Lalwani, C.S., Naim, M.M. and Disney, S.M., (2006), “On assessing the sensitivity to uncertainty in distribution network design”, International Journal of Physical Distribution and Logistics Management, Vol. 36, No. 1, pp5–21. DOI: 10.1108/09600030610642904.

On Assessing the Sensitivity to Uncertainty in Distribution Network Design

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Abstract
The design of distribution networks is prone to risks due to the uncertainties associated with factors that change over time. In this paper we present a new method to identify those factors that the structure of a distribution network is most sensitive to. The new method combines simulation and the Taguchi technique to allow a wide range of factor uncertainties to be evaluated without excessive computation time and effort. The simulation model developed is based on real world data of a European after-sales business in the automotive industry. We show that the optimum design is most at risk due to the uncertainties associated with stock holding costs and delivery frequencies rather than customer volume changes and transport tariffs. This was found to be counterintuitive by the business managers and fore-warned them of the likely future risks.

Key words
Taguchi technique, Analysis of Variance, Risk, Supply chain infrastructure

Introduction
Risk and uncertainty are often seen as synonymous (Helliar, Lonie, Power, and Sinclair, 2001). Risk may be seen as a consequence of uncertainty. Knight (1921), in his seminal work on risk and uncertainty, ascertains that change in itself is not a risk but that the future uncertainties associated with change may well be risky. Risk is defined as the possibility of bringing about misfortune or loss while uncertainty is associated with those things that are not able to be accurately known or predicted (Collins Dictionary, 1996)

The primary supply chain management task is often described as uncertainty reduction (Mason-Jones and Towill, 1998, Davies, 1993). When developing new infrastructure for the supply chain we need to design it for possible future state requirements. We are therefore challenged with predicting what the future holds. In this paper we develop a new method for distribution network design. The new method combines classic distribution planning tools (in this specific case the use of a leading commercial software package) with the Taguchi technique.

We specifically aim to develop a new method that estimates the likely impact of uncertainty on our network design. The method highlights, without excessive computation, those factors that a network design is most sensitive to. We are therefore compelled to concentrate our management efforts on ensuring that we accurately determine the value of those factors. Even given the fact that we may still not be able to accurately estimate those factors we are in a position of not being “surprised” should those factors be proven to be inaccurate in the future. We are therefore in a position to mitigate the risks associated with factor estimation.

The literature review suggests that researchers have made attempts to look into some of the specific issues in distribution design such as logistics planning systems in distribution (Mourits and Evers, 1995), integrating planning in distribution systems involving decisions on facility location and vehicle routing (Eiselt and Laporte, 1989) and the implications of re-location of plants and distribution centres on freight transport (Lemoine and Skjoett-larsen, 2004). Companies who have a large number of suppliers and a large customer base and whose value proposition is stockholding and delivery of goods are often in doubt over the optimality of their distribution network. It is possible that these companies may make an attempt to redesign the network when it is not needed. Alternatively the companies could fail to recognise the need for redesigning the network and therefore run an inefficient operation or fail to offer the service levels customers demand. It should be recognised that when designing the infrastructure for a supply chain those factors that increase the risk of undue cost must be identified and corrected. Companies seek to increase revenue growth, expand their market share, reduce cost through efficient design and increase responsiveness to customer needs.

In this paper we use our new method to identify those factors that the structure of a distribution network is most sensitive to. The next section highlights the new method we developed and tested, combining simulation and the Taguchi technique with brainstorming sessions we held with senior managers involved in a specific network design exercise. The simulation model is based on real case study data of a European after-sales business in the automotive industry. We detail the application of our method and then undertake a sensitivity analysis of the model we have developed. We conclude with the management implications of our findings and the strengths of our method.

Method

The logistics distribution network design method is developed using a case study of an automotive company's aftermarket operations pan-European distribution network that has over 550 suppliers and 10,000 customers, utilising over 20 different transport companies and a number of distribution centres. One of the authors of this paper was embedded within the change programme team of the case study company providing modelling and simulation expertise alongside internal personnel and management consultants. The role of the embedded author was to provide the change management team with decision support in their task of designing the new network. The following models were used on this dataset to generate the required information for the infrastructure design:

- Inventory Model
- Transportation Model
- Optimisation and trade-off Model

The dataset consisted of information on customers including their name, location, annual demand by product group, warehouses delivered to, number of deliveries per year, and existing transport carriers. Similar data on suppliers was also available. Freight transport tariffs or trucking and routing charges and warehouse locations were also available in the dataset.

The major data flows in the infrastructure design modelling are shown in Figure 1 and Table I. The figure shows that the modelling utilises information about the customers, suppliers, distribution centres (DCs), transport, information systems and details about the supply chain, such as locations and distances. The method models transport and inventory costs and optimises the number and location of DCs in the distribution network via a trade-off analysis leading to an optimum solution.

