficiently in real setting, following the proposed framework in Fig. 4, this study developed a SODSS embedded with the vendor evaluation and order allocation models based on AHP algorithm and ILOG OPL (ILOG 2005), respectively. Figure. 6 illustrates serial decision-making procedures for vendor evaluation and selection, order allocation, and consequent MRP plan involved in the developed SODSS. The graphical user interface (GUI) and the data integrator of the SODSS were designed and implemented in a Microsoft Access database application. Then, the SODSS would invoke ILOG OPL with established order allocation models and iteratively solve the two-stage planning model for order allocation through the core MILP engine equipped by ILOG CPLEX. The linkage between the SODSS and its optimization engine was based on ILOG OPL application programming interface. Subsequently, the SODSS could create reports for allocation planning and material preparation that were connected to the supply chain management system in the case company. All data were created in the format of Microsoft Excel for ease of presentation and manipulation.

In addition, the SODSS provided auxiliary functions such as user-defined allocation and current status tracking through the GUI. In particular, the SODSS allowed the decision maker to input intended assignments based on business judgments or special customer requirements. For example, an order might be assigned to a specific vendor in advance according to customer's request though the bill-of-material (BOM) table has defined multiple candidate vendors for the order. Then, GP technique would be

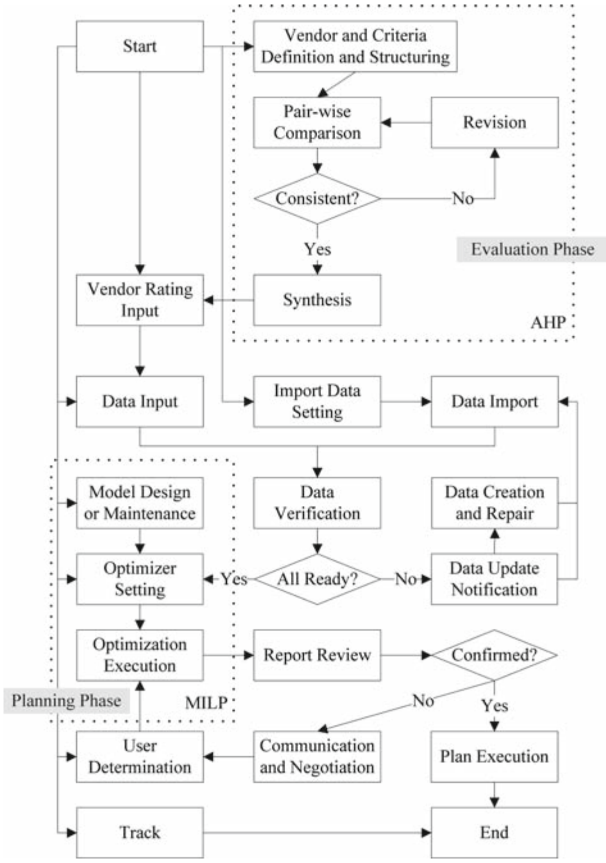

Fig. 6 A decision-making process flow of the developed SODSS

able to resolve possible infeasibility due to user's assignment. The differences between the solution incorporating user's assignments and the optimal solutions generated by SODSS would be reported to support the decision maker to make final allocation decisions. Prior to plan execution, the outcomes of SODSS were reviewed and confirmed by domain experts. Thus, the developed SODSS can also assist in the verification and validation of embedded models (Chien and Wu 2003).

Indeed, the developed SODSS was an integration of multiple subsystems that provided user interface, data transformation, reporting, preference elicitation, and optimization. The SODSS can also extract and transform needed data from various systems including the manufacturing execution system and supply chain management system to facilitate the involved analyses. To ensure data integrity, several data verification procedures were embedded, in which inconsistent data from different sources would be detected and the corresponding data verification and maintenance actions would thus be triggered.

