Vlerick Leuven Gent Management School

the Autonomous Management School of Ghent University and Katholieke Universiteit Leuven

Vlerick Leuven Gent Working Paper Series 2004/08

CONSTRUCTING A TOTAL COST OF OWNERSHIP SUPPLIER SELECTION METHODOLOGY BASED ON ACTIVITY BASED COSTING AND MATHEMATICAL PROGRAMMING

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D/2004/6482/09

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ABSTRACT

In this paper we elaborate on a Total Cost of Ownership supplier selection methodology that we have constructed using real life case studies of three different industrial components groups in a firm. These case studies are presented in this article. Analysing the value chain of the firm, data on the costs generated by the purchasing policy and on supplier performance are collected using Activity Based Costing (ABC). Since a spreadsheet cannot encompass all these costs, let alone optimise the supplier selection and inventory management policy, a mathematical programming model is used. For a specific component group the combination of suppliers is selected that minimises the Total Cost of Ownership. TCO takes into account all costs that the purchase and the subsequent use of a component entail in the entire value chain of the company. The TCO approach goes beyond minimising purchase price and studies all costs that occur during the entire life cycle of the item in the organisation. Possible savings of between 6 and 14% of the total cost of ownership of the current purchasing policy are obtained for the three cases.

Keywords: Activity Based Costing, mathematical programming, supplier selection, purchasing

INTRODUCTION

Purchasing determines an important part of the competitive position of most firms. It accounts for 60% to 70% of total expenditures in manufacturing (Herberling, 1993), leads to long term relationships and influences the activities in the complete value chain of the firm. However, in both the operations management and operations research literature a lot more effort has been put into obtaining cost reductions in further stages of the value chain, especially in increasing production efficiency. Although purchasing probably does not receive the attention it deserves in Western academic literature, it is a field where large cost reductions can be obtained, as is shown by the Japanese who have traditionally paid more attention to this field. The cases reported on here, however, are in a traditional Western firm. The management accounting literature has recently picked up this inter-firm setting as an interesting area to study. Seal et al. (1997) present evidence on the role of accounting in developing a strategic supply partnership in an action research study. Ittner et al. (1999) look at the effect supplier selection has on company performance and the intervening variables in this relationship. Cooper and Slagmulder (1999) present a book with case studies of cost management in the supply chain. Van der Meer-Kooistra and Vosselman (2000) discuss management control issues in interfirm relationships. Baiman and Rajan (2002) provide an overview of the incentive issues in inter-firm relationships identified by the incomplete contracting literature. Dekker (2003) looks at the provision of information to coordinate and optimise the supply chain in a case study.

Within the purchasing framework, decisions that have to be taken include supplier selection and determination of order quantities to be placed with these selected suppliers through time. Supplier selection decisions have a multiple objective character. At least 23 criteria for this selection problem have been identified in the literature (Dickson, 1966; Weber, Current and Benton, 1991). These include amongst others: net price, quality, delivery, supplier performance history, capacity, communication systems, service, geographical location. The problem is how to select suppliers that perform satisfactorily on the desired dimensions.

Published vendor selection models formulate answers to this multiple objective problem. Some authors propose linear weighting models in which suppliers are rated on several criteria and in which these ratings are combined into a single score (e.g. Gregory, 1986; Nydick and Hill, 1992; Willis et al., 1993). These rating models are very subjective and often very sensitive to different rating scales, weights and/or ratings by different people. Total cost approaches (e.g. Monckza and Trecha, 1988; Smytka and Clemens, 1993) attempt to quantify all costs related to the selection of a vendor in monetary units but often fail to include the more qualitative criteria. Mathematical programming models (e.g. Chaudhry et al., 1993; Current and Weber, 1994; Sadrian and Yoon, 1994) often consider only the more quantitative criteria.

In this paper, we combine a total cost approach with mathematical programming because the dimensions of the problem cannot be handled using a simple spreadsheet. We propose a Management Information System (MIS) that simultaneously treats the supplier selection and the inventory management decision for multiple components over several time periods in a mathematical programming model. This MIS is based on Total Cost of Ownership (TCO) and Activity Based Costing (ABC) information (Degraeve and Roodhooft, 2000) and programmed in LINGO (Schrage, 1998). For a specific component group the combination of suppliers is selected that minimises the Total Cost of Ownership. TCO takes into account all costs that the purchase and the subsequent use of a component entail in the entire value chain of the company (Shank and Govindarajan, 1992). The TCO approach goes beyond minimising purchase price and studies all costs that occur during the entire life cycle of the item in the organisation. These include amongst others costs related to service, quality, delivery, administration, inventory holding, communication and defects. ABC makes the quantification of the cost criteria possible.

Several authors have identified TCO analysis as a way to improve purchasing (e.g. Ellram 1995a, Smytka and Clemens, 1993). Ellram (1995b) writes about the link between TCO and ABC, but in our opinion has a fairly limited view on ABC. She asserts that, in purchasing, ABC focuses on the internal administrative costs of the purchasing department and assigns costs to the product, customer or distribution channel. In our opinion, however, ABC can also study costs in other departments that can be influenced by the purchasing policy and “the supplier selection policy” can be used as a cost object instead of the more traditional cost objects mentioned by Ellram.

Mathematical programming (MP) techniques have been applied to purchasing issues frequently, mainly in the domain of determining order quantities, specifically in environments where complex discounts are offered by suppliers (e.g. Benton, 1991; Benton and Park, 1995; Chaudhry et al., 1993; Sadrian and Yoon, 1993; Rosenthal et al., 1995), but also in supplier selection (e.g. Akinc, 1993; Current and Weber, 1994).

Shapiro (1999) argues that mathematical programming models can serve as a template for cost and resource data to be extracted by ABC methods. Our use of MP is classified in what he calls a type 4 model where the objective is to minimise cost over supply chain resources in a multiple period, deterministic environment. To our knowledge, Degraeve and Roodhooft (2000) were the first to make the link between TCO, ABC and mathematical programming for supplier selection. They illustrate this link on an imaginary case. Degraeve and Roodhooft (1999, 1998 resp.) illustrate the use of this method on rather small case studies of buying heating electrodes and ball bearings respectively, at Cockerill Sambre, a Belgian firm in the steel industry.

The incremental contribution of this paper is threefold. Firstly, this is the first time that the management accounting aspect of the methodology is elaborated on and worked out extensively. Previous papers do not describe the value chain and ABC analysis linked to the specificity of the different product groups, nor do these papers discuss how the data are collected and what the problems related to this aspect are. We show how the mathematical programming model serves to define and structure the decision problem at hand. We obtain very good results compared to the current purchasing policy because of our thorough data collection and ABC analysis within this structure.

Secondly, this paper situates the work specifically within the context of the constructive case study research methodology in management accounting (Kasanen, Lukka, Siitonen, 1993), thereby indeed focusing more on the process aspects of the case study. It builds on the previous papers and proves that the financial results of the previous cases can be transferred to other component groups in another firm thereby generalizing previous results.

Thirdly, the model in this paper is far more complex than those in the previous papers on several dimensions. Because of the extended value chain and ABC analysis, the number of criteria and different costs considered are substantially larger. Also the monetary amounts involved are larger (16,011,000 euro vs. 200,000 (Degraeve and Roodhooft, 1999) and 1,303,000 euro (Degraeve and Roodhooft, 1998)). The complexity increase is also indicated by the size of the component groups (1,052 different component types vs. 1 and 33 respectively) and the supplier base from which to select (88 suppliers vs. 3 and 6 respectively). This results in a substantially increased number of variables and constraints in the mathematical programming model. Also, the overlap between the suppliers and component types is substantial, preventing us from using a decomposition method to solve the problem.

Using our theoretical ABC framework for supplier selection we developed a MIS for a division in Europe of a world-wide telecommunications firm that is one of the leaders in the high speed access and transmission market. The firm has 116,000 employees world-wide and is represented in 130 countries. Global sales amount to 23 billion Euro. The division studied offers a complete portfolio of the world-wide firm from micro-electronics and telecommunications to cables and components and employs 4600 people in the country of its location. The purchasing department's mission statement includes "cost of ownership" as an expectation of their (internal) customers:

> *To explore the market and to purchase and deliver […] conform to the requirements, with a maximum of flexibility and reliability, with a competitive "Cost of Ownership", continuously.*
>
> *(stress in original documentation)*

To achieve this goal the firm uses a vendor rating system that takes price, technology, quality, flexibility and delivery reliability into account. An effort is made to buy as much as possible from suppliers with a preferred status. An Economic Order Quantity (EOQ) model calculates the order points, but does not link this decision to the supplier selection decision.

The MIS is developed for three major bought-in product groups: resistors, transformers and printed circuit boards (PCB). These component groups are selected because the relevant criteria and costs differ substantially between them. In this way, the external validity of the study is increased by constructing a toolbox that is widely applicable to similar decision problems in different business contexts. We assume that the component groups are independent from each other and study them separately. Although an occasional supplier delivers items in more than one of the component groups, these links are negligible and the total dimensions of the cases prevent us from looking at the three component groups at the same time. Together, the three component groups account for about 14,000,000 euro in total costs. The dimensions of the cases studied are vast and involve a considerable amount of money, as shown in Table 1. The first column gives the number of different types of components used in the firm. The second column states for how many of these types there was a demand in 1999, the year of study. The third column indicates the number of possible suppliers. The fourth column gives the current monetary purchasing price in euro.

Insert Table 1 About Here

Prices for different types of electrical components may vary substantially. The 1,729 resistor types are classified in two basic types, thickfilm chips and minimelfs with thin film technology. Minimelfs have a lower temperature coefficient, better current-noise characteristics and a better stability with respect to overheating, but are more expensive. Prices quoted for transformers are a function of their core type, the number of windings, the quantity ordered and insulation requirements. The production cost of the Printed Circuit Board (PCB) suppliers depends, amongst others, on type of material, number of layers, drill size, finishes, density, thickness and board area. Asian PCB suppliers are cheaper but have a longer lead time, provide less service and do not have special technologies available.