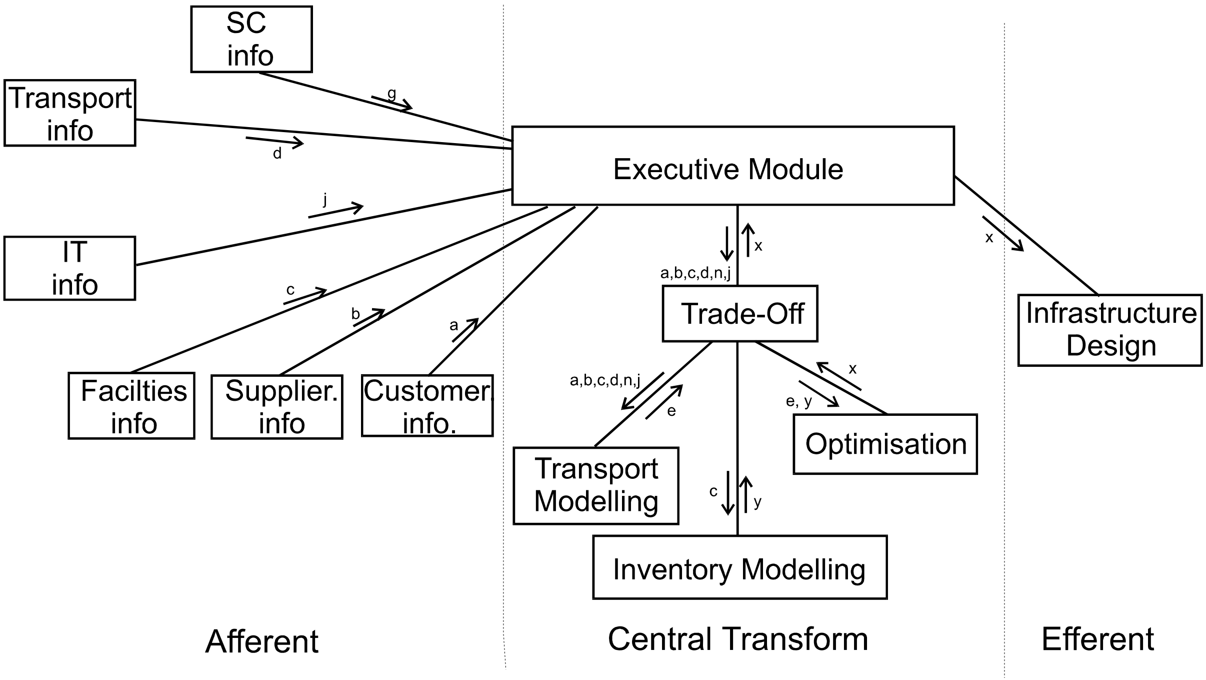

Figure 1. The Data Flows in the Infrastructure Design Modelling

Information Label	Information	Data Flow
a	Customer name, location, annual demand, delivery frequency, transport mode, order cycle time requirements, demand time series	Afferent, Central Transform
b	Supplier name, location, spend, delivery frequency, transport mode	Afferent, Central Transform
c	Facilities (e.g. DCs, warehouses, depots) name, location, inventory throughput, leadtimes	Afferent, Central Transform
d	Transport information, tariffs, costs	Afferent, Central Transform
e	Scenario transportation costs	Central Transform
j	Supply Chain IT system, logistics control structure, ERP, DRP, VMI, cross docking.	Afferent, Central Transform
g	End customer requirements, evolution of the supply chain	Afferent, Central Transform
y	Inventory information	Central Transform
x	Facilities, locations, iso-graphs, decoupling points	Efferent

Table I. Key to the Data Flow Diagram

Once a design has been derived we then proceed to undertake a sensitivity analysis due to those factors that may have a degree of uncertainty associated with them. These factors are identified through brainstorming sessions with managers involved in the network design. Figure 2 shows a flow chart of the Taguchi technique (succinctly described in

Roy, 1990) that we employ to undertake the sensitivity analysis. The simulation experiment identified in Figure 2 requires the repetition of the modelling shown in Figure 1 with varying degrees of factor uncertainty.

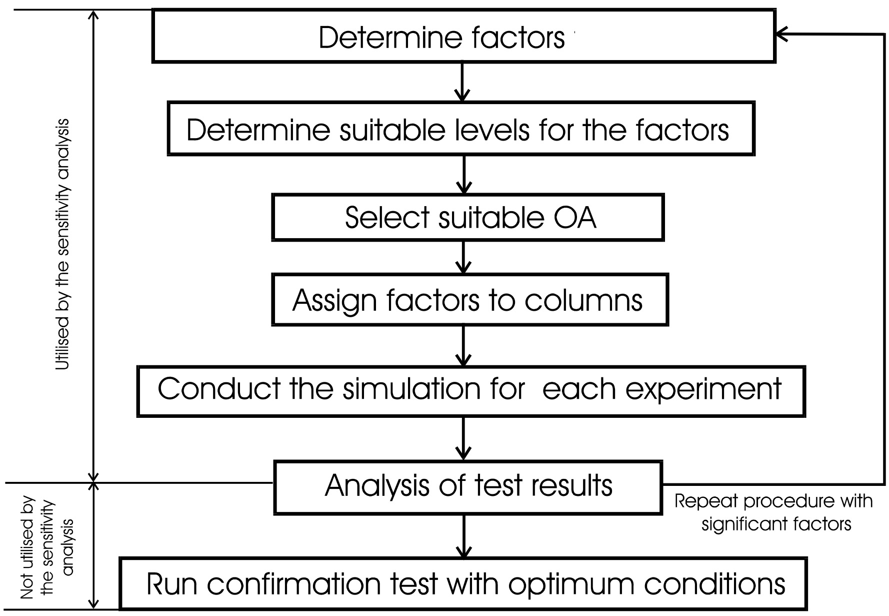

Figure 2. Outline of the Taguchi Method utilised

We now proceed to describe the three models employed in our method before expanding on our method in more detail via its application in the case study.

