Modeling strategic semiconductor assembly outsourcing decisions based on empirical settings

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## **Abstract**

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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. [PUBLICATION ABSTRACT]

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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 (B)

Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 30013, Taiwane-mail: cfchien@mx.nthu.edu.tw

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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 exibility 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 exibility to evaluate the vendors.

Secondly, a number of orders for hundreds of products will be subsequently allocated to qualied 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.

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material preparation by assembly vendors for month 3

material schedule provided by assembly vendors & preparation for month 4

planning horizon

month 1 month 2 month 3

month 2 month 3 month 4

material realization & material schedule

material replenishment lead time = 2 months

month 3 month 4 month 5

plan for execution

plan for material prepation

planed output of the assembly operation

planed output for month 3

month 1 month 2 month 3 month 4 month 5

month 6

now

Fig. 2 Semiconductor assembly outsourcing

Thirdly, each outsourcing order requires specic 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 rst 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 inuence of inated 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

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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

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among supply chain entities to deal with demand uncertainty including buyback, risk sharing, order exibility, and sales rebate would determine the qualications of vendors and the corresponding relationships (Simchi-Levi et al. 2005).

Finally, because of equipment conguration 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-oor control in practice, MRP with nite 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 specic 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 difculty 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 ows of goods and information are specied. 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 ll 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

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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 denes 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 identied the ve 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 nances, consistency, relationship, exibility, technological capability, service, reliability, and price by principle

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component analysis. Sarkis and Talluri (2002) clustered vendor evaluation criteria into strategic performance metrics and organizational factors including cost, quality, time, exibility, 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 specic 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 exibility 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 exibly 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 efciency 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 efcient vendors are those positioning on a frontier with relative efciency values equal to one. Since there

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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

Suppliers speed in development

Support Flexibility Quota exibility

Short setup time

Responsiveness to customer needs

Response to changes and process exibility

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Table 1 continued

Flexibility in changing the order

Flexibility of response to customers requirements

Conict resolution

Service Warranties and claims policies

Repair service

Training aids

Service capability

After sales support

Supplier representatives 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 t

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 efciency value all equal to one, it remains a decision problem for order allocation among the efcient vendors with efciency all equal to one and other vendors with different efciency 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

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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 insufcient, 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 efciency 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 OBrien (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 qualied 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 rst phase deals with

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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 Konings1997)

As extended study Structured

Structured

Simulation + GA (Ding et al.2005)

GA search vendor portfolio as simulation evaluates performance

MOP+DEA(Weber et al. 2000) Limit number of selected vendors in MOP

Structured and semi-structured

TCO + MILP (Degraeve andRoodhooft 2000)

If a vendor is selected, at least some products must be bought

Explicitly modeled

Structured

AHP + LP (Ghodsypour and

OBrien 1998)

AHP ratings are used as coefcients in LP

As extended study

Semi-structured and structured

Fig. 4 Conceptual framework

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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 qualied 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 specied. In practice, to ensure that the selected vendors will reserve sufcient 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 rst phase consists of six steps for vendor evaluation: (1) understand and dene the problem, (2) identify the niche for decision quality improvement, (3) structure the objective hierarchy, generate the alternatives, and clarify inuence 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 reect 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 specic problem, the objectives can be identied 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

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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 identied 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 conict 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 diversication among the qualied 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 qualied 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.

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Fig. 5 An illustrative modeling

3.2 Illustrative modeling

To illustrate modeling involved in the proposed framework, an example that simplies 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 qualied vendors. The notations used in this illustration are specied as follows.