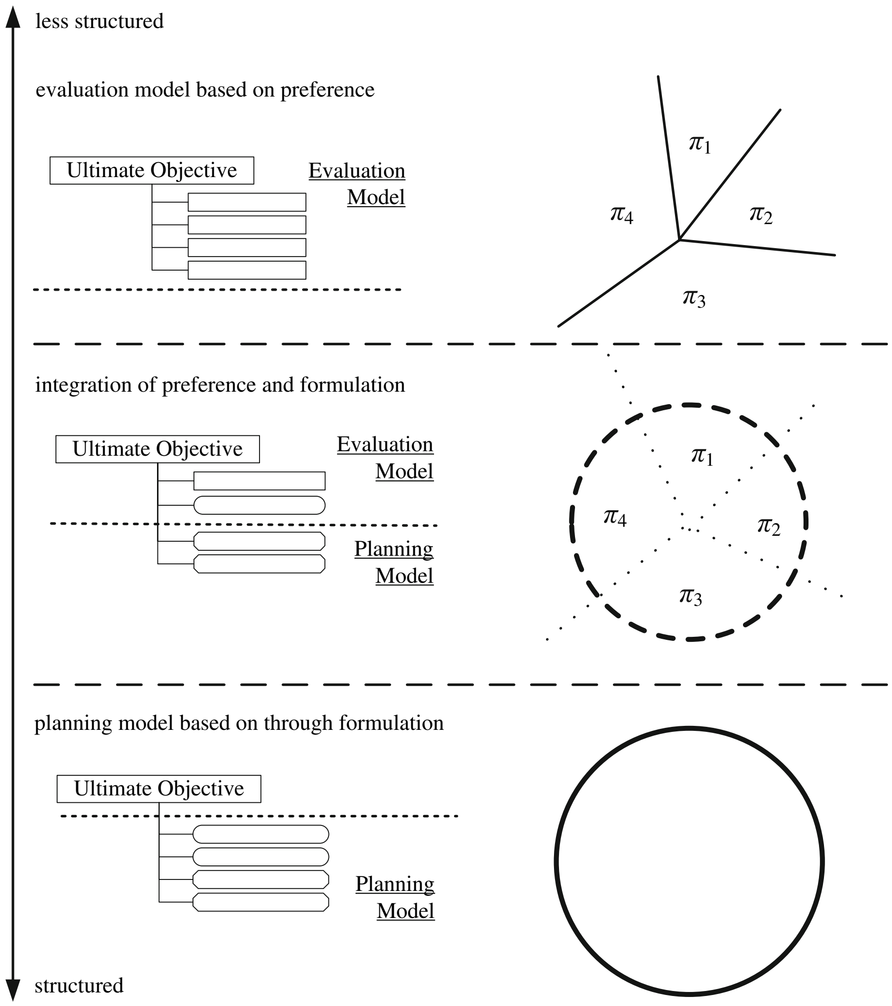

Fig. 7 The spectrum of the degrees of problem structure of different formulations

3.4 The spectrum of problem structure

The limitation of existing approaches for the present problem may be caused by gap between the formulation of strategic vendor evaluation that is indeed a semi-structured decision problem and the formulation of order allocation that is a structured decision problem. Figure 7 illustrates the degrees of problem structure of alternative formulations of a specific decision problem constituting a continuous spectrum. Thus, there is a tradeoff between alternative formulations.

On one hand, existing studies that focused on vendor selection and evaluation models (De Boer et al. 1998; Karpak et al. 1999; Tam and Tummala 2001; Weber 1996) elicit decision maker's preferences over the qualified vendors (and associated allocations implicitly) with respect to the objectives. However, it is difficult to articulate the assessment of each alternative combination of the vendor and its allocated order and thus tend to ignore the combinatorial complexities involved in order allocations.

On the other hand, existing studies (Degraeve and Roodhooft 2000; Ding et al. 2005; Roodhooft and Konings 1997; Weber et al. 2000) that tried to explicitly formulate the present problem focused more on order allocation with quantitative attributes of vendor performance. However, owing to dynamic problem nature of order allocation and multi-attribute tradeoffs among the vendors, it is difficult to have thorough formulation of semi-structured vendor selection and structured order allocation within the same model. Furthermore, the decisions at the strategic and operational levels have different lead time and the involved information requires different granularity, with information asymmetry between the two-level decision makers.

Thus, the proposed framework is designed to explicitly structure the present problem as a whole into two phases and elucidate the hierarchical linkage between the semi-structured vendor selection and structured order allocation. Indeed, the proposed framework incorporates the "authority" in an organization (Simon 1997), in which the superior frames and transmits the decisions with the expectation that they will guide the actions of the subordinate. The subordinate will be bounded by the decisions from the superior and try to follow them as a guideline as much as possible. In practice, the superior decision maker will qualify the vendors based on performance evaluation and then determine the winners with corresponding shares of outsourced business. Then, the subordinate decision maker will qualify the preferred vendors based on operational constraints including their capability and capacity for specific orders and then allocate each of the orders to the qualified vendors to minimize total outsourcing cost, while aligning with strategic attributes such as the shares among preferred vendors. Thus, order qualifiers and winners can be determined and linked in this framework for both the strategic level and operational level, respectively.

4 An illustration based on empirical data

4.1 Background

This study was originally inspired by a realistic assembly outsourcing problem in an integrated semiconductor device manufacturer that is a world leading provider for Mask ROM and Flash memory for various applications in consumer electronics. To manage the relationships with assembly vendors, the executives of this company will evaluate the performance of the vendors and thus determine the qualification of different levels of partnerships with corresponding shares of outsourced business. Then, the manager for planning assembly outsourcing has to determine the allocations of monthly outsourcing orders among the preferred vendors for the next month based on the rolling production plan from their supply chain management system, subject to operational constraints for specific products.

In practice, due to the involved combinatorial complexity of this problem, planning engineers tend to make order allocation decisions based on simple heuristics. However, the existing heuristic is myopic that depends on the experience of the decision maker and simple sorting rules as follows.

Existing heuristic in practice

Step 1: Sort the orders in descending in a list based on the order volume.
Step 2: Select the first order from the list.
Step 3: Allocate the order to a vendor charging the lowest price subject to capacity, available materials, and minimum order requirement.
Step 4: If the order remains unallocated volume, temporarily remove the chosen vendor from the candidate vendor set and go to Step 3; otherwise, remove the chosen order and retrieve the candidate vendor set.
Step 5: If the order list is not empty, go to Step 2.
Step 6: Adjust order allocation results by try-and-error to align with the preference over the vendors as much as possible.
Step 7: Repeat the above steps for next periods until all plans on the horizon were done.