Inventory modelling

The Square Root Law, due to Maister (1975), was used to approximate the amount of stock needed in the distribution system. It states that if inventories of a single product are originally maintained at '*n*' field locations (referred to as a decentralised system), but are consolidated into one central inventory (referred to as a centralised system), then the ratio $\left[\frac{\text{decentralised system inventory}}{\text{centralised system inventory}}\right]$ will be equal to $\sqrt{n}$. This can be also be expressed as follows,

$$X_2 = X_1\sqrt{\frac{n_2}{n_1}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. 1.}$$

where, n_1 = number of existing DCs,
n_2 = number of future DCs,
X_1 = total inventory in existing number of DCs,
X_2 = total inventory in future number of DCs.

The above relationship applies to safety stocks assuming the safety stocks are set as a constant multiple of the standard deviation of demand and that the demands at each location *i* are not correlated. This was recognised by other authors before Maister's contribution in 1976, but Maister demonstrated that it could also be applied to working stocks if inventory was controlled via some form of the Economic Order Quantity (EOQ) based on the Wilson Lot Size Formula (Maister, 1975). This demonstration assumed that all locations before and after the centralisation incur the same fixed cost per order and the same per unit holding cost. It also assumes that the total system demand remains constant.

However the Law can not be applied when the working stock is not controlled by the Wilson Lot Size Formula. In that case the working stock is proportional to the demand in a given period. The relationship between the number of DCs and the total stock based on Maister (1975) is given in Figure 3.

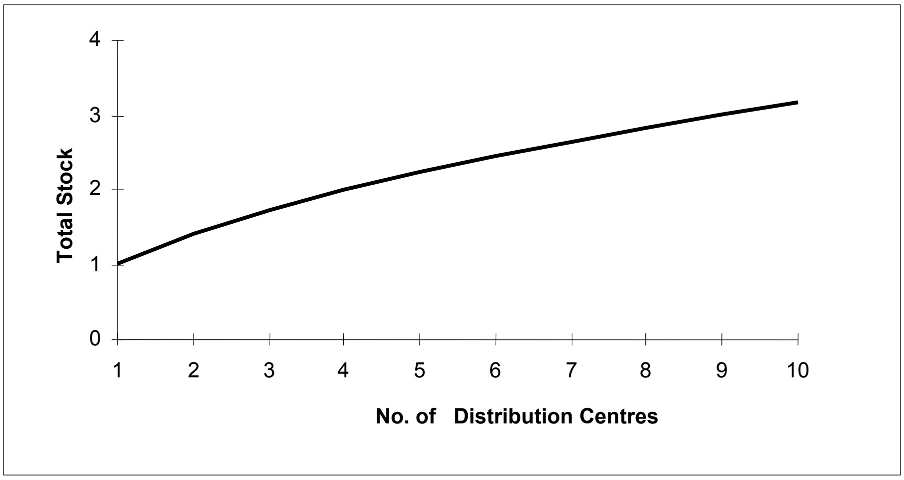

Figure 3. Behaviour of Inventory in a Distribution Network for a Constant Availability (based on Maister, 1975)

The Square Root Law shows how safety stocks (and working stocks under certain conditions) can be reduced in a centralised distribution networks yet provide the same level of availability. This is due to "the advantages of the pooling of uncertainty", where statistical economies of scale are obtained via the central limit theorem (Evers, 1997). As the square root law was used to capture inventory costs in our methodology, we have inherited all the assumptions of this law. However as we needed to balance the inventory costs against the transport costs in our methodology, the case company managers accepted this as a workable solution.

<u>Transportation Modelling</u>
In order to determine the transportation costs in using *'n'* distribution centres, it is important to consider the locations and the material flow channels from suppliers through to customers for each location identified. Hitchings (1969) argues that the transport cost structure should be a part of the modelling method as this could alter the design of the network. Or & Pierskalla (1979) and Jacobsen and Madsen (1980) consider the network location design in association with routing costs.

A simple method used for transport modelling is based upon minimising the Euclidean distance from supplier to a warehouse/distribution centre and from the warehouse/distribution centre to its customers and can be implemented easily on a spreadsheet to provide a solution for distribution centre location. However, for greater accuracy in the determination of the DC locations, we have used a dedicated commercial distribution planning software package by Radical known as CAST-dpm®. The software uses volume and cost based centre of gravity models to assist in calculating the effect of various DC locations, cost and the service levels achieved. It also aims to identify optimum or near-optimum solutions. Most of these models, including CAST-dpm®, use the following data:

- road networks,
- information on speed limits,
- transportation speeds over distances curves,
- methods for integrating the logistical control structure onto the model,
- reflect the value of land and employment rates,
- modelling of the facilities themselves,
- allow inputs for multi-modal transport and incorporate procedures for routing,
- modal selection,
- and cost minimisation, via a DC location optimisation procedure.

