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RESEARCH REPORT 0036

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

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D/2000/2376/36

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Abstract.

In this paper we elaborate on a Total Cost of Ownership supplier selection methodology that we have constructed using three real life case studies which 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. Possible savings of between 6 and 14% are obtained for the three cases.

1. Introduction.

Purchasing determines an important part of the competitive position of most firms. It accounts for 50% to 70% of total costs in manufacturing, 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 has never received much attention, it is a field where still enormous cost reductions can be obtained. 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, etc. The problem is how to select suppliers that perform satisfactorily on the desired dimensions.

Since this multiple objective vendor selection problem cannot be handled by a simple spreadsheet, this paper proposes a Management Information System (MIS) based on mathematical programming that simultaneously treats the supplier selection and the inventory management decision for multiple products and several time periods. 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 product 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). This 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 costs related to service, quality, delivery, administration, inventory holding, communication, defects etc.

The vendor selection methodology is developed using a constructive case study approach (Kasanen, Lukka, Siitonen, 1993). Using our theoretical ABC framework for supplier selection we built the MIS at a telecommunications firm for three major product groups, accounting for almost GBP 10000.000 in total costs. The resistors are classified in 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 the insulation requirements. The production cost of the Printed Circuit Board (PCB) suppliers depends on, amongst others, 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 information is 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. It also discusses the process of finding a solution. The next section interprets the results and discusses strategic insights for the purchasing policy. The last section concludes.

2. The value chain and activities.

In the first step of the vendor selection methodology, the activities in the value chain of the firm that relate to the purchasing policy are studied. 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 these activities, where they are situated in the value chain and how they relate back to the purchasing policy in the case study firm.

- Insert Figure 1 about here-

The purchasing engineer responsible for the product group negotiates with the suppliers on price, discounts, quality, lead time etc. and follows up the relationship. Sometimes the quality team performs a quality audit on site when the supplier is new to the firm or when quality problems arise too frequently. When a supplier is selected, ordering can start. Depending on the supplier/product combination orders can be placed through electronic data interchange (EDI), automatic call off (ACO) or the manual way of sending a fax. 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 product 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. The first time an order is placed for a specific PCB with a supplier, a tooling cost might be charged by its supplier to cover the supplier's costs on films, drilling information and electrical testing. The supplier's lead-time is the time that elapses between the ordering and the delivery of the component. 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. Asian suppliers generally have a longer lead-time than European and American suppliers. A supplier's delivery reliability depends on the history of early and late deliveries around the agreed delivery date. When the product is ordered with a supplier outside the European Community, importing documents have to be filled out and import duty has to be paid. Then the receiving department receives the delivery and inspects it together with the inspecting department. 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 send for verification to the engineer that ordered the component. 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 product 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 sends a credit note or replaces them at his expense, or they are thrown away at the firm's own expense. When the supplier replaces 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 triggers a lot of extra work in troubleshooting the problem, complaining to the supplier, repairing and re-testing the component. For PCBs the cost of discovering a problem in this phase in the value chain is the highest as the entire expensive PCB usually 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. The external customers of this firm ascertain only 1,7% of the 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 production component bought. Instead, they are due to faults in the production process or wrong deliveries.

3. Data collection.

The developments in ABC and the integration of these costing systems with company wide information systems enable us to collect all necessary data on activities and supplier performance.

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. One could, for example, check how much time the inspectors spend on a skip lot inspection or a full inspection. Some resources are linked directly to the activity and need not be assigned through a resource driver. For example, the import duty paid is exclusively related to the importing activity. Columns 1, 2 and 3 of Table 1 indicate the direct or indirect link between resources and activities and which resource drivers are used in the latter case.

- Insert Table 1 about here-

Once the cost of performing an activity is calculated, activity drivers that determine the total cost of the purchasing policy are searched for, using a cost hierarchy with several levels: supplier-, product, order-, batch- and unit-level. ABC approximates the linearity of the cost functions with activities much better than the traditional volume related approaches by using a cost hierarchy where costs become variable at different levels. 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. The product level indicates costs incurred whenever the firm needs to buy this product. Tooling costs for the PCBs are incurred on this level as they are only charged the first time that the product 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. On 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 products 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 products are delivered per batch of the same product, we add an order level in these cases. We include a product level 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 2 shows how the hierarchy differs from case to case and on what levels the costs are incurred.