C optimal cost exclusive of vendors relative ratings

C optimal cost of the order allocation problem inclusive of vendors relative ratingsCv unit cost of vendor v, v {1, 2}Wc relative weight of attribute c, c {QF, PF, CR} Lv minimum order restricted by vendor v, v {1, 2} Q total amount of a batch of divisible orders xv decision variable determining the amount of orders allocated to vendor v, v

{1, 2}

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xv optimal amount of orders allocated to vendor v exclusive of vendors relative ratings, v {1, 2}

X optimal combination of order allocation exclusive of vendors relative ratings

xv optimal amount of orders allocated to vendor v inclusive of vendors relative ratings, v {1, 2}

X optimal combination of order allocation inclusive of vendors relative ratings

Uv capacity limit offered by vendor v, v {1, 2}

Pcv relative preference value of vendor v with respect to attribute c, c

{QF, PF, CR},v {1, 2} v overall relative preference rating of vendor v, v {1, 2} v allocation excess variable with respect to vendor v Yv allocation shortage variable with respect to vendor v Zv 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 exibility (QF), process exibility (PF), and cooperative relationship (CR) are considered. Then, AHP is employed to derive relative weights of these attributes WQF, WPF, and WCR with respect to the strategic objective PR, where WQF + WPF + WCR = 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., PQF1, PPF1, PCR1, PQF2, PPF2, and PCR2, can be derived, where PQF1 + PQF2 = 1, PPF1 + PPF2 = 1, and PCR1 + PCR2 = 1. Thus, the overall relative ratings of Vendor 1 and Vendor 2 can be determined as 1 = WQF PQF1 + WPF PPF1 + WCR PCR1 and 2 = WQF PQF2 + WPF PPF2 + WCR PCR2.

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., x1 and x2, respectively. Without loss of generality, specic 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. x1 + x2 Q. The minimum order quantity and maximum capacity of vendor 1 and vendor 2 are denoted as (L1, U1) and (L2, U2), respectively. The costs of different vendors are denoted as C1 and C2, respectively. Thus, the LP model of order allocation can be constructed to minimize total outsourcing cost, i.e. C1x1 + C2x2, to increase profitability. However, there is a gap between the optimal solution X = (x1, x2) solved for order allocation and strategic preferences over the vendors, i.e. (1,2), 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 specied and linked in terms of order quantities allocated to the corresponding vendor.

To ll the gap, strategic preference over the vendor is used as a proxy attribute denoting corresponding share of outsourced assembly business. Therefore, 1 = C1x1/(C1x1 +C2x2) is derived, implying that the more preferred vendor will get more business. Consequently, the feasible region will be limited to the thick line segment

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as shown in Fig. 4 and the optimal solution will move from X to X = (x1, x2) with additional cost C C > 0. Then, the relative preference evaluated in the rst 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 rstly seeks to minimize the differences from allocation excess or shortage with respect to the relative share of preferred vendors, i.e., (1 + 1 + 2 + 2), subject to constraints as shown in Fig. 4. That is, C1x1 = 1(C1x1 +C2x2)+1 1 and C2x2 = 2(C1x1 +C2x2)+2 2.If the original problem is feasible, GP will obtain minimal difference Z1 and Z2. Then, GP minimizes total allocation cost, i.e., C1x1 + C2x2, subject to the above constraints and additional constraints 1 + 1 = Z1 and 2 + 2 = Z2.

3.3 Strategic outsourcing decision support system

To deal with the present problem efciently 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-dened 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 specic vendor in advance according to customers request though the bill-of-material (BOM) table has dened multiple candidate vendors for the order. Then, GP technique would be

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

able to resolve possible infeasibility due to users assignment. The differences between the solution incorporating users assignments and the optimal solutions generated by SODSS would be reported to support the decision maker to make nal allocation decisions. Prior to plan execution, the outcomes of SODSS were reviewed and conrmed by domain experts. Thus, the developed SODSS can also assist in the verication 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 verication procedures were embedded, in which inconsistent data from different sources would be detected and the corresponding data verication and maintenance actions would thus be triggered.

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less structured

evaluation model based on preference

Evaluation Model

Ultimate Objective

integration of preference and formulation

Evaluation Model

Planning Model

Ultimate Objective

planning model based on through formulation

Ultimate Objective

Planning Model

structured

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 specic 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 makers preferences over the qualied vendors (and associated

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allocations implicitly) with respect to the objectives. However, it is difcult 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 difcult 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 specic orders and then allocate each of the orders to the qualied vendors to minimize total outsourcing cost, while aligning with strategic attributes such as the shares among preferred vendors. Thus, order qualiers 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 qualication 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 specic 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.