The remainder of the paper elaborates on the supplier selection methodology developed. Section 2 explores the activities performed in the value chain of the purchasing firm. Section 3 explains how Activity Based Costing data were gathered to cost out these activities and which types of information are collected about the performance of the suppliers on the different supplier selection criteria that generate costs in the value chain of the firm. Section 4 shows how the data are translated into the objective function and constraints of the mathematical programming models. The next section interprets the results and discusses strategic insights for the purchasing policy. The last section concludes.

THE VALUE CHAIN AND ACTIVITIES

We study the activities in the value chain of the firm that relate to the purchasing policy in the first step of the vendor selection methodology. These can either be activities of the purchasing department itself or activities further down the value chain that are influenced by policy decisions made by the purchasing department. Figure 1 shows the activities, where they are situated in the value chain and how they relate back to the purchasing policy in the case study firm. It is important to perform this value chain analysis, as these activities and their costs will later be modelled in the mathematical programming model. The rest of this section describes the activities in the value chain of the firm.

Insert Figure 1 About Here

The purchasing engineer responsible for a component group negotiates with the suppliers on amongst others price, discounts, quality, lead time and follows up the relationship to sustain the supplier in the supply base. When the supplier is new to the firm or when quality problems arise too frequently, the quality team sometimes performs a quality audit on the supplier's site.

Ordering can start once the relationship with the supplier is set up and the supplier is selected for a certain component type. Depending on the supplier/component combination orders can be placed through electronic data interchange (EDI) via a private network, automatic call-off (ACO) on a frame agreement or the manuals by sending a fax.[2] The first time an order is placed for a specific PCB with a supplier, a tooling cost might be charged by the supplier to cover the supplier's one/off costs on films, drilling information and electrical testing. Suppliers with a shorter lead-time are more flexible in that they can accommodate to a sudden change in demand on a shorter notice period and thus agree a delivery date that is nearer in the future than other suppliers can.[3] A supplier's delivery reliability depends on the history of early and late deliveries around the agreed delivery date. Importing documents have to be filled out and import duty has to be paid when the component is ordered with a supplier outside the European Community.

Then the receiving department receives the delivery and inspects it together with the inspecting department.[4] When no irregularities are discovered during the inspection, the supplier accounting for the delivery is done and the invoice is paid. For transformers and PCBs some suppliers offer component specific discounts on prices for larger orders and this discount may rise with the quantity ordered. Some transformers and PCB suppliers add a lot charge to the invoice. Payment delays typically range from cash payment to 60 days delay, with 0 to 3% payment discounts. However, when a defect is discovered in inspection, components are either sent back to the vendor who will send a credit note or will replace them at his expense, or they are thrown away at the firm's own expense. When the supplier replaces

[2] The minimum order quantity and the lot size have to be adhered to when ordering. Orders for a component thus have to exceed the minimum order quantity for that component with that supplier and be a multiple of the lot size. As a rule, the lot size is always lower than or equal to the minimum order quantity.

[3] Asian suppliers generally have a longer lead-time than European and American suppliers.

[4] Different sorts of inspections are used, depending on the inspection class in which the supplier/component combination is allocated and resulting in more or less time consuming inspection activities. For purchases with certified suppliers, the receiving department may release the components without any quality verification. The trust in these suppliers' quality systems makes extra inspection superfluous, as the details on the specifications, the level of quality, the criteria for acceptation of the delivery, the supplier's auditable quality plan and the markings on the packaging are agreed on in writing in the quality agreement. Other components are inspected visually. A skip lot inspection may be performed for components that are delivered frequently. In this case the first five deliveries and afterwards every fifth batch are each checked taking a sample, whereas the other four are only checked visually. In a few exceptional cases, the reception department releases transformers and PCBs delivered by uncertified suppliers without further inspection because their impact on business processes is considered small. For the odd resistor delivery only the labels on the packaging are compared with the ones on the travel documents without opening the packaging. Occasionally, every PCB lot is checked using a sample from each lot. Some special PCBs are sent for verification to the engineer that ordered the component.

the components, they go through the whole cycle of importing, receiving and inspecting again. After a satisfactory inspection the components are transported to the warehouse where they are held in inventory until the production planning triggers a demand for the component on the production floor. The components are used to manufacture more complex electronic components or end-user products that are sold by the marketing department. However, some defective components that have slipped through incoming inspection turn up during production. This causes a lot of extra work to troubleshoot the problem, complain to the supplier, repair and re-test the component. For PCBs the cost of discovering a problem in this phase in the value chain is the highest because usually the entire expensive PCB has to be thrown away and other components already fixed on it cannot easily be salvaged. Sold products are delivered to the customer who, upon discovering a defect in this final phase of the value chain, files a complaint that results in the after sales department investigating the problem and writing an outgoing credit note.[5]

DATA COLLECTION

The developments in ABC and the integration of these costing systems with company wide information systems could enable us to collect all necessary data on activities and supplier performance. However, in the case study firm, three data collection problems had to be overcome.

Firstly, cost accountants in the firm put effort into defining activities, several non-unit cost drivers such as throughput time and orders are used, and the company's head of cost accounting gives presentations about ABC and how it is applied in the company. The cost accounting system is mainly used for variance analysis between the budgeted and the actual figures as well as for calculation of the tariff for services that are provided internally, such as information technology, training, and accounting. The company clearly expresses the wish to be on the forefront of developments in this area by applying ABC.

But, in our opinion, the company is merely on the way to developing an ABC costing system. The basic features of the accounting system remain of the standard costing type, although a high level of detail is visible. The firm defines about 1500 different resource

[5] The external customers of this firm assess only 1.7% of all defects, while the other complaints come from internal customers in the production department. The analysis of these external customer complaints over the year studied shows that none of them relate back to problems with the original component bought. Instead, they are due to faults in the production process or wrong deliveries.

categories and 400 cost pools that are related to geographical locations, departments or products. Strangely, purchasing department overhead and the cost pool related to reception and inspection are allocated using a normal distribution over groups of suppliers, rated excellent, mediocre and bad on a combination of indices on delivery, quality and flexibility, as a percentage of the purchasing volume with these suppliers. Thus it is assumed that there will always be a specific percentage of each category of suppliers and that purchasing volume is the overall cost driver. Therefore, especially for this purchasing application of ABC, the company required lots of assistance from the authors.

Secondly, the company has several databases that are not always integrated. The first is the accounting database, discussed in the previous paragraph. The second is the Purchasing Management System (PMS), which contains data on all component types and suppliers. Next, the Material Requirements Planning (MRP) provides forecasted demand figures. An economic order quantity (EOQ) calculation system that is directly fed by the MRP was put in place five years ago. The cost updated figures are, however, not automatically plugged into this EOQ model and have not been changed in five years. When the accountant participating in this study was made aware of this during the process of the development of the vendor selection model, he undertook the necessary steps to update the cost figures in the existing EOQ model. Besides these four systems, some purchasing engineers make use of their own spreadsheets. On some occasions, we discovered that the data in these spreadsheets did not correspond to the data in the overall PMS system.

Thirdly, there was a big turnover of personnel involved in the study. Several people left for other firms, including the original champion of our study in the company. Other personnel took up completely different functions within the same company.

The process of collecting the data on costs and supplier performance and refining the costing system to reflect ABC principles was consequently time consuming as we had to consult several databases, always via a variety of company personnel, in order to set up our own ABC system and sort out discrepancies between data in the different files along the way. The most problematic discrepancy concerned the vendor lead time data, where purchasing managers' own spreadsheets were much more up to date than the EOQ system and mostly showed shorter possible vendor lead times. The remainder of this section describes how we proceeded with these difficult tasks.

First the resources available to perform all the activities discussed in the previous section are examined. An example is the gross wage of the inspectors. Resource drivers establish a relationship between these resources and the activities. We checked, for example, how much time the inspectors spend on a skip lot inspection or on a full inspection. Personnel in the firm was asked to participate in several time estimate studies. Some resources are linked directly to the activity and need not be assigned through a resource driver. For example, the yearly EDI service fee is exclusively related to the EDI ordering activity. Columns 1, 2 and 3 of Table 2 indicate the direct or indirect link between resources and activities and shows which resource drivers are used in the latter case.

Insert Table 2 About Here

Once the cost of performing an activity is calculated, activity drivers that determine the total cost of the purchasing policy are searched, using a cost hierarchy with several activity levels: supplier-, component-, order-, batch- and unit-level. The first hierarchical level describes costs incurred and conditions imposed whenever the purchasing company actually uses the supplier over the decision horizon. Costs on the supplier level include a quality audit cost incurred by the buyer for the evaluation of a supplier and the cost of a dedicated purchasing manager. This purchasing manager is responsible for both setting up the relationship with the supplier (e.g. writing up an overall quality agreement) and following up the relationship. The component level indicates costs incurred whenever the firm needs to buy this component. Tooling costs for the PCBs are incurred on this level as they are only charged the first time that the component is ordered with the supplier. Tooling costs vary with the supplier/PCB combination and might even be non existent for some combinations. The order level parameters indicate costs incurred and conditions imposed each time an order is placed with a particular supplier and include, amongst others, costs associated with ordering and invoicing. At batch level the firm incurs costs each time a batch is delivered e.g. costs for reception, inspection, material handling, internal failure (components fail during production) and late delivery of the batch. At the unit level we find costs incurred and conditions imposed related to the units of the components for which the procurement decision has to be made, for example, price, external failure (a component fails when used by the customer) and inventory holding due to early delivery. The three cases studied illustrate that the ABC hierarchy is case dependent, as is suggested in the literature (Ittner, Larcker and Randall, 1997). For the resistor case, a hierarchy with only three levels, i.e. supplier, batch and unit, is used. Since an order for transformers or PCBs can include more than one type of component and the bought-in products are delivered per batch of the same component, we add an order level in these cases.

We include a component level in the hierarchy for the PCB case, as for some suppliers tooling costs are incurred the first time a specific PCB is ordered to cover their costs on films, drilling information and electrical testing. Table 3 shows how the hierarchy differs from case to case and on what levels the costs are incurred.