- Insert Table 2 about here-

It is important to make this classification of activities into separate levels since the overall primary activity driver for each level of activity, (1) number of suppliers, (2) number of products, (3) number of orders, (4) number of batches and (5) number of units procured, is assumed independent of the activities in other hierarchical levels. In turn, the five primary activity drivers determine a number of secondary activity drivers such as for example the number of receptions, the number of orders through an EDI-system, the number of skip lot inspections and the number of hours the purchasing manager negotiates. In this way, all costs caused by the selection of suppliers and the placement of orders with them can be determined. Columns 3, 4 and

5 of Table 1 show the primary and secondary activity drivers that drive the usage of activities by the supplier selection policy. The primary activity 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 on the level of the secondary activity drivers. Often the performance of a supplier changes with the product required, for example the same supplier may deliver both products that can be immediately released by the receiving department without further inspection as well as other products where a sample has to be taken of every batch. For some components an automatic order through the ACO system is possible, while the same supplier may only accept a fax order for other products. Other secondary activity drivers may be the same for all products of the same supplier, e.g. the chance the supplier delivers early or late and the location of the supplier as being inside or outside the European Community. Also data on prices, quantity discounts, supplier's lead time, tooling costs, minimum order quantity and lot size are collected in this phase of the vendor selection methodology. The supplier cannot influence the cost of activities for which only a primary activity driver but no secondary activity driver is defined. Examples are supplier accounting, receiving and material handling. However, the purchasing firm can still work on the efficiency and effectiveness improvement of these activities or try to eliminate them when they are non-value-adding activities such as inventory holding.

4. 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 using a simple spreadsheet. Therefore, we develop mathematical programming models to determine an optimum sourcing strategy for the different product 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.

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 product 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 the previous section, 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 $n=r,t,p$. We consider:

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 product level. 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, $\forall i \in S(p)$, $\forall j \in N(p)$,

plc : total product level costs.

Each type of resistor is ordered separately and also deliveries are done 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 on batch level, whereas for the latter product 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, $\forall i \in S(n)$); $tl_i = 0$ 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 product j, $\forall i \in S(n)$, $\forall j \in N(n)$,

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

rb_i : cost of returning an order to supplier i, $\forall i \in S(n)$,

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, $\forall i \in S(n)$,

ic : cost of incoming credit note,

pi_i : probability of refusal at incoming inspection with incoming credit note per batch with supplier i, $\forall i \in S(n)$,

po_i : probability of refusal at incoming inspection and throwing away of component per batch of supplier i, $\forall i \in S(n)$,

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 product from supplier i, $\forall i \in S(n)$,

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, $\forall i \in S(n)$,

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 product 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 product j, $\forall i \in S(n)$, $\forall j \in N(n)$,

lc_{ij} : lot charge per batch with supplier i for product 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 product 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 products for which a procurement decision has to be made. For $n=r,t,p$ we consider:

p_{ij} : price of product 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, $\forall i \in S(n)$,

$purc$: 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 product 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 product's price,

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

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

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

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

Transformers and resistor suppliers often offer product 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 product 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 product 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 product 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 supplier will be used by the purchasing company 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 product 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 product 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 product 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 products for which a procurement decision has to be made and are defined as follows, for $n=r,t,p$:

x_{ijk} = number of batches of product 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 product 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 product specific discounts, for $n=t,p$:

w_{ijkm} = 1 if product 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 product 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 3 summarises how the main decision variables are associated with the hierarchical levels in the three cases.

- insert Table 3 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;

$$Min\ slc + plc + olc + blc + ulc \tag{1}$$

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 $n=r,t,p$;

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

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.

Define the product level costs for the PCB case, $n=p$;

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

The product 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, $n=r,t,p$;

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

$$\begin{aligned} blcs_{ij} &= ocl_{ij} + lc_{ij} + tl_i + rc + ac + wr + is_{ij} + pv_i cv_i + pi_i ci_i + po_i p_{ij} \\ &\quad + pif_i ifc_{ij} + pl1_i rp + pl2_i cl \qquad \forall i \in S(n), \forall j \in N(n), n = t,p \end{aligned} \tag{5b1}$$

$$\begin{aligned} blcs_{ij} &= oc_{ij} + tl_i + rc + ac + vc + wr + is_{ij} + pv_i cv_i + pi_i ci_i + po_i p_{ij} \\ &\quad + pif_i ifc_{ij} + pl1_i rp + pl2_i cl \qquad \forall i \in S(r), \forall j \in N(r) \end{aligned} \tag{5b2}$$

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

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

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

The batch level costs are incurred only in those time periods k a batch of product 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 per order line, import duty, receiving costs, supplier accounting, material handling and shelving, invoice paying, inspecting costs, the cost of discovering a default during incoming inspection, the cost of a quality problem discovered during production (internal failure) and re-planning and customer dissatisfaction costs when a delivery is late. 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 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 and the price of throwing a defect resistor delivery away. Internal failure costs consist of troubleshooting costs, repair costs, retest costs, complaint costs and the price of the component. 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 order line is now replaced by the full order cost and lot charges and invoicing costs are added, 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 products 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 on 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 product 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. 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, $pef_i = 0$, $\forall i \in S(n)$.