Thus it is possible to incorporate a wide range of factors affecting the distribution network design.

After determining the location of DCs it is necessary to determine the associated transport costs. There are two different approaches for doing this. If a company uses its own transport for distribution then a distance travelled on the servicing of the customers and suppliers is based on the travelling salesman problem that needs to be solved using a fixed cost per hour and variable cost related to the distance. Other factors such as vehicle capacity, driver working conditions and capital employed in transport, must also be taken into account. However if a third party logistics service provider is employed to execute the transport, the cost structure is somewhat simpler as the charges incurred are based on the drop size and distances from warehouses, and the total transport cost can be determined via a look-up table. In the application of our method the latter approach was appropriate. In the transport model we have assumed that there is no congestion and the transport infrastructure built in the software is correct. Company supplier locations are selected from a test on over 22,000 coordinates within Europe. This level of accuracy was assumed to be sufficient by the management team of the case company.

<u>Optimisation and Trade-Off Model</u>

It is now possible to determine the best infrastructure design by analysing the trade-off between inventory and transport costs in the system. Using centre of gravity optimisation a trade-off between the number of distribution centres and the normalised performance of the distribution network was worked out using the case study company data. Figure 4 shows an attempt to do this (based on Hammant, Disney, Childerhouse, and Naim, 1999) but the trade-off shown does not take into account the DC's overhead costs or local factors such as employment costs or any economies of scale in warehouse operation in a consolidated network. However, in the new method proposed in this paper, using the commercial software package as previously described it is possible to determine the customer lead-time satisfaction for different network designs. The results can be used for a strategic decision on the relative benefits between customer satisfaction and total costs as discussed in Hammant et al., (1999). For example, in Figure 4 the optimum costs are for two DCs, but it was found from the analysis of the case study company data that for an increase in operating costs of 11% the customer satisfaction increased by 3% with the use of three DCs. Hammant et al., (1999) did not study or assess the sensitivity to uncertainty in distribution network design.

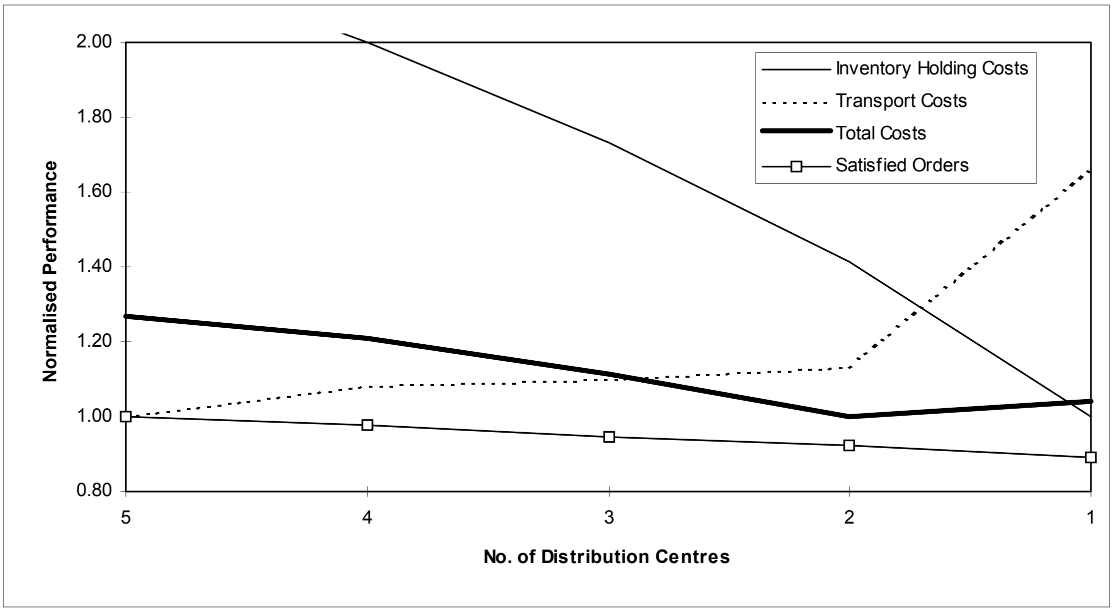

Figure 4. The trade-off between Inventory and Transport Costs (based on Hammant et. al., 1999)

The main assumptions in the trade-off are that the cost components that had the major influence are inventory and transportation related. Aspects such as the technical competence of the labour force and other local factors were assumed to be either constant or negligible.

Modelling the pan-European distribution network

Our application of the three models previously presented is based on the case study company described in the earlier sections of this paper and has been also reported in Hammant et al., (1999).

An important consideration in the design of logistics distribution network is the suitability to the future marketing and operating environment. A study was conducted to determine how the supply chain is expected to evolve over time and this was incorporated into the modelling data set. This data was obtained through brainstorming workshops run for business managers. An example of the outputs from such workshops for a particular UK industrial sector is shown in Figure 5 which indicates how the material flows from and to supply chain members' changes with time from 1990 to 2005. This data was used for origin and destination analysis and the location and level of stocks.

The brainstorming workshops were attended by key Account Mangers from all European markets for all major customer groups. A quasi-delphi study was used to gain agreement on future market trends, both in the marketplace and in the transport service industry. The output from this meeting is summarised in Figure 5.