The resolution of the allocation plan is at the product group level. A specific die-base product group can be identified by a combination of key attributes including package, pin count, body size, green part, and product code, while a specific material can be indicated by its attributes including package, pin count, vendor, pad size, and material type. Different technology processes can be employed to produce different types of product groups for various applications of consumer electronics. For example, as shown in Fig. 8, a wafer-base product going through the wire-bonding assembly process will consume lead frame materials and divide into pin-thru-hole packages, e.g., dual in-line package (DIP) and pin grid array (PGA) package, with multiple pins. In addition, the functionality of a product is specified in the integrated circuits (IC) chip that is encoded as product code in the database. In addition, the green part indicates which kind of alloy is utilized for complying with restriction of the use of hazardous substances during the process.

Then, based on monthly planning outsourcing decision, the associated material requirement planning including assembly material allocation and inventory management is also needed based on the many-to-many relations in a BOM table stored in an enterprise resource planning system. The BOM table was the pivot for products to be allocated to preferred vendors by using designated materials. Everyday each vendor would update the status of assembly materials through the electronic data interchange communication system. The overall required data for outsource planning are multi-dimensional with different combinations of keys as shown in Table 3.

4.2 Problem structuring

Following the proposed framework, the problem is structured into two phases, in which an AHP model is developed for vendor evaluation to determine relative shares of outsourced business among the preferred vendors and a MILP model is constructed to optimize the order allocation while aligning to the business shares of the qualified vendors.

Let g denote green part, h denote product code, i denote package, j denote pin count, k denote body size, l denote pad size, m denote material type, p denote planning

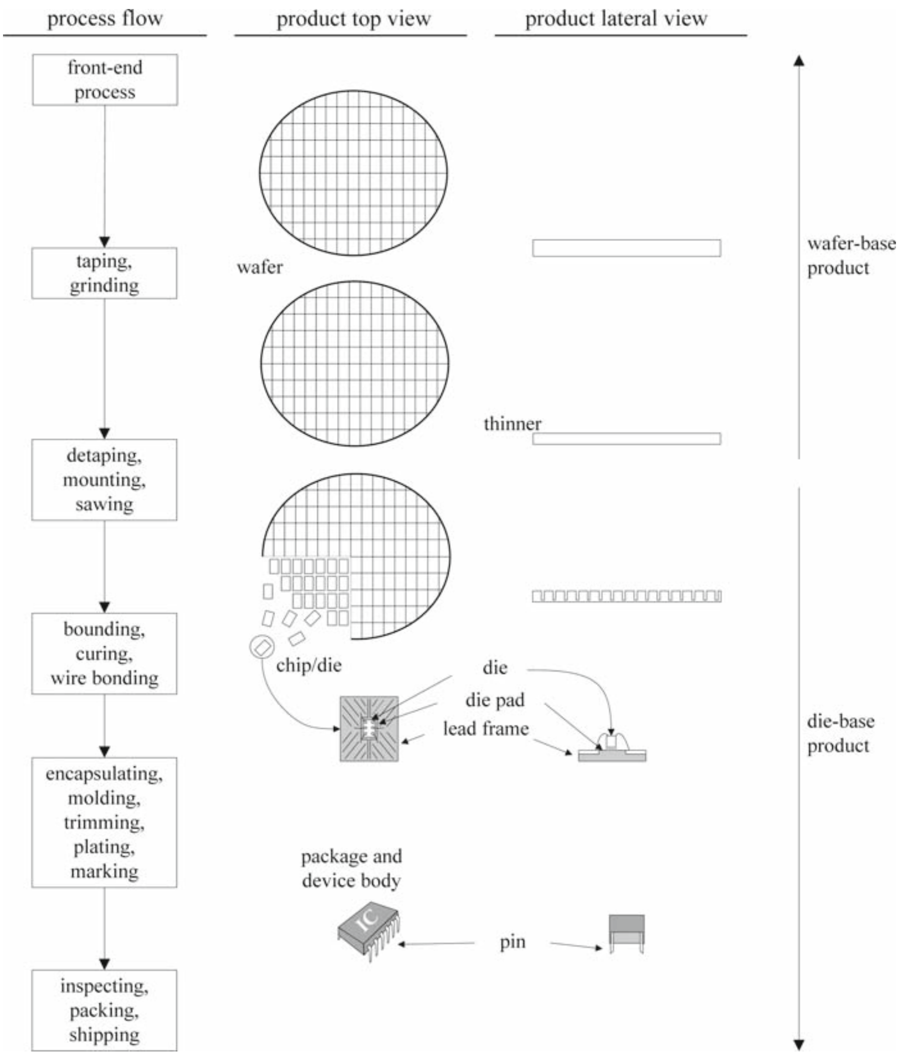

Fig. 8 Illustration of semiconductor wire-bonding assembly process

period, and v denote vendor. The following parameters and variables are used in the models.

B_{lmv}^{ij}	obsolescent material buyback cost
C_{mv}^{gijk}	unit cost of allocation
D_{p}^{ghijk}	demand
L_m	material lifetime
M_{lmv}^{ij}	on-hand material
N_{lmv}^{ij}	on-order material coming next period

Table 3 Datum keys relationship

Data	key							
	Green part	Product code	package	Pin count	Body size	Pad size	Material type	Vendor
BOM	•	•	•	•	•	•	•	•
Capacity			•	•				•
Demand	•	•	•	•	•			
Material buyback			•	•		•	•	•
Material lifetime							•	
Material on-hand			•	•		•	•	•
material on-order			•	•		•	•	•
Minimum batch size			•	•		•	•	•
Unit cost	•		•	•	•		•	•
Vendor rating								•