Define the inventory holding costs;

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

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

Define the backlog inventory costs;

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

A backlog inventory is used whenever the demand for a product is not met in the time period the demand exists, but only in a later time period. In the meantime costs of re-planning the production process and 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. The inclusion of a backlog inventory in the objective function gives the decision maker the possibility to use the mathematical programming model under circumstances of an uncertain demand, where flexibility and the possibility to deliver on a short lead time become very important. When there is a sudden change in the demand that was originally derived from the MRP system, the 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.

This concludes the derivation of the objective function. The constraints relevant to the procurement problem are as follows.
Satisfy the 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 product 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} that 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 product to be delivered in this time period k by supplier i it will have to place this order in time period k-vlt_{ij}. f is equal to the maximum vendor lead time offered by a supplier of the product group studied and 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 product j in later time periods, d_{jk} and the backlog demand from the previous period, bl_{jk-1}, which add 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 be 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;

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

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

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

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

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 product 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;

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

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

If an order is not placed with supplier i in period k, condition (13a) with M a big number will enforce that the amounts of each product that can be bought from the supplier will indeed be zero. Since the minimum order quantity mio_{ij} is expressed in 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 products, transformers or PCBs, to be bought. Condition (14a) ensures that if no product 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 product is bought with supplier i in time period k.

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

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

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

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

Model the product 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 product 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 product if we do not buy anything from the supplier. The discounting percentage is than 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 program. Table 4 gives an indication of the size of the cases studied. The first column gives the number of different components used in the firm. The second column states how many of these were used in 1999, the year of study. The third column indicates the number of possible suppliers. The fourth and fifth columns show in how many variables and constraints, respectively, the mixed integer program uses when the input is read in.

-insert Table 4 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 from a few minutes to a few hours. The existing computer technology and software, however, does not allow solving the case studies reported in this paper in a straightforward way.

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 products 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 products that can be delivered by more than one supplier, in the remainder of the text called multiple sourcing products. The cluster matrix indicates how many products the suppliers have in common and how they are clustered together around product groups. Mathematical programming models for small clusters of multiple sourcing products without links to other products or suppliers can then be solved. The sequence in which the remaining big cluster of suppliers and multiple sourcing products is solved, is determined by going from the suppliers with the least products and least links to other suppliers, for which the mathematical programming models can usually be solved for all products of a supplier in one go, to the bigger suppliers whose products have to be split over several optimising models. 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 solution obtained by LINGO may not be the true optimal solution. However, a solution within x % of the true TCO optimum is guaranteed. On larger mixed integer models like these, the alternative of getting a solution within a few percentage points of the true optimum after several minutes of runtime, as opposed to the true 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 product group at once, because the sequence of the products and 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 to generate the order and inventory policy only can be solved. A simpler ABC hierarchy as e.g. the three level resistor hierarchy compared to the five level PCB hierarchy, does not lead to the models being solved more easily in these cases. Going from PCBs over transformers to resistors the number of possible suppliers that can deliver a component increases, and thus increases the number of variables in that way again.

5. 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 5 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 product groups in GBP. 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 5 about here-

The purchasing policy proposed is able to save 14%, 6% and 11% on TCO on the product groups resistors, transformers and PCBs respectively. 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. The main part of possible savings also lie on 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 product specific discounts for transformers and especially PCBs. Using this TCO model, the selection of these lower price suppliers can now be made with the assurance that quality and other costs were taken into account and that the overall effect on TCO is positive. Almost all products have a single source that is clearly better than the other possible suppliers. The current policy increases TCO by splitting orders of the same product over several suppliers.

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 are possible by ordering with suppliers that 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 product. For components with a low unit price such as resistors, inventory holding costs already make up a smaller percentage of the cost structure.