Insert Table 3 About Here

It is important to make this classification of activities into separate levels since the overall process driver for each level of activity, (1) number of suppliers, (2) number of components, (3) number of orders, (4) number of batches and (5) number of units procured, is assumed independent of the activities in other hierarchical levels. Column 4 of Table 2 shows the more detailed cost pools at which level the information was gathered. From the variables in the mathematical programming model, the level of variability of these details becomes clear: per supplier (e.g. import duty dependent on location of supplier insider or outside the European Community), per supplier-component combination (e.g. for some components an automatic order through the automatic call off system is possible, while the same supplier may only accept a fax order for other components) or only dependent on the purchasing firm (e.g. material handling). Remark, however, that the purchasing firm can still work on the efficiency and effectiveness improvement of the latter activities, or try to eliminate them when they are non-value-adding activities such as inventory holding.

In this way, all costs caused by the selection of suppliers and the placement of orders with them can be determined. Column 5 of Table 2 shows the process drivers that drive the usage of activities by the supplier selection policy. These process drivers determine the level in the ABC hierarchy where the costs are incurred and will become the decision variables in the mathematical programming models.

In the next step, information is gathered on supplier performance at the detailed level of the cost pools and also data on prices, quantity discounts, supplier's lead time, tooling costs, minimum order quantity, lot size as well as probabilities of detecting default in inspection, production or by the external customer, are collected.

Before we proceed, an important caveat is in order. Applying Activity Based Costing assumes that the costs are linear (or step-linear) with the cost drivers. Research (e.g. Noreen (1991), Bromwich (1997), Maher and Marais (1998)), however, has shown that the conditions under which ABC provides accurate costs are rather stringent and in some cases hard to meet, especially when resources are provided on a joint and indivisible basis. Noreen and Soderstrom (1994) empirically test this linearity assumption for different categories of overheads and conclude that it is often not met. Datar and Gupta (1994) look at other possible errors in costing systems in general (not just ABC) and show that there exists a trade off between reducing specification and aggregation error (which is often used as a justification for implementation of ABC systems) and increasing measurement error. We do acknowledge all these possible problems with any application of ABC in general and ours in particular. We would, however, argue that the use of ABC is already a leap forwards as it approximates the linearity of the cost functions much better than the traditional volume related approaches, by using a cost hierarchy where costs become variable at different levels. Costs that were previously considered fixed or falsely considered variable at the unit level, can now become variable at one of the other levels in the hierarchy. For our case in particular we have three further reasons why the use of ABC may not be that problematic. Firstly, we have made a deliberate attempt to reduce measurement error in units of allocation bases (Datar and Gupta, 1994) by not asking for too detailed information of personnel in their time allocation estimates. Secondly, as you will learn from our result section, important parts of the possible savings (between 3 and 11% of TCO of the current purchasing policy) are immediate cash savings on price for which there cannot exist any measurement or accounting error. We acknowledge, however, that the other part of the savings may require a thorough re-engineering exercise to actually get rid of the freed up capacity or put it to an alternative use. Thirdly, and most importantly, no joint resources are (or needed to be) included in our ABC exercise since only those resources for which the resource consumption is different if different suppliers are used are included in the model, as it is our objective to select those suppliers that minimise TCO. Because of the focused scale of our ABC exercise, we did not have to deal with joint resources such as investments in marketing and the brand name of the firm, as they do not vary with the supplier selection policy, which is our cost object.

THE MATHEMATICAL PROGRAMMING MODEL

It is impossible to optimise the supplier selection and inventory management decision taking all the relevant costs throughout the entire value chain of the firm into account in a simple spreadsheet. Therefore, we develop mathematical programming models to determine an optimum sourcing strategy for the different component groups. The models generate a purchasing policy that minimises the Total Cost of Ownership taking into account constraints relevant to the problem. As a result, the quantification of the vendor selection criteria and the trade-off between them is no longer a problem because the objective function is defined as the TCO related to the purchasing decision, and the supplier selection criteria are weighted by their respective ABC costs.

Typically, a mathematical programming model consists of two main building blocks: the objective and the constraints. The objective of the model is to minimise the Total Cost of Ownership of the supplier selection and ordering policy for the decision period of the year. As discussed in the previous section, the structure of the models is based on case specific ABC hierarchies. This is shown in the objective function as it reflects net prices and resources consumed by the activities in the three to five hierarchical levels distinguished: supplier, component, order, batch and unit level. Subsequently, the mathematical programming model defines the costs incurred on each of these levels and establishes cost drivers as decision variables on all of these levels. The most important constraint for this procurement model is that demand for each component in each time period has to be satisfied.

A more detailed explanation of the mathematical programming models, the exact mathematical notation and information on the solving procedure can be found in the appendix to the paper.

RESULTS

We have made an extensive comparison of our suggested purchasing policy with the actual purchasing policy used. As we are not allowed to make the actual data available due to confidentiality reasons, we present the results in Table 6 as percentages. The first row indicates the possible savings as a percentage of the TCO of the current policy. The second row gives the approximate TCO figures for the different component groups in euro. The next eight rows show the hierarchy of costs for the optimal purchasing policy, as percentages of the optimal TCO. The final seven rows indicate how the cost hierarchy is built up for the current policy, as percentages of the optimal TCO.

Insert Table 6 About Here-

The purchasing policy proposed is able to save 14%, 6% and 11% on TCO on the component groups resistors, transformers and PCBs respectively, compared to the current purchasing policy[6]. As the benefits of applying the vendor selection model can be measured in terms of the possible savings compared to the current purchasing policy, this methodology overcomes the concern raised by Foster and Gupta (1997) about the difficulty of quantifying benefits if new management accounting systems have to stand the cost/benefit test.

Several strategic insights can be gained form the analysis of the data and the solving of the mathematical programming model.

As is to be expected in any purchasing application of ABC, the cost structure is unit level dominated, since the whole turnover is taken into account on this level. Price, a unit level cost, remains an important component of the TCO, in the optimal case making up between 92 and 98% of TCO. As most of the purchasing entailed activities (as defined in Figure 1) that have cost drivers at a higher level in the hierarchy are non value adding activities, a cost structure dominated by price is good business practice in this case. Most of the costly value adding activities such as the different steps in the production process were not included in the analysis as supplier performance does not make a difference to the use of their activity drivers. It would, however, be this type of activities that might shift the cost structure from unit level dominated to batch level dominated. The dominance of unit level illustrates the importance of getting the unit level costs right, also in an ABC environment where several other levels are studied. You can also see in table 6 that the optimal policy cuts down on these non-value added activities compared to the current policy.

Most of the possible savings also lie at unit level. Immediate cash savings could amount to savings of 11.5%, 3% and 9% respectively by selecting a supplier with a lower price and making optimal use of component specific discounts for transformers and especially PCBs. We acknowledge that this is not an effect directly related to our ABC implementation, but more a consequence of the operations research aspect of our methodology that brings in more structure and objectivity. Using this TCO model, the selection of these lower price suppliers can now be made with the assurance that quality and other costs are taken into account and that the overall effect on TCO is positive. Almost all components have a single

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[6] These possible savings percentages are calculated for the last year for which full data were available. The TCO model is used to retrospectively calculate the cost of the purchasing policy for that year by fixing all the decision variables (when what was bought from which supplier) in the model to the values they took in that particular year's purchasing policy. In this way, we can calculate the TCO of the purchasing policy that was executed that year (termed "current policy"). We then run the mathematical programming model again, this time to solve for the optimal policy and compare the total cost of both (savings indicated as a percentage of the TCO of the current policy). These savings could have been obtained had the company used the new method to determine purchasing policy in that year instead of using the purchasing policy they actually implemented. Because the firm faces a quite stable demand environment for these component groups, we can predict a level of savings of a similar size for the next year.

source that is clearly better than the other possible suppliers. The current policy increases TCO by splitting orders of the same component over several suppliers and therefore does not make optimal use of the available quantity discounts.

In the rest of this section we report on non-cash savings that amount to 2.7%, 3% and 1.7% respectively. These are possibilities to save on resources, which would require a re-engineering exercise to turn them into cash savings. Alternative allocations and selling off of resources would need to be considered.

For transformers and PCBs, substantial savings on inventory holding costs (also on unit level) are possible by ordering with suppliers who do not have a record of early deliveries, and by placing orders just in time for the suppliers lead-time to be sufficient to deliver the component exactly when needed. This saves a lot on warehousing costs that do not add any value to the component. The savings we find here are partially due to the main purchasing information system (PMS) not being updated regularly with respect to vendor lead times, that had a tendency to decrease over time, and were only correctly written down in the respective purchasing engineers own spreadsheets that were not linked to PMS. As a result, the automatically placed orders were placed too early. Part of these inventory holding savings could also be considered cash savings as there is an one-off freeing up of working capital due to a lower inventory level. For components with a low unit price such as resistors, inventory holding costs already make up a smaller percentage of the cost structure.

Savings can also be made on the batch level, by reducing quality problems for transformers and PCBs. In our opinion, the savings created by a smaller percentage of expensive defects often outweigh the cost of a quality audit. The batch level cost savings for resistors, for which quality problems are not common, are a result of a policy of less frequent ordering.

The firm can only make minor savings at order level costs for transformers and PCBs. Rather surprisingly, the possible way of ordering through EDI, ACO or fax, do not save much on ordering costs for the time being. The reason for this is that the cost differences between these ordering techniques are small since the EDI system in place still requires checking every order confirmation line by line, as the supplier can change quantities and prices without the purchaser immediately noticing this. This is an example of an area where the ABC results had an important policy impact as previously management had assumed that EDI was the most cost-efficient way of ordering and pushed EDI systems take-up with their suppliers. They decided to first sort out the technical aspects of the EDI system and automate order confirmation checking, before stressing its importance in negotiations with suppliers any further.

The component level for the PCBs turns out to be insignificant since the tooling costs that are charged whenever an PCB is ordered for the first time with a particular supplier, are small relative to the other costs, and often even non existent. Only minor savings are possible.