O^{ij}_{lmv} minimum material order batch size
U^{ij}_{v} capacity upper limit
ε a small positive number
π_{pv} allocation ratio, i.e. the relative rating of each vendor
φ_{pv} allocation excess variable
γ_{pv} allocation shortage variable
x^{ghijk}_{lmpv} allocation order quantities variable
η^{ij}_{lmpv} material requirement variable
λ^{ij}_{lmpv} material shortage variable
z^{ij}_{lmpv} material requirement indicator variable
ξ^{ij}_{lmpv} anticipating obsolescent material
ζ^{ij}_{lmpv} obsolescent material slack

The proposed framework utilized GP as an intermediary to maintain the integration of two-phase decisions. GP firstly solve the alignment problem (P1) to minimize total allocation excesses and shortages with respect to the relative shares of the preferred vendors, subject to the constraints including demand satisfaction, minimum order constraints, and capacity limits. Then, the allocation plan can be obtained by solving the cost minimization problem (P2) that minimizes the total allocation cost restricted by the above constraints inclusive of a constraint representing the adjustment of relative shares of the vendors. Both problems are formulated as MILP.

In (P1), (1) is to minimize total allocation excesses and shortages; (2) calculates the allocation excesses and shortages; (3) ensures demands being fulfilled; (4) satisfies capacity limits. In addition, (5) to (7) express the equilibrium relation between order allocation and material requirement; (8) and (9) estimate anticipating obsolescent materials; (10) limits the minimum quantities for material replenishment; (11) and (12) restrict variables boundaries.

After (P1) is solved, (P2) replaces the objective function with the total cost function as shown in (13), while (14) guarantees minimum allocation excesses and shortages with a very small positive ε to avoid infeasibility caused by round-off errors during computation on computers. Indeed, a larger ε can relax constraint (14), which thus contributes to the reduction of total cost and the increase of allocation deviations (excesses and shortages) from the desired shares among the preferred vendors. In other words, ε plays a role of tradeoff between alignment and total costs. However, it is suggested to keep ε small, e.g., 0.001, to ensure the achievement of the first order objective, i.e., minimizing the allocation excesses and shortages, considering strategic preference over the vendors.

Alignment problem (P1)

$$\min \sum_{pv} (\varphi_{pv} + \gamma_{pv}) \tag{1}$$

subject to

$$\sum_{ghijklm} C_{mv}^{gijk} x_{lmpv}^{ghijk} = \pi_{pv} \sum_{ghijklmv} C_{mv}^{gijk} x_{lmpv}^{ghijk} + \varphi_{pv} - \gamma_{pv}, \quad \forall p, v \tag{2}$$

$$\sum_{lmv} x_{lmpv}^{ghijk} = D_p^{ghijk}, \quad \forall g, h, i, j, k, p \tag{3}$$

$$\sum_{ghkmv} x_{lmpv}^{ghijk} \le U_v^{ij}, \quad \forall i, j, p, v \tag{4}$$

$$\sum_{ghk} x_{lm1v}^{ghijk} = M_{lmv}^{ij} + \eta_{lm1v}^{ij} - \lambda_{lm1v}^{ij}, \quad \forall i, j, l, m, v \tag{5}$$

$$\sum_{ghk} x_{lm2v}^{ghijk} = N_{lmv}^{ij} + \lambda_{lm1v}^{ij} + \eta_{lm2v}^{ij} - \lambda_{lm2v}^{ij}, \quad \forall i, j, l, m, v \tag{6}$$

$$\sum_{ghk} x_{lmpv}^{ghijk} = \lambda_{lm,p-1,v}^{ij} + \eta_{lmpv}^{ij} - \lambda_{lmpv}^{ij}, \quad \forall i, j, l, m, v, p > 2 \tag{7}$$

$$\sum_{ghk} \sum_{1<p\le 1+L_m} x_{lmpv}^{ghijk} = \lambda_{lm1v}^{ij} - \xi_{lm1v}^{ij} + \zeta_{lm1v}^{ij}, \quad \forall i, j, l, m, v \tag{8}$$

$$\sum_{ghk} x_{lm,p+L_m,v}^{ghijk} = \lambda_{lmpv}^{ij} - \eta_{lm,p-1,v}^{ij} - \xi_{lmpv}^{ij} + \zeta_{lmpv}^{ij}, \quad \forall i, j, l, m, v, p > 1 \tag{9}$$

$$O_{lmv}^{ij} \times z_{lmpv}^{ij} \le \eta_{lmpv}^{ij} \le BigM \times z_{lmpv}^{ij}, \quad \forall i, j, l, m, p, v \tag{10}$$

Table 4 Unit cost

Vendor	Body size of the product	
	a	b
A	\$ 20	\$ 10
B	\$ 25	\$ 12

$$x_{lmpv}^{ghijk} \geq 0, \quad \forall g, h, i, j, k, l, m, p, v \tag{11}$$

$$z_{lmpv}^{ij} \in \{0, 1\}, \eta_{lmpv}^{ij}, \lambda_{lmpv}^{ij}, \xi_{lmpv}^{ij}, \zeta_{lmpv}^{ij} \geq 0, \quad \forall i, j, l, m, p, v \tag{12}$$