Also on batch level savings can be made 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, where quality problems are not common, are a result of a policy of less frequent ordering. Combining orders for several product types of one supplier, as in the transformers and PCB cases, could lead to more savings.

The firm can only make minor savings on order level costs for transformers and PCBs. Rather surprisingly, the possible way of ordering through EDI, ACO or fax, cannot save much on ordering costs for the time being. Reason here 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.

Besides, the Economic Order Quantity (EOQ) model currently in use at the company calculates the ordering point with dated cost figures for ordering, inspecting and inventory holding activities. As the figures used by the firm for ordering and inspecting on one hand and inventory holding on the other hand are both higher than actual figures, it is not clear whether the current incentives steer towards to few or to frequent ordering. 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.

The product 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 products 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 on 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 even 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 with one supplier of a product group not studied here on a pilot project for VMI. 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.

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 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 can be identified.

Second, also areas where external improvements by suppliers are able to generate decreases in TCO can be pinpointed. The model then can 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.

6. Conclusion.

In this paper we develop a Total Cost of Ownership supplier selection methodology. In a first step, the activities in the value chain that relate to the purchasing policy are studied. 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 overlook 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. Possible savings of between 6 and 14 % are obtained for the three cases.

Figure 1: The value chain and activities influenced by the purchasing policy.