Because the purchasing engineers spend most of their time on the specifications for the components, which are independent of the suppliers selected, the supplier level costs do not make up a very substantial amount in the cost hierarchy. Narrowing down the supplier base can result in savings at supplier level. The proposed supplier selection policy narrows down supplier bases from 21 to 17, from 37 to 35 and from 16 to 13 for resistors, transformers and PCBs respectively.

Since non-price costs make up between 3 and 9 percent of the cost structure, and still between 2 and 8 percent in the proposed purchasing policy, it would be interesting to investigate a broader use of vendor managed inventories (VMI), also called consignment stocks, as this cuts down costs of activities performed in the value chain of the purchasing firm and eliminates some of these activities. As for now, the firm is working on a pilot project for VMI with one supplier of a component group - not studied here -. The consignment inventory is kept at or near the purchasing firm's site, but the inventory holding responsibility rests with the supplier as the components remain property of the supplier until the purchasing firm takes them out in agreed lot sizes. The supplier is responsible for keeping the components in stock in sufficient quantities to keep production going. His inputs for the replenishing of the inventory are forecasts directly from the purchasing firm's MRP planning, an agreed minimum and maximum stock level and component consumption data given by the production department on a weekly basis. The value chain of activities related to the purchasing process can thus be drastically shortened. Ordering is eliminated as the supplier draws his information directly from the company's MRP planning. Reception is also eliminated and incoming inspection is replaced by outgoing inspection. The supplier is responsible for material handling costs that includes transport to warehouse, removal of the packaging and shelving the duly labelled components on the assigned locations. The purchasing firm usually supplies the warehouse, but fire and water hazard insurance and warehousing personnel costs, also part of the inventory holding cost are for the supplier's account. The supplier finds compensation in cost cuts in his own production, a larger share of the business and increased partnership.

In summary, our recommendations to management to reduce the TCO of their supplier selection policy were the following: narrow down the supplier base; select some lower price suppliers with the assurance that quality and other costs are taken into account in the model; make better use of discounts for transformers and PCBs; rely on a single sourcing policy on the level of each component (not for the whole component group!), on top of penalizing late deliveries (which is already purchasing policy), also penalize early deliveries as inventory holding costs are high; reduce quality problems for transformers and PCBs, order less frequently for resistors, look into the possibility of extending the use of VMI and search for improvement in the EDI system.

Apart from providing purchasing management with a better supplier selection and inventory management policy, the model can be used in two other ways. Firstly, the model can give decision support using scenario analyses dealing with both strategic decision making and cost management issues. The TCO of alternative procurement strategies can be calculated, e.g. imposing a minimum or a maximum number of suppliers, excluding a supplier etc. Management then can decide whether they are willing to pay the increase in TCO compared to the optimal supplier selection policy to pursue these strategies. Areas can be identified where internal improvements such as reducing cost driver rates of performing value-added activities and/or eliminating non-value added activities, such as moving materials, can generate the highest reduction in TCO.

Secondly, also areas where external improvements by suppliers are able to generate decreases in TCO can be pinpointed. The model can then be used as a negotiation tool with suppliers since proposals of discounts, quality improvements, lead-time reduction etc. made by suppliers can be easily assessed. This clear communication on what drives costs in the purchasing firm will enable companies to develop interorganisational activity based management opportunities, given the importance of close relationships between the purchaser and a limited number of reliable suppliers that might lead to buyer-supplier partnerships.

CONCLUSION

In this paper we develop a Total Cost of Ownership supplier selection methodology using Activity Based Costing data. In a first step, the activities in the value chain that relate to the purchasing policy are analysed. Next, resources available to perform all these activities are examined and resource drivers linking them are established. Once the costs of performing the activities are calculated, activity drivers that determine the total cost of the purchasing policy are defined, using case dependent cost hierarchies with three to five levels. Then, information is gathered on supplier performance on these activity drivers. Since a spreadsheet cannot encompass all these costs, let alone optimise the supplier selection and inventory management policy, mathematical programming models minimising the TCO of the purchasing decision are programmed and solved with a stepwise procedure. The ABC hierarchy forms the backbone of the mathematical programming model, with decision variables on each level of the hierarchy. Possible savings of between 6 and 14% are obtained for the three cases.

Along the way, several other lessons for accounting were learned. Firstly, the problem of ABC not being applicable to joint costs (Noreen, 1991) does not need to be an issue in every case study. Here, the focus of the case was such that we did not need to include any joint costs since they do not vary with our cost object, the supplier selection policy. Secondly, we illustrate that the ABC hierarchy is case dependent, even for several component groups within the same firm. Thirdly, people may hold subjective beliefs on rankings of costs of activities that may actually not be true. In this particular case, the belief that EDI ordering was (a lot) cheaper than ordering via the traditional fax way turned out to be wrong when the correct figures where put into the equation. Fourthly, from an information systems point of view, we can re-iterate the need for regular updating of figures in all the decision models (as e.g. in this case in the EOQ model) to ensure correct decision-making and integration of all the databases used to avoid discrepancies between data. Fifthly, this case study illustrates how survey evidence on the use of modern cost accounting concepts such as ABC may be positively biased. We think that, would management accountants within this firm have been asked to fill out such a survey, they would have ticked the ABC box. However, having dug into the details of their costing system, we would argue that a full-blown ABC system was not yet put in place.

There are several avenues for future research. Firstly, the research reported on here studies off the shelve items. The biggest part of the purchasing entailed activities in the value chain that are dependent on performance of the suppliers are non value adding and thus the cost structure is dominated by unit level, although the savings generated by the ABC exercise on the higher levels are still important. It would, however, be interesting to build a similar model for a case study where more involvement of the suppliers is required in for example research and design. More value adding activities that are influenced by the suppliers would be included in the purchasing entailed value chain and higher ABC levels would gain in importance. Secondly, research into the quantification of opportunity costs of lost sales due to quality problems or late deliveries is very difficult but would be very useful in decision-making practice. Ittner (1999) reports on a few companies that make an effort on calculating quality related opportunity costs and quantifying the magnitude of lost sales.

REFERENCES

Akinc, U. (1993). ‘Selecting a set of vendors in a manufacturing environment’. Journal of Operations Management, 11, 107-122.

Baiman, S., Rajan, M.V. (2002). ‘Incentive issues in inter-firm relationships’. Accounting, Organizations and Society, 27, 213-238.

Benton, W.C. (1991). ‘Quantity discounts decisions under conditions of multiple items, multiple suppliers and resource limitations’. International Journal of Production Research, 29(10), 1953-1961.

Benton, W.C., Park S. (1996). ‘A classification of literature on determining the lot size under quantity discounts’. European Journal of Operational Research, 92, 219-238.

Bromwich, M. (1997). ‘Accounting for overheads. Critique and reforms.’ Acta Universitatis Upsaliensis. Studia Oeconomiae Negotiorum, 41.

Chaudhry, S.S., Forst, F.G., Zydiak, J.L. (1993). ‘Vendor selection with price breaks’. European Journal of Operational Research, 70, 52-66.

Cooper,R., Kaplan, R.S. (1998). The design of cost management systems, 2nd edition, Prentice Hall, New Jersey.

Cooper, S., Slagmulder, R. (1999). Supply chain development for the lean enterprise – interorganizational cost management, Productivity Press, Portland.

Current, J., Weber, C. (1994). ‘Application of facility location modeling constructs to vendor selection problems’. European Journal of Operational Research, 76, 387-392.

Datar, S.M., Gupta, M. (1994). ‘Aggregation, specification and measurement errors in product costing’. The Accounting Review, 69, 567-591.

Degraeve, Z., Roodhooft, F. (1998). ‘Determining sourcing strategies: a decision model based on activity and cost driver information’. Journal of the Operational Research Society, 48(8), pp.781-789.

Degraeve, Z., Roodhooft, F. (1999). 'Improving the efficiency of the purchasing process using total cost of ownership information: the case of heating electrodes at Cockerill Sambre S.A.' European Journal of Operational Research, 112(1), 42-53.

Degraeve, Z., Roodhooft, F. (2000). 'A mathematical programming approach for procurement using Activity Based Costing'. Journal of Business Finance and Accounting, 27(1-2), 69-98.

Dekker, H.C. (2003). 'Value chain analysis in interfirm relationships: a field study.' Management Accounting Research, 14(1), 1-23.

Dickson, G.W. (1966). 'An analysis of vendor selection systems and decisions'. Journal of Purchasing, 2(1), 5-17.

Ellram, L.M. (1995a). 'Total Cost of Ownership: an analysis approach for purchasing'. International Journal of Physical Distribution & Logistics Management, 25(8), 4-23.

Ellram, L.M. (1995b). 'Activity Based Costing and Total Cost of Ownership: a critical linkage'. Journal of Cost Management, winter, 22-30.

Foster, G.; Gupta, S.M. (1997). 'Frontiers of Management Accounting Research'. Journal of Management Accounting Research, 9, 63-77.

Gregory, R.E. (1986). 'Source selection: a matrix approach'. Journal of Purchasing and Materials Management, summer, 24-29.

Herberling, M.E. (1993). 'The rediscovery of modern purchasing'. International Journal of Purchasing and Materials Management, 29(4), 48-53.

Ittner, C.D. (1994). 'Activity-based Costing concepts for quality improvement'. European Management Journal, 17(5), 492-500.

Ittner, C.D., Larcker, D.F., Nagar, V., Rajan, M.V. (1999). 'Supplier selection, monitoring practices and firm performance'. Journal of Accounting and Public Policy, 18(3), 253-281.

Ittner, C.D., Larcker, D.F., Randall, T. (1997). 'The Activity-Based Cost hierarchy, production policies and firm profitability'. Journal of Management Accounting Research, 9, 143-162.

Kasanen, E., Lukka, K., Siitonen, A. (1993). ‘The constructive approach in management accounting research’. Journal of Management Accounting Research, 5, 243-264.

Maher, M.W., Marais, M.L. (1998). ‘A field study on the limitations of Activity-Based Costing when resources are provided on a joint and indivisible basis’. Journal of Accounting Research, 36(1), 129-142.

Monczka, R.M., Trecha, S.J. (1988). ‘Cost-based supplier performance evaluation’. Journal of Purchasing and Materials Management, spring, 2-7.