Cost minimization problem (P2)

$$\min \sum_{ghijklmpv} C_{mv}^{gijk} x_{lmpv}^{ghijk} + \sum_{ijlmv} B_{lmv}^{ij} \xi_{lmpv}^{ij} \tag{13}$$

subject to (2)–(12) and

$$\sum_{pv} (\varphi_{pv} + \gamma_{pv}) \leq Z^* + \varepsilon \tag{14}$$

4.3 Numerical example

Assume two qualified vendors $\{A, B\}$ are evaluated based on their performance and their relative shares of orders as 0.7 and 0.3 are determined based on pair comparisons in AHP. The orders of two products with body size $\{a, b\}$ consuming the same material will be outsourced to these two vendors. Other product descriptions, e.g., product code, package, green part, and so forth, are assumed to be identical for this example. The planning horizon is 3, in which demands of Product a and b over time are $\{400, 500, 600\}$ and $\{600, 550, 500\}$, respectively, that are all below capacity limits of the vendors. There are 100 units of material on-hand and 150 units are on-order for each vendor. Minimum material order quantities are 50 units. The lead time for material replenishment is 1. Material lifetime is 2. Material buyback cost is \$ 7 per unit. Parameters of unit costs are shown in Table 4.

Let BigM = 5,000. The alignment problem (P1) for this example can be expanded as the following model (P1′):

Alignment problem (P1′)

$$\min \varphi_{1A} + \varphi_{2A} + \varphi_{3A} + \gamma_{1B} + \gamma_{2B} + \gamma_{3B} \tag{1′}$$

subject to

$$x_{1A}^{a} + x_{1A}^{b} = 0.7(x_{1A}^{a} + x_{1A}^{b} + x_{1B}^{a} + x_{1B}^{b}) + \varphi_{1A} - \gamma_{1B} \tag{2′-1}$$

$$x_{2A}^a + x_{2A}^b = 0.7(x_{2A}^a + x_{2A}^b + x_{2B}^a + x_{2B}^b) + \varphi_{2A} - \gamma_{2B} \tag{2'-2}$$

$$x_{3A}^a + x_{3A}^b = 0.7(x_{3A}^a + x_{3A}^b + x_{3B}^a + x_{3B}^b) + \varphi_{3A} - \gamma_{3B} \tag{2'-3}$$

$$x_{1A}^a + x_{1B}^a = 400 \tag{3'-1-a}$$

$$x_{2A}^a + x_{2B}^a = 400 \tag{3'-2-a}$$

$$x_{3A}^a + x_{3B}^a = 400 \tag{3'-3-a}$$

$$x_{1A}^b + x_{1B}^b = 600 \tag{3'-1-b}$$

$$x_{2A}^a + x_{2B}^a = 600 \tag{3'-2-b}$$

$$x_{3A}^a + x_{3B}^a = 600 \tag{3'-3-b}$$

$$x_{1A}^a + x_{1A}^b = 100 + \eta_{1A} - \lambda_{1A} \tag{5'-A}$$

$$x_{1B}^a + x_{1B}^b = 100 + \eta_{1B} - \lambda_{1B} \tag{5'-B}$$

$$x_{2A}^a + x_{2A}^b = 150 + \lambda_{1A} + \eta_{2A} - \lambda_{2A} \tag{6'-A}$$

$$x_{2B}^a + x_{2B}^b = 150 + \lambda_{1B} + \eta_{2B} - \lambda_{2B} \tag{6'-B}$$

$$x_{3A}^a + x_{3A}^b = \lambda_{2A} + \eta_{3A} - \lambda_{3A} \tag{7'-A}$$

$$x_{3B}^a + x_{3B}^b = \lambda_{2B} + \eta_{3B} - \lambda_{3B} \tag{7'-B}$$

$$x_{2A}^a + x_{3A}^a + x_{2A}^b + x_{3A}^b = \lambda_{1A} - \xi_{1A} + \zeta_{1A} \tag{8'-A}$$

$$x_{2B}^{a} + x_{3B}^{a} + x_{2B}^{b} + x_{3B}^{b} = \lambda_{1B} - \xi_{1B} + \zeta_{1B} \tag{8$'$-B}$$

$$50z_{pv} \leq \eta_{pv} \leq 5000z_{pv}, \quad \forall p \in \{1, 2, 3\}, v \in \{A, B\} \tag{10$'$}$$

$$x_{1A}^{a}, x_{2A}^{a}, x_{3A}^{a}, x_{1B}^{a}, x_{2B}^{a}, x_{3B}^{a}, x_{1A}^{b}, x_{2A}^{b}, x_{3A}^{b}, x_{1B}^{b}, x_{2B}^{b}, x_{3B}^{b} \geq 0 \tag{11$'$}$$

$$z_{pv} \in \{0, 1\}, \eta_{pv}, \lambda_{pv}, \xi_{pv}, \zeta_{pv} \geq 0, \quad \forall p \in \{1, 2, 3\}, v \in \{A, B\} \tag{12$'$}$$

Let $\varepsilon = 0.001$. Then, the cost minimization problem (P2) can be modeled as follows (P2$'$).

Cost minimization problem (P2$'$)

$$\begin{aligned} \min\, & 20(x_{1A}^{a} + x_{2A}^{a} + x_{3A}^{a}) + 10(x_{1A}^{b} + x_{2A}^{b} + x_{3A}^{b}) \\ & + 25(x_{1B}^{a} + x_{2B}^{a} + x_{3B}^{a}) + 12(x_{1B}^{b} + x_{2B}^{b} + x_{3B}^{b}) + 7(\xi_{1A} + \xi_{1B}) \end{aligned} \tag{13$'$}$$

subject to (2$'$)–(12$'$) and

$$\varphi_{1A} + \varphi_{2A} + \varphi_{3A} + \gamma_{1B} + \gamma_{2B} + \gamma_{3B} \leq 0.001 \tag{14$'$}$$

The minimal total outsourcing cost of (P2$'$) will be \$ 47,100, in which the optimal order allocation plan suggests in the first period allocating 300 units of product b to vendor B and the rest to vendor A.