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Existing heuristic in practice

Step 1: Sort the orders in descending in a list based on the order volume.

Step 2: Select the rst 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 specic die-base product group can be identied by a combination of key attributes including package, pin count, body size, green part, and product code, while a specic 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 specied 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 qualied 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

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Fig. 8 Illustration of semiconductor wire-bonding assembly process

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

Bijlmv obsolescent material buyback cost

Cgi jkmv unit cost of allocation

Dghi jkp demand

Lm material lifetimeMijlmv on-hand materialNijlmv on-order material coming next period

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Table 3 Datum keys relationship

Data key

Green Product package Pin Body Pad Material Vendor part code count size size type

BOM Capacity Demand Material buyback Material lifetime Material on-hand material on-order Minimum batch size Unit cost Vendor rating

Oijlmv minimum material order batch size

Uijv capacity upper limit a small positive numberpv allocation ratio, i.e. the relative rating of each vendor pv allocation excess variable pv allocation shortage variable xghi jklmpv allocation order quantities variable ijlmpv material requirement variable ijlmpv material shortage variable zijlmpv material requirement indicator variable ijlmpv anticipating obsolescent material ijlmpv obsolescent material slack

The proposed framework utilized GP as an intermediary to maintain the integration of two-phase decisions. GP rstly 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 fullled; (4) satises capacity limits. In addition, (5) to (7) express the equilibrium relation between order allocation and material requirement; (8) and (9) estimate anticipating obsoles-cent materials; (10) limits the minimum quantities for material replenishment; (11) and (12) restrict variables boundaries.

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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 to avoid infeasibility caused by round-off errors during computation on computers. Indeed, a larger 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, plays a role of tradeoff between alignment and total costs. However, it is suggested to keep small, e.g., 0.001, to ensure the achievement of the rst order objective, i.e., minimizing the allocation excesses and shortages, considering strategic preference over the vendors.

Alignment problem (P1)

min [summationdisplay]

pv

subject to

ghi jklm

[summationdisplay]xghi jklmpv = ijlm,p1,v + ijlmpv ijlmpv, i, j, l, m,v, p > 2 (7)

ghk

[summationdisplay][summationdisplay]xghi jklmpv = ijlm1v ijlm1v + ijlm1v, i, j, l, m,v (8)

[summationdisplay]xghi jklm,p+Lm,v = ijlmpv ijlm,p1,v ijlmpv + ijlmpv, i, j, l, m,v, p > 1 (9)

Oijlmv zijlmpv ijlmpv BigM zijlmpv, i, j, l, m, p,v (10)

(pv + pv) (1)

[summationdisplay]Cgi jkmv xghi jklmpv = pv [summationdisplay]

ghi jklmv

[summationdisplay]xghi jklmpv = Dghi jkp, g, h, i, j, k, p (3)

ghkmv

[summationdisplay]xghi jklmpv Uijv , i, j, p,v (4)

[summationdisplay]xghi jklm1v = Mijlmv + ijlm1v ijlm1v, i, j, l, m,v (5)

[summationdisplay]xghi jklm2v = Nijlmv + ijlm1v + ijlm2v ijlm2v, i, j, l, m,v (6)

Cgi jkmv xghi jklmpv + pv pv, p,v (2)

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Table 4 Unit cost Vendor Body size of the product

a b

A $ 20 $ 10

B $ 25 $ 12

xghi jklmpv 0, g, h, i, j, k, l, m, p,v (11)

zijlmpv {0, 1},ijlmpv,ijlmpv,ijlmpv, ijlmpv 0, i, j, l, m, p,v (12)

Cost minimization problem (P2)

min [summationdisplay]

ghi jklmpv

subject to (2)(12) and

4.3 Numerical example

Assume two qualied 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 1A + 2A + 3A + 1B + 2B + 3B (1 )

subject to

xa1A + xb1A = 0.7(xa1A + xb1A + xa1B + xb1B) + 1A 1B (2 -1)