Noreen, E. (1991). ‘Conditions under which Activity-Based Costing systems provide relevant costs. Journal of Management Accounting Research, 3, 159-168.

Noreen, E., Soderstrom, N. (1994). ‘Are overhead costs strictly proportional to activity?’ Journal of Accounting and Economics, 17(1/2), 255-278.

Nydick, R.L., Hill, R.P. (1992). ‘Using the Analytic Hierarchy Process to structure the supplier selection procedure’. International Journal of Purchasing and Materials Management, spring, 31-36.

Rosenthal, E.C., Zydiak, J.L., Chaudhry, S.S. (1995). ‘Vendor selection with bundling’. Decision Sciences, 26(1), 35-48.

Sadrian, A.A., Yoon, Y.S. (1994). ‘A procurement decision support system in business volume discount environments’. Operations Research, 42(1), 14-23.

Schrage, L. (1998). Optimization Modeling with LINGO. Lindo Systems inc., Chicago, USA.

Seal, W., Cullen, J., Dunlop, A., Berry, T., Ahmed, M. (1997). ‘Enacting a European supply chain: A case study on the role of management accounting’. Management Accounting Research, 10(3), 303-322.

Shank, J.K., Govindarajan, V. (1992). ‘Strategic cost management: the value chain perspective’. Journal of Management Accounting Research, 4, 179-197.

Shapiro, J.F. (1999). ‘On the connections among activity-based costing, mathematical programming models for analyzing strategic decisions, and the resource-based view of the firm’. European Journal of Operational Research, 118, 295-314.

Smytka, D.L., Clemens, M.W. (1993). ‘Total cost supplier selection model: a case study’. International Journal of Purchasing and Materials Management, winter, 42-49.

van der Meer-Kooistra, J., Vosselman, E. (2000). ‘Management control of interfirm transactional relationships: The case of industrial renovation and maintenance.’, Accounting, Organizations and Society, 25(1), 51-77.

Weber, C.A., Current, J., Benton, W.C. (1991). ‘Vendor selection criteria and methods’. European Journal of Operational Research, 50, 2-18.

Willis, T.H., Huston, C.R., Pohlkamp, F. (1993). ‘Evaluation measures of just-in-time supplier performance’. Production and Inventory Management Journal, 2nd quarter, 1-5.

Winston, W.L. (1994). Operations Research: applications and algorithms, 3rd edition Duxbury Press, California.

APPENDIX

The details of the mathematical programming model.

Before stating the model, we provide a summary of the notation for later reference.

r : symbol referring to the resistors,

t : symbol referring to the transformers,

p : symbol referring to the printed circuit boards (PCBs),

n : index denoting resistors, $n=r$, transformers, $n=t$, or PCBs, $n=p$,

N(n) : set of resistors, $n=r$, transformers, $n=t$, or PCBs, $n=p$, index *j*,

K : set of monthly time periods, index *k*,

S(n) : set of suppliers for resistors, $n=r$, or transformers, $n=t$, or PCBs, $n=p$, index *i*,

$M(n)_{ij}$: set of discount intervals given by supplier *i* for component *j*, $\forall i \in S(n)$, $\forall j \in N(n)$, $n=t,p$, index *m*.

The parameters indicate the data required and all are expressed on an annual basis. As discussed in section 3, the structure of the models is based on the case specific ABC hierarchy. At the first hierarchical level, the supplier level, the parameters describe costs incurred and conditions imposed whenever the purchasing company actually uses the supplier over the decision horizon. Unless otherwise stated, the parameters and expressions are valid for the three models, i.e. for $n=r,t,p$. The structure of the models differs from case to case as indicated in those paragraphs that are only valid for some of the component groups. We consider at supplier level:

qc_i : quality audit cost incurred by the buyer for the evaluation of supplier *i*, $\forall i \in S(n)$,

mh_i : annual hours of a dedicated purchasing manager for supplier *i* for the time devoted to managing and negotiating, $\forall i \in S(n)$,

wg : gross hourly wages of the purchasing manager who manages and negotiates with the suppliers,

mis : minimum number of suppliers to be used,

mas : maximum number of suppliers to be used, *slc* : total supplier level costs.

For the PCB case we introduce a component level in the hierarchy. The parameters describe the costs incurred and the conditions imposed whenever the purchasing company actually buys the PCB. For $n=p$ we consider:

tlc_{ij} : tooling cost, $\forall\, i \in S(p),\ \forall\, j \in N(p),$

clc : total component level costs.

Each type of resistor is ordered separately and also deliveries are per type. However, orders for transformers and PCBs can include several types of components and are delivered in batches of the same type. Costs related to both the delivery and ordering of resistors are thus incurred at batch level, whereas for the latter component groups an order level is introduced to take ordering costs into account.

For transformers and PCBs we introduce an order level where the parameters indicate cost incurred and conditions imposed each time an order is placed with a particular supplier. For $n=t,p$ we consider:

vc : invoice cost per order,

oco : order cost per order for opening order line,

$olcs_i$: order level cost for supplier i, $\forall\, i \in S(n),$

olc : total order level costs.

The batch level parameters indicate cost incurred and conditions imposed each time a batch is delivered by a particular supplier. For $n=r,t,p$ we consider:

tl_i : import duty per order from supplier *i*, *" i Î S(n));* tl_i = 0 for European Union suppliers,

rc : reception cost per order,

ac : supplier accounting cost per order,

is_{ij} : inspection cost per order with supplier *i* of component *j*, *" i Î S(n), " j Î N(n),*

wr : material handling cost per order in transportation to warehouse and shelving,

rb_i : cost of returning an order to supplier *i*, *" i Î S(n),*

ri : cost of re-inspecting a new delivery after a refusal,

pv_i : probability of refusal at incoming inspection at vendor expense per order with supplier *i*, *" i Î S(n),*

ic : cost of incoming credit note,

pi_i : probability of refusal at incoming inspection with incoming credit note per batch with supplier *i*, *" i Î S(n),*

po_i : probability of refusal at incoming inspection and throwing away of component per batch of supplier *i*, *" i Î S(n),*

ts : cost of troubleshooting, repairing and re-testing when defect of component is discovered during production,

ch : cost of complaint handling,

pif_i : probability of defect discovered during production per batch of component from supplier *i*, *" i Î S(n),*

rp : cost of re-planning the production process,

$pl1_i$: probability of a late delivery by supplier *i* of less than 1 month late per order with supplier *i*, *" i Î S(n),*

cl : cost of customer dissatisfaction due to late delivery,

$pl2_i$: probability of a late delivery by supplier i of more than 1 month late per order with supplier i, $\forall i \in S(n)$,

$blcs_{ij}$: batch level costs for supplier i and component j, $\forall i \in S(n)$, $\forall j \in N(n)$,

blc : total batch level costs.

For $n=t,p$ we consider:

ocl_{ij} : order cost per order line placed with supplier i for component j, $\forall i \in S(n)$, $\forall j \in N(n)$,

lc_{ij} : lot charge per batch with supplier i for component j, $\forall i \in S(n)$, $\forall j \in N(n)$.

For $n=r$ we consider:

oc_{ij} : order cost per order with supplier i of component j, $\forall i \in S(r)$, $\forall j \in N(r)$.

On the final hierarchical level, the unit level parameters specify costs incurred and conditions imposed related to the units of the components for which a procurement decision has to be made. For $n=r,t,p$ we consider:

p_{ij} : price of component j with supplier i, $\forall i \in S(n)$, $\forall j \in N(n)$,

dp_i : price discount as a percentage due to payment delay and conditions, $\forall i \in S(n)$,

$purc$: total monetary purchasing costs,

ocn : cost of outgoing credit note,

cq : cost of customer dissatisfaction due to quality problems,

pef_i : probability of defect discovered by external customer per unit of component from supplier i, $\forall i \in S(n)$,

eqc : total costs related to quality problems discovered by external customers,

h : inventory holding costs per period k as a percentage of the component's price,

ap_j : average price of component j, $\forall j \in N(n)$,

ls_{ij} : lot size for component j when bought with supplier i, $\forall i \in S(n)$, $\forall j \in N(n)$,

ame_i : average number of months, i.e. the number of time periods k, supplier i is early when he delivers early, $\forall i \in S(n)$,

pe_i : probability of early delivery for supplier i, $\forall i \in S(n)$,

$invc$: inventory costs,

bc : backlog costs, as explained infra.,

mo_{ij} : minimum order quantity in number of batches for component j when bought with supplier i, $\forall i \in S(n)$, $\forall j \in N(n)$,

b_j : beginning inventory of component j, $\forall j \in N(n)$,

d_{jk} : demand for component j in time period k, $\forall j \in N(n)$, $\forall k \in K$.

Transformers and resistor suppliers often offer component specific discounts when components are ordered in larger quantities. For $n=t,p$ we consider:

lb_{ijm} : minimum quantity to buy in discount interval m set by supplier i for component j, $\forall i \in S(n)$, $\forall j \in N(n)$, $\forall m \in M(n)_{ij}$,

ub_{ijm} : maximum quantity to buy in discount interval m set by supplier i for component j, $\forall i \in S(n)$, $\forall j \in N(n)$, $\forall m \in M(n)_{ij}$,

dc_{ijm} : price discount as a percentage given by supplier i for component j in discount interval m, $\forall i \in S(n)$, $\forall j \in N(n)$, $\forall m \in M(n)_{ij}$.

The decision variables can also be subdivided in the same hierarchical levels. The supplier decision variable models whether or not the purchasing company will use the supplier over the planning horizon. It is as follows, for $n=r,t,p$:

z_i = 1, if we buy from supplier i, 0 otherwise, $\forall i \in S(n)$.

The component level decision variable only exists in the PCB case, for $n=p$:

yk_{ij} = 1, if PCB *j* is ordered at least once with supplier *i*, 0 otherwise, $\forall i \in S(p), \forall j \in N(p)$.

The order level decision variable only exists in the transformer and PCB cases. For $n=t,p$:

yj_{ik} = 1, if any component is ordered with supplier *i* in time period *k*, 0 otherwise, $\forall i \in S(n), \forall k \in K$.