The method adopted includes the use of a commercial software package as previously described. As well as modelling locations, product flows, routines, transport cost structures and logistic control structures, the software also allows the examination of customer satisfaction within a given distribution lead-time, which the case study company was particularly interested in evaluating.

Material flows to \ Material flows from	Systems Manufacturer	OE/Aftermarket Operator	Strategically Aligned Distributo	National Wholesalers	Inter Factor	Central Stores	Independant Wholesalers	Fitters	Retailers	End User	Specialist
Systems Manufacturer											
OE/Aftermarket Operator	1,2,3										
Strategically Aligned Distributor		3			3	3					
National Wholesalers		1,2			2,3	2					
Inter Factor		1,2,3									
Central Stores		2,3									
Independant Wholesalers				1,2,3	3						
Fitters		3	3	1	1	3	1,2,3				2,3
Retailers		1					1,2,3				
End User			3					1,2,3	1,2,3		2,3
Specialist		2,3			3						

Figure 5. Matrix representation of the 1990 (1), 1997 (2) and 2005 (3) automotive aftermarket supply chain structures of material flow channels, (1990 values adapted from Harland et al (1993))

After analysis of the stock control system used by the case study company, it was considered that the use of the square root rule for inventory modelling was justified in determining the likely stock levels in the redesigned system. The case study company calculated the stock holding cost at 20% of the stock value held. This was to conform to the use of Economic Value Added (EVA) (Young, 1997), the formulation of which is outlined in Figure 6, recently imposed by the corporate function on the case study company for internal financial reporting.

The driving force behind the use of the apparently arbitrary figure of 20% was that this is the return on equity investors expect from the use of the capital loaned to the company through the purchase of shares. Thus any capital used by the business has to generate 20% per annum growth before returning a real profit for the company and its shareholders. Assuming that there are no currency exchange rate effects and that there is no increase in the value of stock per unit as a result of inter-trading among the various business units, the cost of holding stock can be taken as constant. In reality, there is variation in stock costs as a result of currency exchange rates. However, after discussion with the case study company it was assumed that the effect of these variations were negligible.

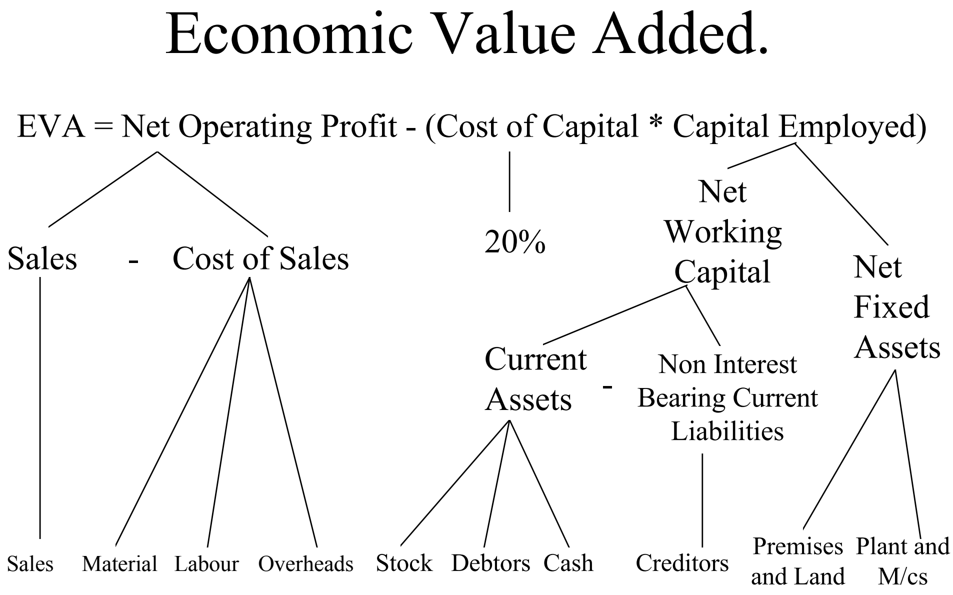

Figure 6. Economic Value Added

The purpose of the network redesign was to move fixed costs to variable costs after the introduction of EVA. The best way of doing this is to outsource non-core activities such as warehousing and logistics to reduce the capital employed. The overhead costs would then be incorporated into the variable costs charged to the company for use of the services provided.

There are some important features in the structure of the relationship between the fixed and variable costs, as shown in Figure 7. As the fixed costs are transformed into variable costs, the operational gearing (the ratio of fixed costs and variable costs) is lowered, thus increasing the risk of a lower profit margin as a percentage of sales. However, a low break-even point has both positive and negative attributes (Gattorna and Walters, 1996). The reduced break-even point reduces the volume related risk in the business, the reduced margin discourages competitors entering the market and decreases the prospect of price competition. This implies that the potential gains are smaller.