Cgi jkmv xghi jklmpv + [summationdisplay]

ijlmv

Bijlmvijlmpv (13)

[summationdisplay](pv + pv) Z + (14)

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xa2A + xb2A = 0.7(xa2A + xb2A + xa2B + xb2B) + 2A 2B (2 -2)

xa3A + xb3A = 0.7(xa3A + xb3A + xa3B + xb3B) + 3A 3B (2 -3)

xa1A + xa1B = 400 (3 -1-a)

xa2A + xa2B = 400 (3 -2-a)

xa3A + xa3B = 400 (3 -3-a)

xb1A + xb1B = 600 (3 -1-b)

xa2A + xa2B = 600 (3 -2-b)

xa3A + xa3B = 600 (3 -3-b)

xa1A + xb1A = 100 + 1A 1A (5 -A)

xa1B + xb1B = 100 + 1B 1B (5 -B)

xa2A + xb2A = 150 + 1A + 2A 2A (6 -A)

xa2B + xb2B = 150 + 1B + 2B 2B (6 -B)

xa3A + xb3A = 2A + 3A 3A (7 -A)

xa3B + xb3B = 2B + 3B 3B (7 -B)

xa2A + xa3A + xb2A + xb3A = 1A 1A + 1A (8 -A)

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xa2B + xa3B + xb2B + xb3B = 1B 1B + 1B (8 -B)

50z pv pv 5000z pv, p {1, 2, 3},v {A, B} (10 )

xa1A, xa2A, xa3A, xa1B, xa2B, xa3B, xb1A, xb2A, xb3A, xb1B, xb2B, xb3B 0 (11 )

z pv {0, 1},pv,pv,pv,pv 0, p {1, 2, 3},v {A, B} (12 )

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

Cost minimization problem (P2 )

min 20(xa1A + xa2A + xa3A) + 10(xb1A + xb2A + xb3A)

+25(xa1B + xa2B + xa3B) + 12(xb1B + xb2B + xb3B) + 7(1A + 1B) (13 )

subject to (2 )(12 ) and

1A + 2A + 3A + 1B + 2B + 3B 0.001 (14 )

The minimal total outsourcing cost of (P2 ) will be $ 47,100, in which the optimal order allocation plan suggests in the rst 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 inuence 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 OBrien 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 OBrien 1998).

Based on the AHP in SODSS, the relative preferences over the qualied 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.

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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 [summationdisplay]

ghi jklmpv

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 condentiality 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 nal 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 fulll demand of the next month. In average, an anticipating demand was allocated to one or two vendors selected from three to ve candidate vendors.

We found that the proposed model tended to nd the best vendor(s) with the lowest costs but the TVP model sought vendors with the minimal weighted costs. To meet the allocation prole, 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 specic 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 2550%, 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 qualied 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 tting the predetermined allocation ratios in complicated decisions. On the other hand, the TVP model focused the objective of maximizing the

pvCgi jkmv xghi jklmpv (15)

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Table 5 Comparison of allocation results

Proposed model Heuristic in practice TVP model

Vendor Target Cost Alignment Cost Alignment Cost Alignment ratio (%) difference (%) difference (%) difference (%)

v v C1v |v[summationtext] C1v C1v| C2v |v[summationtext] C2v C2v| C3v |v[summationtext] C3v C3v|/ [summationtext] C1v / [summationtext] C2v / [summationtext] C3v

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 TVPm = [summationtext] v Cmv 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 TVPm = [summationtext] v Cmv 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 conrms that the developed SODSS and the embedded models contributed to significant improvement of alignment between strategic vendor preference and operational allocation. They conrmed the benets that0.37% 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

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decision-making had enabled the case company with exibility for quick response to dynamic order changes and unanticipated demand variation due to variability amplication 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 lled 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 exibility of the case company to deal with amplied 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 conguration to maximize the utilization of fab equipment for semiconductor manufacturing. Although this study addresses a specic 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.

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