The batch level decision variable is, for $n=r,t,p$:

y_{ijk} = 1 if component *j* is ordered by supplier *i* in time period *k*, 0 otherwise, $\forall i \in S(n), \forall j \in N(n), \forall k \in K$.

The unit level decision variables pertain to the units of the components for which a procurement decision has to be made and are defined as follows, for $n=r,t,p$:

x_{ijk} = number of lot sizes of component *j* ordered with supplier *i* in time period *k*, $\forall i \in S(n), \forall j \in N(n), \forall k \in K$,

vi_{jk} = inventory of component *j* at the end of time period *k*, $\forall j \in N(n), \forall k \in K$.

For the transformer and PCB cases two extra decision variables are introduced to model the component specific discounts, for $n=t,p$:

w_{ijkm} = 1 if component *j* is bought with supplier *i* in discount interval *m* in time period *k*, 0 otherwise, $\forall i \in S(n), \forall j \in N(n), \forall k \in K, \forall m \in M(n)_{ij}$,

xw_{ijkm} = number of batches of component *j* ordered with supplier *i* in discount interval *m* in time period *k*, $\forall i \in S(n), \forall j \in N(n), \forall k \in K, \forall m \in M(n)_{ij}$.

Table 4 summarises how the main decision variables are associated with the hierarchical levels in the three cases.

Insert Table 4 About Here

With the notation given above, the mathematical decision model is described below.

Objective: minimise the Total Cost of Ownership of the supplier selection policy over the time horizon;

$$Min\ slc + clc + olc + blc + ulc \qquad (1)$$

The objective function (1) reflects net prices and resources consumed by the activities in the five hierarchical levels distinguished.

Define the supplier level costs, for *n=r,t,p*;

$$slc = \sum_{i \in S(n)} \left(qc_i + mh_i wg \right) z_i \qquad (2)$$

The supplier level costs are incurred whenever the purchasing company actually uses supplier *i* over the planning horizon, i.e. z_i=1. The time spent by a dedicated purchasing manager on negotiating, managing and following up the relationship with supplier *i* can be put to some alternative use if supplier *i* is not chosen, i.e. z_i=0 nor does a quality audit need to be performed as the supplier is no longer kept in the supply base. What are called supplier level costs in this paper is often referred to as vendor-sustaining costs in the ABC literature (Cooper and Kaplan, 1998).

Define the component level costs for the PCB case, *n=p;*

$$clc = \sum_{i \in S(p)} \sum_{j \in N(p)} tlc_{ij} yk_{ij} \qquad (3)$$

The component level costs are incurred the first time a specific PCB is ordered with a particular supplier and consist of tooling costs.

Define the order level costs for the transformers and PCB cases, *n=t,p;*

$$olc = \sum_{i \in S(n)} \sum_{k \in K} (oco + vc) yj_{ik} \tag{4}$$

The order level costs are incurred in those time periods *k* an order is placed with supplier *i* and are made up of ordering costs for the first order line and invoicing costs.

Define the batch level costs, *n=r,t,p;*

$$blc = \sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} blcs_{ij} y_{ijk} \tag{5a}$$

$$blcs_{ij} = ocl_{ij} + lc_{ij} + tl_i + rc + ac + wr + is_{ij} + pv_i cv_i + pi_i ci_i + po_i p_{ij}$$

$$+ pif_i ifc_{ij} + pl1_i rp + pl2_i cl \qquad \forall i \in S(n), \forall j \in N(n), n = t, p \tag{5b1}$$

$$blcs_{ij} = oc_{ij} + tl_i + rc + ac + vc + wr + is_{ij} + pv_i cv_i + pi_i ci_i + po_i p_{ij}$$

$$+ pif_i ifc_{ij} + pl1_i rp + pl2_i cl \qquad \forall i \in S(r), \forall j \in N(r) \tag{5b2}$$

$$cv_i = rb_i + tl_i + rc + ri + wr \qquad \forall i \in S(n) \tag{5c}$$

$$ci_i = rb_i + ic \qquad \forall i \in S(n) \tag{5d}$$

$$ifc_{ij} = ts + ch + p_{ij} / ls_{ij} \qquad \forall i \in S(n), \forall j \in N(n) \tag{5e}$$

The batch level costs are incurred only in those time periods *k* a batch of component *j* is ordered with supplier *i* resulting in a delivery, i.e. y_{ijk}=1. As is indicated in (5b1), (5c), (5d) and (5e), the batch level costs for the transformers and PCBs are made up of ordering costs *ocl*, lot charges *lc*, import duty *tl*, receiving costs *rc*, supplier accounting *ac*, material handling and shelving *wr*, inspecting costs *is*, the cost of discovering a default during incoming inspection $pv\,cv + pi\,ci + po\,p$, the cost of a quality problem discovered during production (internal failure) $pif\ ifc$ and re-planning and customer dissatisfaction costs when a delivery is late $pl1\,rp + pl2\,cl$. The cost of discovering a default during incoming inspection consists of the costs related to refusing a delivery and sending it back at vendor expense $pv\,cv$ in which case the supplier replaces the resistors that will have to be re-inspected, the costs related to refusing a delivery and receiving a credit note from the supplier $pi\,ci$ and the price of throwing a defect resistor delivery away $po\,p$. Internal failure costs consist of troubleshooting, repair and retest costs *ts*, complaint costs *ch* and the price of the component p/ls. We assume that the probabilities of discovering a default during incoming inspection and internal default apply equally over all batches of a component bought-in from a specific supplier. When a delivery is less than a month late only re-planning costs are incurred, but when there is more delay, the purchasing firm will have problems in delivering its products to its own customers. The batch level costs for resistors are very similar to those in the transformer and PCB cases, except that the order cost per line is now replaced by the full order cost *oc*, invoicing costs *vc* are added and lot charges *lc* are deleted, as indicated in (5b2), (5c), (5d) and (5e). Order costs for resistors, order costs per line for transformers and PCBs and inspecting costs are different for different components *j* with the same supplier *i* since they are dependent upon the type of agreement with the supplier for this specific component. Note that, in contradiction to EOQ models, part of the inventory related cost is recognised at batch level as material handling cost per batch in transportation to warehouse and shelving costs are included on this level.

Define the unit level costs, $n=r,t,p$;

$$ulc = purc + eqc + invc + bc \tag{6}$$

Specifically, the unit level costs consist of the monetary purchase cost, the quality costs of defects discovered by external customers, inventory holding costs and backlog inventory costs.

Define the annual purchasing costs;

$$purc = \sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} \sum_{m \in M(n)_{ij}} xw_{ijkm} \left(1 - dc_{ijm}\right)\left(1 - dp_i\right) p_{ij} \tag{7}$$

The annual purchasing costs are equal to the sum of all purchases made from all suppliers, taking the component specific discounts and the payment delay and discount offered into account.

Define the external failure costs;

$$eqc = \sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} efc \ pef_i ls_{ij} x_{ijk} \tag{8a}$$

$$efc = ch + ocn + cq \tag{8b}$$

External failure costs are incurred when external customers of the firm discover a quality problem. They consist of complaint handling, making an outgoing credit note and cost of customer dissatisfaction due to quality problems. We assume the probability of external default applies equally to all units of a specific component bought-in from a specific supplier. For the cases considered here, however, external complaint records showed that none of the customer complaints about the final product related back to defect components delivered by the supplier. These problems were always discovered in earlier stages in the value chain, either in incoming inspection or during production. Thus, $pef_i = 0,\ \forall i \in S(n)$.. Therefore there was no need for us to go into detailed calculation of the opportunity costs of lost sales due to customer dissatisfaction. However, this would prove a fruitful area for future research.

Define the inventory holding costs;

$$invc = \sum_{j \in N(n)} \sum_{k \in K} h\, ap_j vi_{jk} + \sum_{i \in S(n)} \sum_{j \in n(n)} \sum_{k \in K} h\, ap_j ls_{ij} x_{ijk}\, pe_i ame_i \qquad (9)$$

The inventory holding cost applies to the total amount of component *j* held in inventory during each time period *k*, denoted by vi_{jk}, and to the components that are delivered early and thus have to be kept in inventory longer than necessary.

Define the backlog inventory costs;

$$bc = \sum_{j \in N(n)} \sum_{k \in K} (rp + cl) bl_{jk} \qquad (10)$$

Backlog inventory is a term used in Operations Research (e.g. Winston, 1994, p.870). A backlog inventory is used whenever the demand for a component is not met in the time period the demand exists, but only in a later time period. It could be seen as a negative inventory. In the meantime, costs of re-planning the production process and a very high cost of customer dissatisfaction due to late delivery are incurred. There is no cost of production standstill as the case study firm only starts producing when all necessary components are available. A backlog inventory could for example be used when a supplier who scores excellent on all other TCO issues doesn't have a short enough lead time. In this paper, however, we did not attempt to quantify the opportunity costs related to late delivery and customer satisfaction as this is an extremely difficult task. As demand in this case study is quite stable and predictable, we plugged in a prohibitively high figure for this cost so that when running the model well in advance of the time period considered, the optimal solution would never make use of the backlog inventory and order well in time with a supplier whose lead time is low enough to cover demand in time. The inclusion of a backlog inventory in the objective function, however, gives the decision maker the possibility to use the mathematical programming model also under circumstances of an uncertain demand, where flexibility and the possibility to deliver on a short lead time become extremely important. In this case, management should make several estimates of the opportunity cost of late deliveries and customer dissatisfaction and run the model again under these different scenarios. When there is a sudden change in the demand that was originally derived from the MRP system, the demand figures d_{jk} can be adapted from that time period *k* on and all earlier placed orders (before time period *k*) can be fixed in the model. When running the optimisation model again, it will choose these suppliers with a short enough vendor lead time to adapt to the new demand constraints or make use of backlog inventories that generate an opportunity cost to be included in the TCO.

This concludes the derivation of the objective function. The constraints relevant to the procurement problem are as follows.