4.4 Validation and discussion

To enhance the construct validity, we hold many working meetings and interviews with domain experts to understand the problem nature and examine the logic and influence relationships involved in the decision elements of the proposed approach during the problem structuring and modeling. Moreover, the developed SODSS and the embedded models were revised several times in operational model validation. To enhance the content validity, we reviewed theoretical models (e.g., Buffa and Jackson 1983; De Boer et al. 2001; Degraeve and Roodhooft 2000; Ghodsypour and O'Brien 1998; Narasimhan et al. 2001; Weber et al. 1991) to investigate the objectives of alternative problem formulations and models. To estimate the criteria-related validity, we employed the developed SODSS to conduct analysis based on empirical data and compared the outputs of the SODSS with those of the heuristic in the case company from historical data and the TVP model (Ghodsypour and O'Brien 1998).

Based on the AHP in SODSS, the relative preferences over the qualified vendors are derived. The results are consistent with business judgments in which the vendors receiving higher relative values were those leading companies in the assembly industry and the vendors receiving lower relative values had inconsistent quality and delivery with lower cost.

To further estimate the validity, this study compared the proposed order allocation planning approach with the existing heuristic and the TVP model (P3) constructed by replacing the objective function with the TVP objective as follows:

The total value of purchasing (TVP) model (P3)

$$\min \sum_{ghijklmpv} \pi_{pv} C_{mv}^{gijk} x_{lmpv}^{ghijk} \tag{15}$$

subject to (3)–(12).

Empirical data from February 2004 to March 2004 in the case company that consisted of planning horizon with 12 planning months, 7 vendors, 368 products, 639 BOM records, 189 materials, and 113 unit costs were used to estimate the validity of this approach. For ensuring confidentiality of the case company, data were transformed by reserving comparative results without loss of generality for further explanation.

The outputs of the allocation plans were the tables of the allocation and the material requirement. For comparison, the realized results of the existing heuristic were collected while the outcomes were derived for the proposed approach and the TVP model. The scales of the proposed approach were of about 12,000 continuous variables, 4,000 binary variables, and 21,000 constraints. The final allocation table of SODSS simultaneously determined about 7,800 possible allocation combinations for the coming 12 months, in which about 270 allocations would be suggested to fulfill demand of the next month. In average, an anticipating demand was allocated to one or two vendors selected from three to five candidate vendors.

We found that the proposed model tended to find the best vendor(s) with the lowest costs but the TVP model sought vendors with the minimal "weighted costs." To meet the allocation profile, about 50 and 800 relative materials should be accordingly prepared for the next month and the coming 12 months, respectively.

Table 5 shows the comparison of allocation results among the proposed model, the heuristic employed in practice, and the TVP model. It depicts that the rearrangement of order allocation could reduce the total outsourcing cost, though some allocation might be unfavorable to specific vendors based on the proposed model. As shown in Table 5, the proposed model dominates the allocation results in terms of the total cost as well as the total absolute difference to the allocation cost according to the target order allocation ratio. Indeed, the total costs of the proposed approach were lower than those of the heuristic, though the cost saving might not be significant in 2 months in Table 5. Nevertheless, the deviations of desired shares among preferred vendors were minimized via the proposed approach. In particular, the improvements of alignment to strategic objectives are about 25–50%, i.e., improved from 7.18 to 4.28% in February and from 10.98 to 6.19% in March. Notably if there is no preference over the qualified vendors, i.e., each of the seven vendors has equal 1/7 share, the total costs would become 218,043 and 179,611 for February and March, respectively.

During the investigation of historical data for validation, we also found the incapability of planning engineers to consolidate multi-dimensional considerations to minimize total costs while fitting the predetermined allocation ratios in complicated decisions. On the other hand, the TVP model focused the objective of maximizing the

Table 5 Comparison of allocation results

Vendor	Target ratio (%)	Proposed model Cost	Proposed model Alignment difference (%)	Heuristic in practice Cost	Heuristic in practice Alignment difference (%)	TVP model Cost	TVP model Alignment difference (%)
v	πv	C_{1v}	$\lvert\pi_v \sum C_{1v} - C_{1v}\rvert / \sum C_{1v}$	C_{2v}	$\lvert\pi_v \sum C_{2v} - C_{2v}\rvert / \sum C_{2v}$	C_{3v}	$\lvert\pi_v \sum C_{3v} - C_{3v}\rvert / \sum C_{3v}$
February 2004							
A	37.60	85,931	1.20	87,102	1.64	85,767	0.91
B	33.44	74,532	0.22	77,293	1.38	73,248	0.55
C	12.99	24,995	1.70	22,258	2.96	24,213	2.12
D	10.71	23,114	0.27	22,378	0.63	23,433	0.19
E	2.84	5,925	0.16	6,632	0.15	7,688	0.61
F	1.28	3,240	0.18	3,590	0.34	3,992	0.51
G	1.14	3,717	0.54	2,705	0.08	4,363	0.82
Total	100.00	221,454	4.28	221,958	7.18	222,704	5.71
$\text{TVP}_m = \sum \pi_v \times C_{mv}$		63,208		64,150		62,717	
March 2004							
A	37.60	64,075	2.47	60,366	4.83	59,678	5.22
B	33.44	60,419	0.31	61,725	0.07	59,978	0.90
C	12.99	26,808	1.71	33,359	5.12	27,634	2.00
D	10.71	21,428	1.04	20,208	0.26	23,776	2.19
E	2.84	5,624	0.24	5,277	0.02	6,629	0.76
F	1.28	1,761	0.31	2,384	0.01	3,633	0.69
G	1.14	2,272	0.11	882	0.66	2,973	0.47
Total	100.00	182,387	6.19	184,201	10.98	184,301	12.23
$\text{TVP}_m = \sum \pi_v \times C_{mv}$		50,282		50,026		48,900	