A significant advantage of outsourcing is apparent from the use of the graphs shown in Figure 7. As market profiles change over time, the infrastructure needed to serve these markets also changes. Ownership of the infrastructure will result in significant averaging over time as it will not be responsive to changing market profiles without resorting to high exit (for example, redundancies) and start-up costs (associated with a learning curve) every time the infrastructure needs to be realigned (Beccia and Davis, 1997). However, if a third party logistics service provider was to provide the infrastructure, risks of increased costs are minimised as the resources can be deployed for use by other customers. Hence higher investment in warehouses and operating systems can be justified as the warehouse is not subject to a short lifecycle. Thus, reduced variable costs are possible when compared to in-house logistics creating the margin for the third party logistics provider. Other advantages include sharing the risks with other customers using the warehouse.

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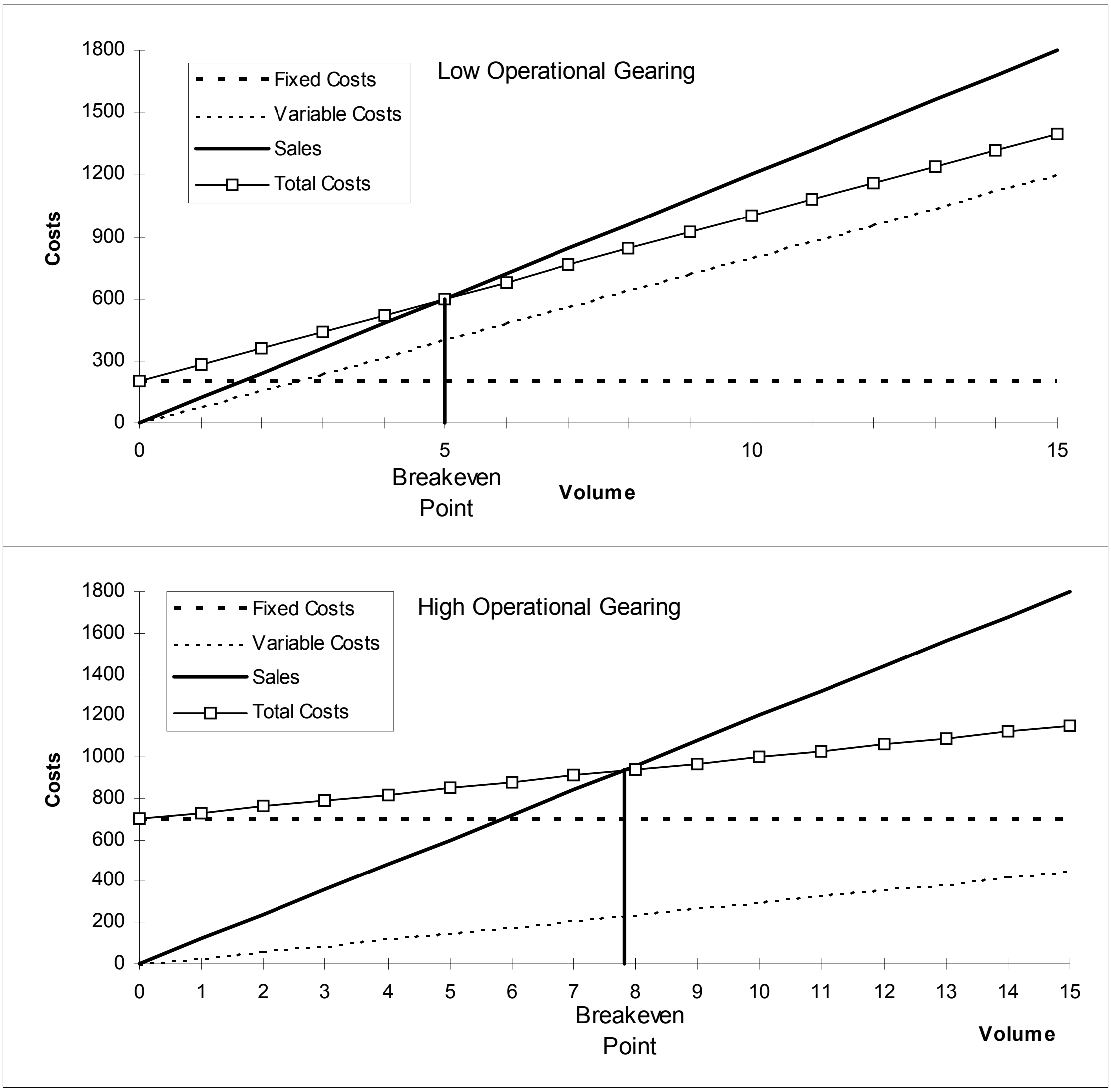

Figure 7. Relationship between Fixed and Variable Costs, (Adapted from Gattorna and Walters, 1996)

Overhead costs can be ignored as they are absorbed into the transportation costs charged by the third party logistics provider. The analysis undertaken shows that the optimum number of DCs was two as already given in Figure 4. Also plotted in Figure 4 is the percentage customer satisfaction, defined as the percentage of demand reached within the desired order cycle time, which is a standard time allowed for sales order processing, picking and packing and delivery. The level of 92% customer satisfaction was considered adequate risk by the case study company managers for a two DC network solution.