Satisfy demand;

$$b_j + \sum_{i \in S(n)} ls_{ij} x_{ij(f - vlt_{ij})} - vi_{jf} + bl_{jf} = d_{jf} \qquad \forall j \in N(n) \qquad (11a)$$

$$vi_{jk-1} + \sum_{i \in S(n)} ls_{ij} x_{ij(k - vlt_{ij})} - vi_{jk} + bl_{jk} - bl_{jk-1} = d_{jk} \quad \forall j \in N(n), \forall k \in K \setminus \{f\} \quad (11b)$$

The demand for each component in the first time period *f*, d_{jf}, modelled by constraint (11a), can be satisfied from either beginning inventory b_j, and/or from purchases from the potential suppliers, $x_{ij(f-vlt_{ij})}$, and/or be put in a backlog inventory bl_{jf} which is only satisfied in a later time period. The amount that remains is the end-of-period inventory vi_{jk}. When purchasing management wants a component to be delivered in this time period k by supplier i it will have to place this order in time period $k\text{-}vlt_{ij}$. f is equal to the maximum vendor lead time offered by a supplier of the component group studied. f determines how many time periods in advance the model has to be solved in a deterministic environment in order not to mount up the considerable cost of using a backlog inventory. In a stochastic environment where demand is uncertain, f can be used to fix the current time period and the orders placed before f, and re-run the model with the new demand data. Constraints (11b) model the demand for each component j in later time periods, d_{jk} and the backlog demand from the previous period, bl_{jk-1}, which adds to the normal demand in time period k. This demand is satisfied either from begin-of-period inventory, which equals the ending inventory of the previous period vi_{jk-1}, and/or from purchases from potential suppliers, $x_{ij(k-vlt_{ij})}$, and/or is put in a backlog inventory bl_{kj}. Again, the amount that remains is the end-of-period inventory, vi_{jk-1}.

Enforce the bounds on the number of suppliers used;

$$\sum_{i \in S(n)} z_i \geq mis \qquad (12a)$$

$$\sum_{i \in S(n)} z_i \leq mas \qquad (12b)$$

$$z_i \leq \sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} y_{ijk} \qquad \forall i \in S(n) \qquad (12c)$$

$$y_{ijk} \leq z_i \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K \qquad (12d)$$

Conditions (12a) and (12b) force the purchasing plan to have at least the minimum number, mis, and at most the maximum number, mas, of suppliers over the complete time horizon for each component group. Using constraint (12c), the decision variable z_i will be equal to 0 if the model suggests not to buy from supplier i, while constraint (12d) forces z_i to be equal to 1 if during some time period k an order has been placed with supplier i.

Enforce the proper relationships between x_{ijk} and y_{ijk} and impose the minimum order quantity;

$$x_{ijk} \leq M \; y_{ijk} \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K \quad (13a)$$

$$mio_{ij} y_{ijk} \leq x_{ijk} \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K \quad (13b)$$

If an order is not placed with supplier i in period k, condition (13a) with M a large number will ensure that the amounts of each component that can be bought from the supplier will indeed be zero. Since the minimum order quantity mio_{ij} is expressed as a number of batches, condition (13b) forces the batch size to be at least this amount if an order is placed.

Enforce the proper relationships between y_{ijk} and yj_{ik} for the transformer and PCB case, $n=t,p;$

$$yj_{ik} \leq \sum_{j \in N(n)} y_{ijk} \qquad \forall i \in S(n), \forall k \in K \qquad (14a)$$

$$nn \; yj_{ik} \geq \sum_{j \in N(n)} y_{ijk} \qquad \forall i \in S(n), \forall k \in K \qquad (14b)$$

with nn the number of components, transformers or PCBs, to be bought. Condition (14a) ensures that if no component is bought in time period k with supplier i yj_{ik} is 0. Condition (14b) ensures that yj_{ik} takes the value of 1 when a component is bought with supplier i in time period k.

Enforce the proper relationships between y_{ijk} and yk_{ij} for the PCB case, $n=p;$

$$yk_{ij} \leq \sum_{k \in K} y_{ijk} \qquad \forall i \in S(n), \forall j \in N(n) \qquad (15a)$$

$$nk \; yk_{ij} \geq \sum_{k \in K} y_{ijk} \qquad \forall i \in S(n), \forall j \in N(n) \quad (15b)$$

with *nk* the number of time periods over the time horizon. Condition (15a) ensures that if, over the time horizon, component *j* is not bought with supplier *i*, yk_{ij} is 0. Condition (15b) ensures that yk_{ij} takes the value of 1 when component *j* is bought with supplier *i* over the time horizon.

Model the component specific quantity discounts, for *n=t,p*;

$$\sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} \sum_{m \in M(n)_{ij}} xw_{ijkm} = \sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} x_{ijk}$$

$$\forall i \in S(n), \forall j \in N(n), \forall k \in K \quad (16a)$$

$$ls_{ij} xw_{ijkm} \geq lb_{ijm} w_{ijkm} \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K, \forall m \in M(n)_{ij} \quad (16b)$$

$$ls_{ij} xw_{ijkm} \leq ub_{ijm} w_{ijkm} \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K, \forall m \in M(n)_{ij} \quad (16c)$$

$$\sum_{i \in S(n)} \sum_{j \in N(n)} \sum_{k \in K} \sum_{m \in M(n)_{ij}} w_{ijkm} \leq z_i \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K \quad (16d)$$

Expression (16a) computes the amount bought over all discount intervals. The lower bound on the amount of component *j* to buy in the discount intervals is set by constraint (16b), while constraint (16c) imposes the same condition for the upper bound. Condition (16d) ensures that we cannot obtain discounts on a component if we do not buy anything from the supplier. The discounting percentage is then applied in equation (7).

Integrality and nonnegativity;

$$z_i \in \{0,1\} \qquad \forall i \in S(n) \quad (17a)$$

$$yk_{ij} \in \{0,1\} \qquad \forall i \in S(n), \forall j \in N(n), n = t, p \quad (17b)$$

$$yj_{ik} \in \{0,1\} \qquad \forall i \in S(p), \forall k \in K \quad (17c)$$

$$y_{ijk} \in \{0,1\}, x_{ijk} \geq 0 \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K \quad (17d)$$

$$w_{ijkm} \in \{0,1\}, xw_{ijkm} \geq 0 \qquad \forall i \in S(n), \forall j \in N(n), \forall k \in K, \forall m \in M(n)_{ij} \quad (17e)$$

To conclude the model specification, constraints (17a) through (17e) impose the proper integrality and nonnegativity conditions that apply to the decision variables.

Model (1) through (17e) is a mixed integer linear programming model.

Table 5 indicates the dimensions of the mathematical programming model, reporting on the number of variables and constraints, respectively, the mixed integer program uses when the input is read in.

Insert Table 5 About Here

Problems of a smaller size can be solved straightforwardly with optimising software such as LINGO (Schrage, 1998) on any IBM-compatible 486 or higher PC in times going from a few minutes to a few hours. The existing computer technology and software, however, does not allow to solve the case studies reported in this paper in a straightforward way because of the very large dimensions.

Therefore we have developed a stepwise procedure to achieve a good approximation to the optimal supplier selection and inventory management policy while analysing the data. In a first step, all components for which only a single source exists and for which therefore no better supplier selection is possible, are solved in separate models per supplier to optimise the ordering policy. Then a cluster matrix is drawn for all components that can be delivered by more than one supplier, which we called multiple sourcing components in the remainder of the paper. The cluster matrix indicates how many components the suppliers have in common and how they are clustered together around component groups. Mathematical programming models for small clusters of multiple sourcing components without links to other components or suppliers, can then be solved. The sequence in which the remaining big cluster of suppliers and multiple sourcing components is solved, starts with the suppliers with the least components and with the least links to other suppliers, for which the mathematical programming models can usually be solved for all components of a supplier in one go. Then we solve the optimising models for part of the components of the bigger suppliers. For each group of components we include all the possible suppliers for these components, and proceed until we have solved models for all components. Each time the supplier level costs $slcs_i$ in the input of a subsequent mathematical programming model are set to zero if this supplier is already chosen in an earlier solved model to avoid double counting. For the transformer and PCB cases also the order level costs $olcs_{ik}$ are set to zero when in earlier solved models an order is already placed with supplier *i* in time period *k*, i.e. if $yj_{ik} = 1$. All the mathematical programming models are solved with an optimality tolerance between 0 and 3%. The optimality tolerance indicates to the branch-and-bound solver in LINGO that it should only search for integer solutions with objective values at least x % better than the best integer solution found so far. The results of modifying the search procedure in this way are twofold. First, on the positive side, solution times can be improved enormously. Second, on the negative side, the final global solution obtained by LINGO may not be the optimal solution. However, a solution within x % of the TCO optimum is guaranteed. On larger mixed integer models like these, the alternative of getting a solution within a few percentage points of the optimum after several minutes of runtime, as opposed to the optimum after several days, makes the use of an optimality tolerance quite attractive. Using this procedure, the TCO reached might be slightly higher than the optimal TCO that could be reached if it were possible to solve the mathematical programming model for the whole component group at once, because the sequence of the components and the optimality tolerance percentage used influence the solution obtained. However, possible savings of between 6 and 14% compared to the current policy of the firm, discussed in the next section, prove this procedure definitely obtains good results. Going through this solution procedure on a yearly basis is sufficient. Selected suppliers can then be fixed and smaller models can be solved to generate the order and inventory policy only. The firm in this case study could decide to continue to use their existing EOQ model to determine the ordering policy on an operational basis and use the TCO model for strategic supplier selection decision making.

A simpler ABC hierarchy as the three level resistor hierarchy compared to the five level PCB hierarchy, does not help to solve the models in these cases more easily. Less hierarchical levels may lead to less decision variables, but in the cases studied here the number of possible suppliers that can deliver a component increases when the number of hierarchical levels decreases, and thus the number of variables is increased in that way again.