total value of purchasing, yet it could not effectively integrate and align the objectives of strategic vendor preference and the cost saving of order allocation.

As shown in the results, the allocation results could not be completely consistent with the desired shares according to the vendors' ratings. It implies that there is a gap between strategic decisions and operational considerations especially when strategic preference and operational constraints are all taken into account for detailed planning. The existing approaches including TVP model lacks such insight and have not provided the mechanism to bridge the gap.

Indeed, the developed SODSS has been implemented on line in the case company since May 2004. The management confirms that the developed SODSS and the embedded models contributed to significant improvement of alignment between strategic vendor preference and operational allocation. They confirmed the benefits that 0.37% assembly outsourcing cost has been saved per year in average and the decision-making time was significantly shorten from about 2 days to less than 1 min. The developed SODSS can ensure decision quality without relying less on human judgments when experienced planning engineers will have job rotations. The capability of rapid decision-making had enabled the case company with flexibility for quick response to dynamic order changes and unanticipated demand variation due to variability amplification in the supply chain. The proposed framework enabled transparency and rationale in decision-making with operational excellence when semi-structured and structured decision factors must be considered at the same time in the present problem. The proposed framework could minimize the difference between vendor preference and order allocation so that the implicit relationship and long-term profitability can be preserved.

5 Concluding remarks

While most of existing studies focus on either vendor selection or order allocation, there is a gap to be filled in practice. This study proposes a decision analysis framework for semiconductor assembly outsourcing to integrate semi-structured decision problem for strategic vendor evaluation and structured decision problem for order allocation. The systematic approach can help elicit important factors and complex business rules from domain experts and consolidate them into a transparent decision-making process. In particular, the proposed framework incorporates AHP for vendor evaluation and MP for optimizing order allocation aligning to the evaluation results subject to operational constraints. The associated MRP are also derived in the developed SODSS that implements the proposed approach in real setting. In addition, the developed SODSS can also perform data validation and integration and report generation with friendly graphic user interface. To estimate the validity, an empirical study was conducted using the SODSS and the results showed practical viability of this approach for cost saving and outsourcing strategy alignment. Indeed, the case company has implemented the SODSS for regular long-term to mid-term planning solutions for vendor performance evaluation and order allocation. Furthermore, the decision time has been significantly reduced to enable quick response and decision flexibility of the case company to deal with amplified order variability in semiconductor supply chain. Further research has been done to integrate the proposed approach with daily lot assignment and dispatching to corresponding vendors.

Future research can be done to extend the proposed framework to other segments of supply chains. For example, it can be used to link the decisions between manufacturing strategy of allocating customers with different products to the fabs equipped with different process technologies and capacity configuration to maximize the utilization of fab equipment for semiconductor manufacturing. Although this study addresses a specific problem of semiconductor assembly outsourcing, the present problem does show common characteristics that can be generalized to other problems. Further research can be done to extend the proposed approach to other problems in similar contexts.

Acknowledgments This research is partially supported by National Science Council (NSC 96-2628-E-007-035-MY3), Macronix International Ltd, and the Faulty Empowerment Award of National Tsing Hua University from the funding of the Ministry of Education in Taiwan. Special thanks go to domain experts in Macronix Backend Operations including Dr. C.Y. Lu, Y.H. Chao, Allen Dai, W.S. Pan, Y.P. Chen, Y.L. Whang, T.S. Huang, and Y.D. Weng. The authors appreciate the insightful and constructive comments from anonymous reviewers.

References

Arunkumar N, Karunamoorthy L, Anand S, Ramesh Babu ST (2005) Linear approach for solving a piecewise linear vendor selection problem of quantity discounts using lexicographic method. Int J Adv Manuf Technol 28(11–12):27–34

Bevilacqua M, Petroni A (2002) From traditional purchasing to supplier management: A fuzzy logic-based approach to supplier selection. Int J Logistics 5(3):235–255

Buffa FB, Jackson WM (1983) A goal programming model for purchase planning. J Purch Mater Manage 19(3):27–34

Chien CF (2002) A Portfolio-evaluation framework for selecting R&D projects. R&D Manage 32(4): 359–368

Chien CF (2005) Decision analysis: a UNISON framework for total decision quality enhancement. Yeh Yeh Book Gallery, Taipei

Chien CF (2007) Made in Taiwan: shifting paradigms in high-tech industries. Ind Eng 39(2):47–49

Chien CF, Wu J (2003) Analyzing repair decisions in the site imbalance problem of semiconductor test machines. IEEE Trans Semiconductor Manuf 16(4):704–711

Chien CF, Lo F, Lin JT (2003) Using DEA to measure the relative efficiency of the service center and improve operation efficiency through reorganization. IEEE Trans Power Syst 18(1):366–373