Sensitivity analysis

Using the output from our brainstorming sessions that highlighted factors perceived to be important in the future of the distribution network, an initial set of simulation experiments was conducted in order to verify the perceptions of the key Account Managers. A number of suggestions from them were eliminated at this early stage, as either they were implausible scenarios or clearly had insignificant impact on the network design. We then undertook a sensitivity analysis on those factors most likely to have a strong influence on the final outcome of our network design such as the optimum number of distribution facilities in a network and on the total logistics costs (inventory and transportation costs) involved. Sensitivity analysis therefore acts as surrogate for uncertainty as we test the implications of varying the factors identified by a certain percentage of error. The factors were identified via the brainstorming workshops previously described.

The sensitivity analysis was carried out using the company data to have insight on how the distribution network design changed with different company policies and market conditions. This sensitivity analysis or robustness test was performed using the Taguchi technique. It can be seen from Figure 2 that the last part of the Taguchi technique was not used in the method. The technique is only used to the point where the ANalysis Of VAriances (ANOVA) is conducted and re-tested with the main contributing factors to determine their percentage contribution to the design. The Taguchi technique is not used to its full extent, where typically in a hardware system the design is optimised, as here we use it to identify a set of simulation experiments to develop distribution models of the network.

Taguchi method consists of the following three phases:

- Designing the experiment
- Running and analysis
- Verifying and validating the experiment

We have used the Taguchi method for designing the experiment. Once the variables to be studied are selected, the method depends on assigning the factors to an orthogonal array (OA), which distributes the factors and their levels in a balanced manner. These arrays formulate a procedure of conducting the minimum possible number of experiments that would yield the full set of variables to which the performance is sensitive (Roy, 2001). During the brainstorming session with the managers of the case study company we identified eight uncertainty factors and their levels that play a part in future scenario risks. The *first* factor was the inventory holding costs that was calculated as a percentage of the inventory value. The *second* factor was the transport tariffs.

A commercially important sensitivity analysis that can be conducted is the risk to the network of changing market shares in different European regions. For example, what if the company's market share in Spain was to increase / decrease and as a result the demand for the company's products was to increase / decrease by a factor of 25%? Thus factors *three to seven* represent these changes to the UK, France, Germany, Spain and Italy market regions. Factor *eight* included in the sensitivity analysis was the delivery frequency to each individual customer.

The sensitivity analysis considers the effect of these eight selected factors on the design of the network. To determine the main effects of each of these factors on logistics distribution design network, an analysis was carried out using Taguchi's Orthogonal Arrays (OA). To determine how each of the five main regional market shares affects the solution (Spain, Italy, France, Germany and the UK), each individual customer demand was altered by a factor of 0.75, 1 or 1.25 within each region. The corresponding supply base was also scaled across the board to make supply equal demand as appropriate. Inventory carrying costs were subjected to a capital holding cost of 6%, 20% and 40% to reflect shareholder expectation via the EVA framework that our case study company had adopted (Young 1997). Transportation costs were scaled by a factor of 1, 1.25 and 1.5 as they were expected only to rise, rather than fluctuate around a nominal value. Finally the delivery frequency to the customer was multiplied by a factor of 1 and 2 on a customer by customer basis. All the preceding values are used as the three levels in the experimental design and orthogonal arrays. All these factors and levels were highlighted by the key Account Managers from all European markets for all major customer groups of the case company participating in the brainstorming sessions as previously described.

The eight factors have two main influences; firstly on the optimum number of facilities (distribution centres / depots) in a network, and secondly, the total logistics costs (inventory and transportation costs) involved. Hence, for each of the simulations that were required, we optimised the network, by finding the optimum number and location of the DCs in the network and simulated the network performance to determine the inventory and transportation costs.

Data analysis and results

Taguchi's technique as outlined in Figure 2 was used to estimate the contribution of each factor with the least number of analytical investigations, significantly reducing computer time in the simulation environment. The use of the L18 OA allows the full factorial design of 4374 experiments (which would have been time consuming even with present day computing power) to be examined with just 18 experiments. This is a significant saving of computer analysis time. The design of experiments using L18 OA was carried out in consultation with the case company managers.

An L18 OA was chosen for the first analysis. It consists of one two-level factor and seven three-level factors. The two-level factor (column 1) was assigned to the delivery frequency to reflect the need to be robust to increased customer demands. The remaining seven factors were assigned to the remaining three level columns. The experimental results of this analysis are shown in Table II.

Based on this experimental design the ANOVA was carried out to determine the percentage contribution of each factor to the simulation outputs of the total costs and number of depots in the logistics distribution network. The ANOVA results are shown in Table III.

The results show that 84% of the influence on the optimum number of distribution centres in a network is due to the percentage interest rate chosen by a company for inventory carrying costs. However, the inventory carrying costs only makes a 47% contribution to the total logistics costs.

Table III shows that the contribution of the demand profile in different countries was relatively insignificant on both the number of DCs and total logistics costs in the distribution network. Taguchi recommends that the ANOVA procedure is repeated with insignificant factors removed. This was carried out using the L9 orthogonal array in the design of experiments. The significant factors studied in this revised analysis are the delivery frequency, the transport costs and the inventory costs as shown in Table IV. All other factors were held at the nominal state. The orthogonal array and experimental results are also shown in Table IV.