FIGURE 1

The value chain and activities influenced by the purchasing policy

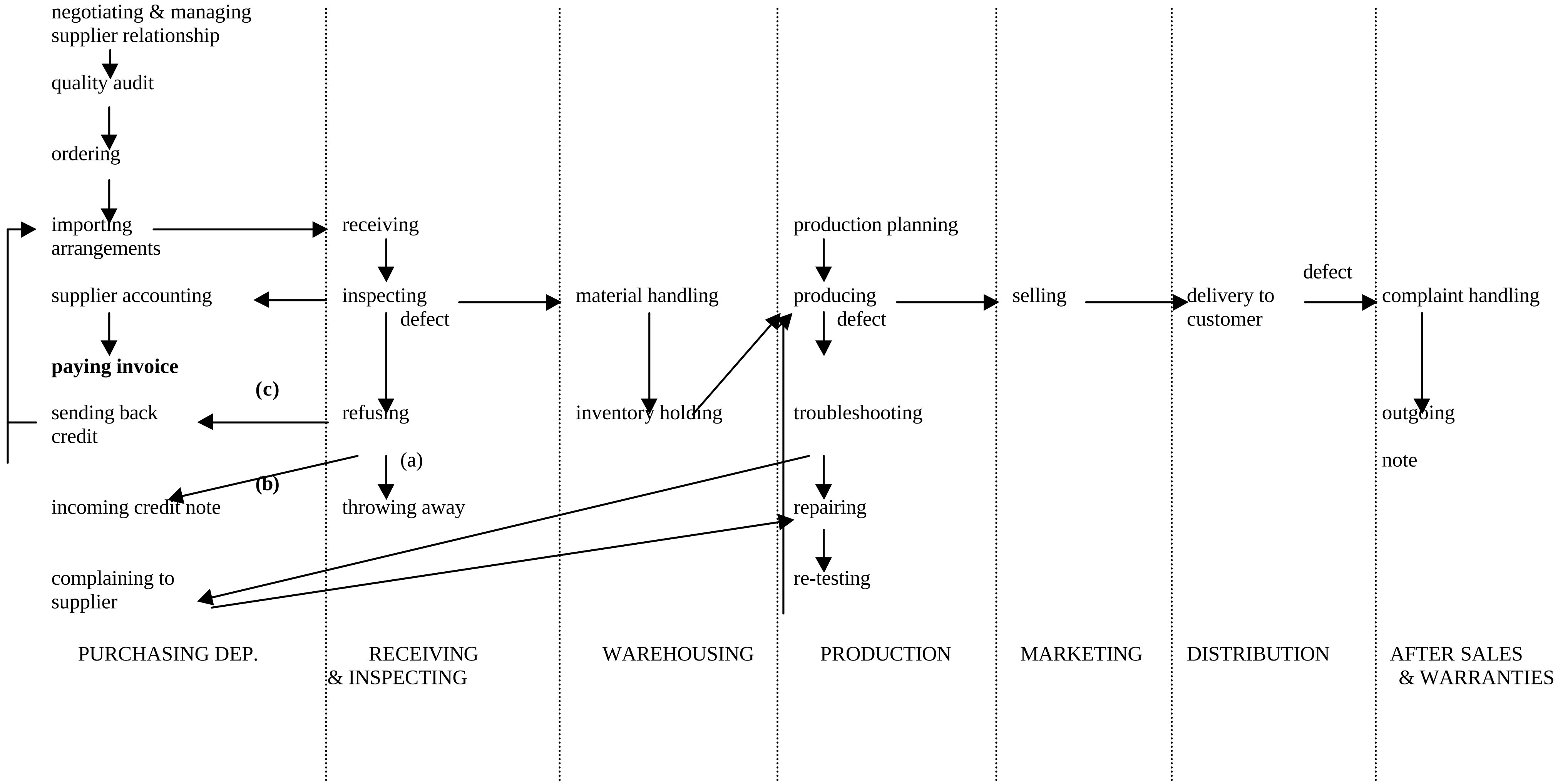

TABLE 1

Dimensions of the case studies

	total number of different component ty	number of different component ty needed in 1999	number of suppliers	current monetary purchasing price in euro
Resistors	1729	660	25	1,225,000
Transformers	543	260	39	8,044,000
PCBs	336	132	24	5,263,000

TABLE 2

The ABC details for the supplier selection cases

Resources	Resource drivers	Activities	Detailed activity cost pools	Activity driver as decision variable in mathematical programming model	PURCHASING POLICY
gross wages of purchasing manager	% of time spent	negotiating & managing relationship	hours negotiating & managing	# suppliers	
gross wages of auditor + quality engineer	% of time spent	quality audit	0/1 quality audit	# suppliers	
gross wages of secretaries, buyers and purchasing engineers	% of time spent on EDI orders	ordering	EDI orders	# orders	
	% of time spent on ACO orders				
	% of time spent on manual orders		ACO orders		
yearly EDI service fee + gateway fee	direct with EDI ordering		manual orders		
computer used for EDI	direct EDI ordering				
fax machine	direct with manual ordering				
gross wages of secretaries, buyers and purchasing engineers	% of time spent on invoices	invoicing		# orders	
import duty	direct with importing	importing	batches from outside E.U.	# batches	
gross wages of secretaries	% of time spent on import declarations				
gross wages of accountant	% of time spent	supplier accounting		# batches	
gross wages of receiving personnel	% of time spent	receiving		# batches	
gross wages of inspecting personnel	% of time spent on immediate releases	inspecting	immediate releases	# batches	
	% of time spent on visual inspections		visual inspections		
	% of time spent on comparisons of labels on packaging		comparisons of labels on packaging		
	% of time spent on skip lot inspections		skip lot inspections		

	% of time spent on engineer verifications		engineer verifications	
	% of time spent on sample inspections of lot		sample inspections of every lot	
inspecting equipment	direct with inspecting			
gross wages of inspecting personnel	% of time spent on refusing incoming orders or batches	refusing a delivery		# batches
gross wages of receiving personnel	% of time spent on refusing incoming orders or batches			
gross wages of purchasing personnel	% of time spent on refusing incoming orders or batches			
price	direct with throwing away	throwing away		# batches
gross wages of secretaries	% of time spent on sending back & administration	sending back	sending back to E.U. supplier	# batches
gross wages of accountant	% of time spent on accounting for sending back			
postage	direct with sending back		sending back to outside E.U. supplier	
export duty to outside E.U. suppliers	direct with sending back outside E.U.			
gross wages of accountant	% of time spent on incoming credit notes	incoming credit note		# batches
gross wages of warehousing per	% of time spent on transporting orders or batches to warehouse and shelving	material handling		# batches
gross wages of production personnel	% of time spent on troubleshooting after discovery of defect component	troubleshooting		# batches
gross wages of production personnel	% of time spent on repairing after discovery of defect component	repairing		# batches
repairing equipment	direct with repairing			
gross wages of production personnel	% of time spent on re-testing after discovery of defect component	re-testing		# batches
testing equipment	direct			

gross wages of warehousing per	% of time spent on maintaining inventory	inventory holding		# units of component	
heating costs	m²				
warehouse maintenance	m²				
fire insurance	m²				
opportunity cost	interest % to be gained on risk free investr				
obsolescence cost	% of unit price				
gross wages of personnel in com handling department	% of time spent on complaint handling	complaint handling		# units of component	
gross wages of personnel in com handling department	% of time spent on making up outgoing credit note	outgoing credit note		# units of component	

: number of

TABLE 3

Activity Based Costs and Hierarchy for the three case studies

	resistors	transformers	printed circuit boards
supplier level costs	quality audit negotiating and managing	quality audit negotiating and managing	quality audit negotiating and managing
component level co	N/A.	N/A.	tooling cost
order level costs	N/A.	ordering opening line invoicing	ordering opening line invoicing
batch level costs	ordering invoicing importing supplier accounting receiving inspecting refusing throwing away sending back incoming credit note material handling to warehouse late delivery troubleshooting repairing re-testing	ordering subsequent lines importing supplier accounting receiving inspecting refusing throwing away sending back incoming credit note material handling to warehouse late delivery troubleshooting repairing re-testing	ordering subsequent lines importing supplier accounting receiving inspecting refusing throwing away sending back incoming credit note material handling to warehouse late delivery troubleshooting repairing re-testing
unit level costs	inventory holding (normal & early delivery price complaint handling outgoing credit note	inventory holding (normal & early delive price complaint handling outgoing credit note	inventory holding (normal & early delivery price complaint handling outgoing credit note

TABLE 4

The decision variables

	Resistors	***Transformers***	PCBs
Supplier level	z_i	z_i	z_i
Component level	N/A.	N/A.	yk_{ij}
Order level	N/A.	yj_{ik}	yj_{ik}
Batch level	y_{ijk}	y_{ijk}	y_{ijk}
Unit level	x_{ijk}	x_{ijk}	x_{ijk}

TABLE 5

Dimensions of the mathematical programming model

	number of variables	number of constraints
Resistors	117,125	95,231
Transformers	59,268	62,497
PCBs	31,456	28,904

TABLE 6

Results

		Resistors	Transformers	PCBs	Total
possible savings	as a percentage of TCO of current policy	14.26%	5.97%	11.00%	8.49%
optimal TCO	in EURO	1,151,000	7,974,000	4,827,000	13,952,000
optimal policy as a % of optimal TCO	optimal TCO	100%	100%	100%	100%
	SLC	1.76%	0.42%	0.33%	0.50%
	CLC	N/A.	N/A.	0.06%	0.02%
	OLC	N/A.	0.03%	0.03%	0.03%
	BLC	3.96%	1.21%	0.51%	1.19%
	ULC	94.82%	98.34%	99.06%	98.25%
	PURC	92.82%	97.71%	98.52%	97.58%
	INV	1.46%	0.63%	0.54%	0.67%
current policy as a % of optimal TCO	SLC	2.28%	0.43%	0.37%	0.56%
	CLC	N/A.	N/A.	0.08%	0.03%
	OLC	N/A.	0.03%	0.03%	0.03%
	BLC	6.61%	2.03%	0.79%	1.98%
	ULC	107.75%	103.86%	111.09%	106.68%
	PURC	106.33%	100.87%	109.02%	104.14%
	INV	1.42%	2.99%	2.07%	2.54%