Chien CF, Wang H, Wang M (2007) A UNISON framework for analyzing alternative strategies of IC final testing for enhancing overall operational effectiveness. Int J Prod Econ 107(1):20–30

Choi TY, Hartley JL (1996) An exploration of supplier selection practices across the supply chain. J Oper Manage 14:333–343

Clemen RT (1996) Making hard decision, 2nd edn. Duxbury, Belmont

De Boer L, van der Wegen L, Telgen J (1998) Outranking methods in support of supplier selection. Eur J Purch Supply Manage 4(2–3):109–118

Degraeve Z, Roodhooft F (2000) A mathematical programming approach for procurement using activity based costing. J Bus Finance Account 27(1–2):69–98

De Boer L, Labro E, Morlacchi P (2001) A review of methods supporting supplier selection. Eur J Purch Supply Manage 7:75–89

Degraeve Z, Labro E, Roodhooft F (2000) An evaluation of vendor selection models from a total cost of ownership perspective. Eur J Oper Res 125(1):34–58

Dickson GW (1966) An analysis of vendor selection systems and decisions. J Purch 2(1):5–17

Ding H, Benyoucef L, Xie X (2005) A simulation optimization methodology for supplier selection problem. Int J Comput Integr Manuf 18(2–3):210–224

Ellram LM (1995) Total cost of ownership: an analysis approach for purchasing. Int J Phys Distrib Logistics Manage 25(8):4–23

Fleischmann BH, Meyer H, Wagner M (2000) Advanced planning. In: Stadtler H, Kilger C (eds) Supply chain management and advanced planning. Springer, Berlin pp. 71–96

Gaonkar RS, Viswanadham N (2005) Strategic sourcing and collaborative planning in Internet-enabled supply chain networks producing multigeneration products. IEEE Trans Autom Sci Eng 2(1):54–66

Ghodsypour SH, O'Brien C (1998) A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. Int J Prod Econ (56–57):199–212

Grunow M, Guenther HO, Yang G (2003) Plant coordination in pharmaceutics supply networks. OR Spectr 25(1):109–141

ILOG (2005) ILOG OPL® development studio. ILOG Inc

Jayaraman V, Srivastava R, Benton WC (1999) Supplier selection and order quantity allocation: a comprehensive model. J Supply Chain Manage 35(2):50–58

Jones SW (2005) Integrated circuit economics report. IC Knowledge LLC

Karpak B, Kumcu E, Kasuganti R (1999) An application of visual interactive goal programming: a case in vendor selection decisions. J Multi-Criteria Decis Anal 8:93–105

Keeney RL, Raiffa H (1993) Decisions with multiple objectives: preferences and value tradeoffs. Cambridge University Press, New York

Korhonen P, Wallenius J (1988) A PARETO race. Nav Res Logistics 35:615–623

Leachman RC, Ding SW, Chien CF (2007) Economic efficiency analysis of wafer fabrication. IEEE Trans Autom Sci Eng 4(4):501–512

Min H (1994) International supplier selection: a multi-attribute utility approach. Int J Phys Distrib Logistics Manage 24(5):24–33

Narasimhan R (1983) An analytical approach to supplier selection. J Purch Mater Manage 19(4):27–32

Narasimhan R, Talluri S, Mendez D (2001) Supplier evaluation and rationalization via data envelopment analysis: An empirical examination. J Supply Chain Manage 37(3):28–37

Roodhooft F, Konings J (1997) Vendor selection and evaluation: an activity based costing approach. Eur J Oper Res 96(1):97–102

Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, New York

Sadrian AA, Yoon YS (1994) A procurement decision support system in business volume discount environments. Oper Res 42(1):14–23

Sarkis J, Talluri S (2002) A model for strategic supplier selection. J Supply Chain Manage 38:18–28

Simchi-Levi D, Kaminsky P, Simchi-Levi E (2005) Designing and managing the supply chain: concepts, strategies, and case studies, 2nd edn. McGraw-Hill, Boston

Simon HA (1973) The structure of ill-structured problems. Artif Intell 4:181–201

Simon HA (1997) Administrative behavior: a study of decision-making processes in administrative organizations, 4th edn. Free, New York

Stamm CL, Golhar DY (1993) JIT purchasing: attribute classification and literature review. Prod Plann Control 4(3):273–282

Taal M, Wortmann JC (1997) Integrating MRP and finite capacity planning. Prod Plann Control 8(3): 245–254

Tam MCY, Tummala VMR (2001) An application of the AHP in vendor selection of a telecommunications system. Omega 29(2):171–182

Verma R, Pullman ME (1998) An analysis of the supplier selection process. Omega 26(26):739–750

Weber CA (1996) A data envelopment analysis approach to measuring vendor performance. Supply Chain Manage 1(1):28–39

Weber CA, Current JR (1993) A multiobjective approach to vendor selection. Eur J Oper Res 68(2): 173–184

Weber CA, Current JR, Benton WC (1991) Vendor selection criteria and methods. Eur J Oper Res 50(1): 2–18

Weber CA, Current JR, Desai A (2000) An optimization approach to determining the number of vendors to employ. Supply Chain Manage Int J 5(2):90–98

Wei C, Chien CF, Wang MJ (2005) An AHP-based approach to ERP system selection. Int J Prod Econ 96:47–62

Wuttipornpun T, Yenradee P (2004) Development of finite capacity material requirement planning system for assembly operations. Prod Plann Control 15(5):534–549