Level 3	na	1.50	40%	1.25	1.25	1.25	1.25	1.25		
Level 2	2.00	1.25	20%	1	1	1	1	1		
Level 1	1.00	1.00	6%	0.75	0.75	0.75	0.75	0.75		
Experiment	Delivery Frequency	Transport Costs	Inventory Costs	UK Demand	French Demand	Germany Demand	Italy Demand	Spain Demand	Depots	Total Costs (£) (normalised)
1	1	1	1	1	1	1	1	1	5	10000
2	1	1	2	2	2	2	2	2	1	13756
3	1	1	3	3	3	3	3	3	1	17840
4	1	2	1	1	2	2	3	3	5	12501
5	1	2	2	2	3	3	1	1	1	16453
6	1	2	3	3	1	1	2	2	1	20168
7	1	3	1	2	1	3	2	3	5	14530
8	1	3	2	3	2	1	3	1	4	12501
9	1	3	3	1	3	2	1	2	1	22563
10	2	1	1	3	3	2	2	1	5	14071
11	2	1	2	1	1	3	3	2	2	19513
12	2	1	3	2	2	1	1	3	1	24020
13	2	2	1	2	3	1	3	2	5	15922
14	2	2	2	3	1	2	1	3	2	22426
15	2	2	3	1	2	3	2	1	2	28099
16	2	3	1	3	2	3	1	2	5	19647
17	2	3	2	1	3	1	2	3	3	25474
18	2	3	3	2	1	2	3	1	2	31817

Table II. The L18 orthogonal array and experimental results

Factor	% contribution to total logistics costs	% contribution to the number of DC's in the network
Delivery Frequency	34.36	0.95
Transport Costs	10.59	4.44
Inventory Costs	47.39	84.44
UK Demand	2.16	1.9
French Demand	0.96	0.63
Germany Demand	1.37	1.9
Italy Demand	0.58	2.53
Spain Demand	0.41	2.52
Error	2.15	0.63

Table III. ANOVA results for the L18 experimental design

Level 3	n/a	1.50	0.40		
Level 2	2.00	1.25	0.20		
Level 1	1.00	1.00	0.06		
Exper-iment	Delivery Frequency	Transport Costs	Inventory Costs	Depots	Total Costs (normalised)
1	1	1	1	5	10000
2	1	2	2	3	17247
3	1	3	3	2	25380
4	2	1	2	3	21688
5	2	2	3	2	31953
6	2	3	1	5	22228
7	3	1	3	1	16209
8	3	2	1	5	8186
9	3	3	2	2	14670

Table IV. The L9 orthogonal array and experimental results

The ANOVA for the total logistics costs and for the optimal distribution centres in the network are shown in Table V.

Factor	% contribution to total logistics costs	% contribution to the number of DC on the network
Delivery Frequency	50.98	3.52
Transport Costs	7.81	0
Inventory Costs	40.92	91.76
Error	0.29	4.71

Table V. ANOVA results for the L9 OA

The results from the L9 array tests support the L18 analysis, with the delivery frequency accounting for nearly 51% of the total costs, but the inventory costs contribute 92% towards the number of distribution centres in the network. From this analysis it can be concluded that the main influence on the design is the cost of inventory holding capital.

Table V also shows that the most influential factor on the total logistics costs is the delivery frequency, accounting for half of the contribution. This is intuitively due to the economies of scale in the transport cost structure. The inventory costs are accounting for 40% of the total logistics costs. Interestingly, the distribution network design is quite robust to transport cost changes, as they account for only a 7.81% contribution.

Research Implications and Conclusions

In assessment of the sensitivity to uncertainties and associated risks in the design of the distribution networks, the research presented in this paper has shown that the transport costs and the demand profile of the different market regions were relatively unimportant in terms of affecting the design. When this was presented to the business managers they found that the result was somewhat surprising. We show that the optimum design is most at risk due to uncertainties associated with stock holding costs and delivery frequencies. The results further suggest that the delivery frequency came out as an important factor for total logistics costs. For the case study company, transport services were provided by third parties. The transport costs incurred were based on tariff grids and the company did not incur any part of the variable and fixed costs. The inventory holding costs had the biggest effect on both number of DC's and logistics costs. In a company with products with high hidden inventory costs such as obsolescence and short product life issues, there may be a need to reduce the number of DC's.

The analysis indicates that when developing the network a careful consideration has to be given to reliably estimating the inventory holding costs and the mechanism for determining the capital holding charge. The model is sensitive to these variables and hence a company is prone to higher risk of designing the wrong network if these variables are incorrectly estimated.

Furthermore, our analysis suggests that higher customer expectations on delivery frequency have an impact on total logistics costs and therefore companies should consider charging customers different rates for different levels of customer service. Although this paper is a specific case study, we believe the results may be useful for general use when the demand is approximately related to where people live (as shown with 10,000 customers in our case study, we assume this is close to the distribution of where people in Europe), and the vehicle fill is dominated by weight rather than volume.

A useful generic method has been presented in this paper for investigating the sensitivity of a scenario without incurring expensive analysis costs such as a very large number of simulation runs. This novel approach combines the use of simulation, brainstorming, Taguchi technique and ANOVA with distribution design modelling. In this case the latter was undertaken using a leading commercial software package. Also, while it could be argued that the factors identified may not be the most important in some people's view, nevertheless the method described is independent of the factors under consideration and can be repeated for any factors judged to be appropriate.

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