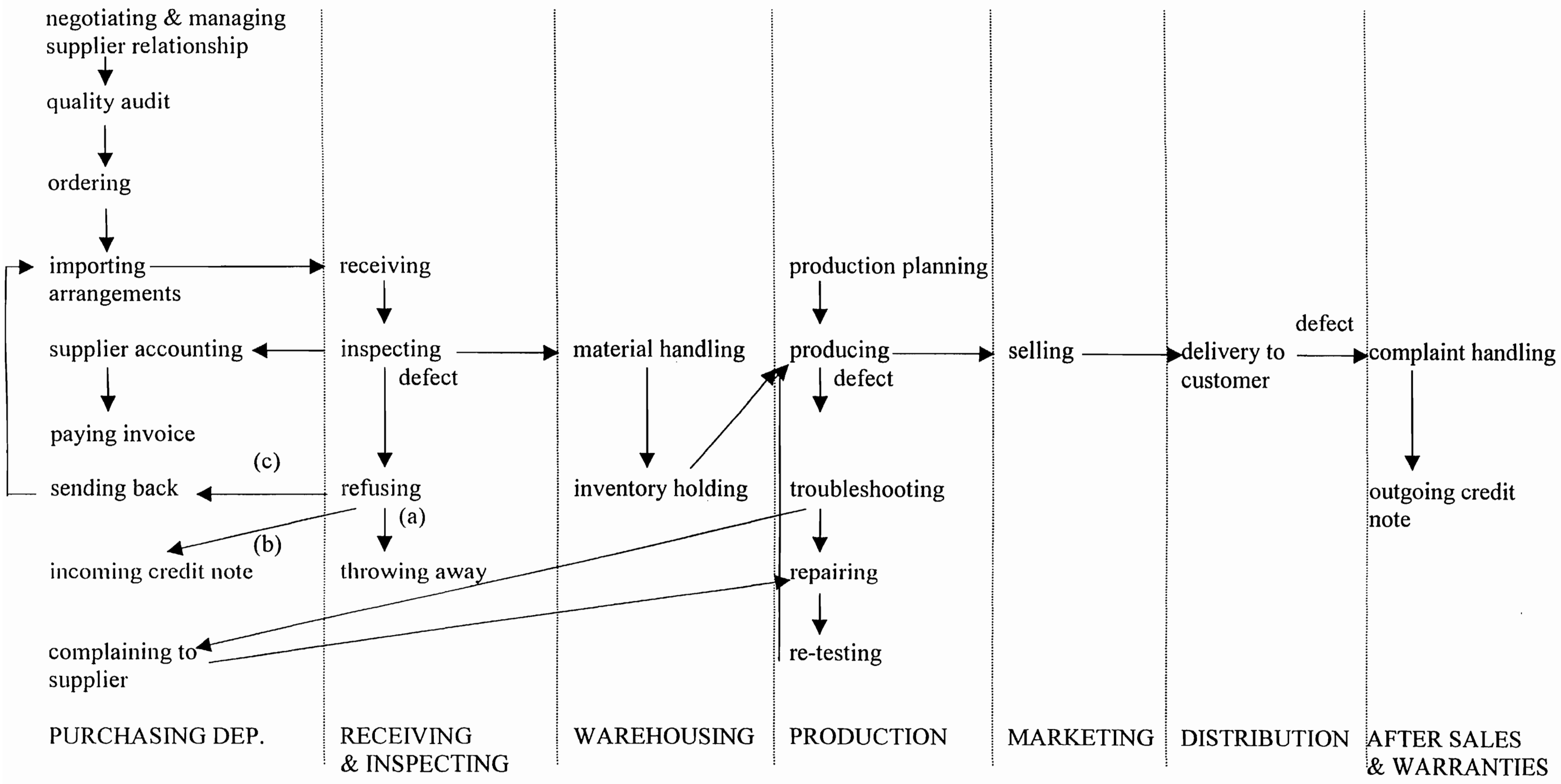

Table 1: The ABC details for the supplier selection cases.

Resources	Resource drivers	Activities	Primary activity driver	Secondary activity driver	PURCHASING POLICY
gross wages of purchasing manager	% of time spent	negotiating & managing relationship	# suppliers	# hours negotiating & managing	
gross wages of auditor + quality engineer	% of time spent	quality audit	# suppliers	0/1 quality audit	
gross wages of secretaries, buyers and purchasing engineers	% of time spent on EDI orders	ordering	# orders	# EDI orders	
	% of time spent on ACO orders				
	% of time spent on manual orders			# ACO orders	
yearly EDI service fee + gateway fee	direct			# manual orders	
computer used for EDI	direct				
fax machine	direct				
gross wages of secretaries, buyers and purchasing engineers	% of time spent on invoices	invoicing	# orders		
import duty	direct	importing	# batches	# orders or batches from outside E.U.	
gross wages of secretaries	% of time spent on import declaration				
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	# batches	# immediate releases	
	% 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 inspection			# skip lot inspections	

	% of time spent on engineer verifications			# engineer verifications	
	% of time spent on sample inspections every lot			# sample inspections of every lot	
inspecting equipment	direct				
gross wages of inspecting personnel	% of time spent on refusing incoming orders or batches	refusing a delivery	# batches	# problems discovered on inspecting / # 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	throwing away	# batches	# problems discovered on inspecting and thrown away # batches	
gross wages of secretaries	% of time spent on sending back & administration	sending back	# batches	# problems discovered on inspecting and send back to EU supplier / # batches	
gross wages of accountant	% of time spent on accounting for sending back				
postage	direct			# problems discovered on inspecting and send back to outside EU supplier / # batches	
export duty to outside E.U. suppliers	direct				
gross wages of accountant	% of time spent on incoming credit notes	incoming credit note	# batches	# problems discovered on inspecting and send back / # batches	
gross wages of warehousing personnel	% 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	# problems discovered in production / # batches	

gross wages of production personnel	% of time spent on repairing after discovery of defect component	repairing	# batches	# problems discovered in production / # batches	
repairing equipment	direct				
gross wages of production personnel	% of time spent on re-testing after discovery of defect component	re-testing	# batches	# problems discovered in production / # batches	
testing equipment	direct				
gross wages of warehousing personnel	% of time spent on maintaining inventory	inventory holding	# units of product		
heating costs	m²				
warehouse maintenance	m²				
fire insurance	m²				
opportunity cost	interest % to be gained on risk free investment				
obsolescence cost	% of unit price				
gross wages of personnel in complaint handling departme	% of time spent on complaint handlin	complaint handling	# units of product	# problems complained about by customers / # units	
gross wages of personnel in complaint handling departme	% of time spent on making up outgoing credit note	outgoing credit note	# units of product	# outgoing credit notes / # units	

: number of

Table 2: 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
product level costs	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 deliver price complaint handling outgoing credit note	inventory holding (normal & early delive price complaint handling outgoing credit note	inventory holding (normal & early deliver price complaint handling outgoing credit note

Table 3: The decision variables.

	Resistors	Transformers	PCBs
Supplier level	z_i	z_i	z_i
Product 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 4: Dimensions of the case studies and the mathematical programming model.

	total number of different product types	number of different product types needed in 1999	number of suppliers	number of variables	number of constraints
Resistors	1729	661	25	117,125	95,231
Transformers	543	274	39	59,268	62,497
PCBs	336	131	24	31,456	28,904

Table 5: 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 GBP	812,000	5,625,000	3,405,000	9,842,000
optimal policy as a % of optimal TCO	optimal TCO	100%	100%	100%	100%
	SLC	1.76%	0.42%	0.33%	0.50%
	PLC	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%
	PLC	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%

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