PRODUCTION PLANNING & CONTROL, 1995, VOL. 6, NO. 3, 270–277

Product universality and design for supply chain management

HAU L. LEE and MARGUERITA M. SASSER

Keywords supply chain management, product design, universality, standardization, inventory management

Abstract. We describe our experience of developing models in which the principles of design for supply chain management (DFSCM) have been implemented for new product development at Hewlett-Packard Company (HP). This experience arises from the development of a new product that is scheduled to be released in 1995. A key design decision faced by the product development team was whether to use a universal module or regionally dedicated modules to satisfy global market requirements. We describe a wide range of factors—including manufacturing and logistics costs—that could be used to support the design decision; these factors associated with product and process design contribute to total supply chain costs. We review the analytical model used to evaluate the cost and service implications of the two design alternatives. Finally, we discuss qualitative considerations that might influence the eventual decisions as well as the lessons learned from this real world experience.

1. Introduction

At many high-technology companies like Hewlett-Packard Company (HP), product design is increasingly recognized as a major factor in effective supply chain management. In the last decade, these companies have rigorously pursued design for manufacturability (DFM) concepts in product design. Although such advancements are admirable in light of the traditional functional separation of design and manufacturing, the significance of logistics costs and service performance are often underestimated. Growing awareness of these cost factors has led many organizations to move beyond DFM to the more advanced concepts of design for supply chain management (DFSCM). In general, DFSCM aims at designing products and processes so that the supply-chain-related costs and performance can be more effectively

Authors: Hau L. Lee, Department of Industrial Engineering and Engineering Management, Stanford University, Stanford, CA 94305, USA. Marguerita M. Sasser, Strategic Planning and Modeling, Hewlett-Packard Company, 3000 Hanover Street, MS 20DT, Palo Alto, CA 94304, US.

HAU L. LEE is a professor in industrial engineering and engineering management at Stanford University. His research focuses on supply chain inventory management, product design, and re-engineering of supply chains, and he has worked with companies like Hewlett-Packard, Apple, IBM, Digital Equipment Corp. and SUN Microsystem in these areas. He received his B.S. from the University of Hong Kong, MSc from the London School of Economics, and PhD from the Wharton School of the University of Pennsylvania. He is currently Department Editor of *Management Science*, and the Editor of the *IIE Transactions in Scheduling and Logistics*.

MARGUERITA M. SASSER is a process technology manager working in the Strategic Planning and Modeling Group at Hewlett-Packard Company. Her work focuses on analytical modeling of inventory systems to support strategic planning at the division level. She received a B.S. in mechanical engineering at the University of California at Davis, and M.S. in mechanical engineering at the University of California at Berkeley.

managed. This paper describes a modelling effort at Hewlett-Packard Company (HP) that was used in a new product development project to achieve significant benefits by implementing the principles of DFSCM.

It is now generally recognized that the total cost of producing and delivering a product is largely determined by the design of the product itself (Child *et al.* 1991). Manufacturing is only one element of this total cost envelope. In the 1990s, leading organizations realize that logistics costs account for an increasing share of total costs; they are finding ways to contain such costs while maintaining or improving customer service. For more successful companies, skillful management of logistics is becoming a source of competitive advantage (Fuller *et al.* 1993). For this reason, some companies are beginning efforts to design products for effective supply chain management. A supply chain is a network of manufacturing and distribution facilities in which the flow of materials and information affects logistics costs as well as customer service performance. For a general introduction to supply chain management, the reader is referred to Cohen and Lee (1988), Lee and Billington (1992) and Davis (1993).

Introduced by Lee and Billington (1992), DFSCM is a powerful concept. This concept states that the product line structure, bill of materials, and customization processes of a product are designed in such a way that the logistics costs and customer service performance are optimized. In several subsequent papers (Lee 1993, Lee and Billington 1993, and Lee and Tang 1994) principles such as delayed product differentiation, commonality, standardization, process steps switching, and postponement are described. In the examples presented in these works, existing products were redesigned to effectively implement the principles of DFSCM.

It is evident, however, that any attempt at redesign for supply chain management is severely limited by the basic design of the product, which can seldomly be altered significantly once it has entered the marketplace. Ideally, DFSCM would be introduced in the early design phase of a new product development to realize the maximum potential benefits. The project described in this paper offered a golden opportunity in new product development at HP. Aware of the advantages of DFSCM, management asked the product development team to consider the sophisticated concepts early in the development cycle. With a renewed sense of mission, the team undertook an analytical modelling effort that would enable management to compare design alternatives on the basis of total supply chain costs incurred. In the next section of this paper, we briefly describe this key decision faced by HP, which led to the need for an analytical model to support the decision-making process. The model formulation, the analysis we performed, and important factors that were not explicitly captured by our model are then presented. We conclude by summarizing our experience and learnings obtained from this project.

2. The Rainbow Project

Rainbow is the code name for a new product, a computer peripheral device, produced by one of the divisions at HP. Design work involving DFSCM principles was initiated for Rainbow in late 1992, and the product was scheduled to be released in 1995. With this planning approach, supply chain issues could be considered by the product development team more than 3 years before the product's introduction. These efforts represent a significant advance at HP and indicate a strong commitment to DFSCM on the part of upper management.

Traditionally, this family of peripherals offered only a limited number of options to the market. However, as customer expectations have risen and needs have changed, the once simple product structure will no longer meet the requirements of the marketplace. For this reason, Rainbow involves a more complex product structure than previous peripherals of this type, which explains why management began paying more attention to DFSCM. There are several reasons why HP must increase the variety of the product offered to the market. For one, the company continually adds new geographical regions to its customer base, and each region can have unique localization requirements for manuals, software and hardware. Second, because there are many standards in the computer industry, peripherals today must be able to satisfy multiple standards. Finally, there are increasing expectations that peripherals will support several office technologies, including applications based on DOS or Macintosh operating systems. All of these factors support the need for high product variety, a typical phenomenon for high-technology products.

As mentioned above, one contributor to product variety is the need to support a global marketplace. For Rainbow to be sold in Europe as well as North America, it must support power supply requirements for each continent: 110 V for North America and 220 V for Europe. Historically, a dedicated power supply for this product line has been built into the engine supplied by an Asia-Pacific strategic partner, which requires a long planning lead time, as well as a long transit time for ocean transportation. These long intervals of time required HP buyers to specify the quantity of each power supply type several months prior to production. Figure 1 describes a simplified version of the supply chain for Rainbow.

Product differentiation characterized by dedicated power supplies has been the source of major headaches for HP's supply chain managers. In the past, forecast errors in North American and European demand have led to several inventory imbalances: excess inventory in one continent and shortages in another. This unbalanced situation produced widely distributed customer dissatisfaction along with expensive inventory write-offs.

This prompted HP management's desire to explore the

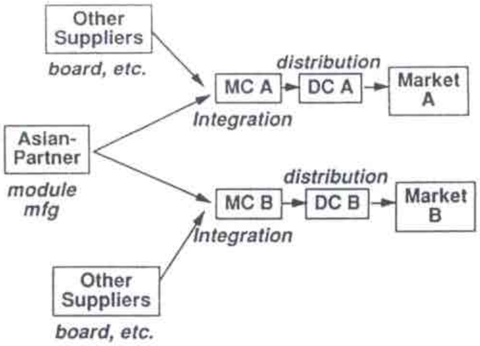

Figure 1. Rainbow supply chains.

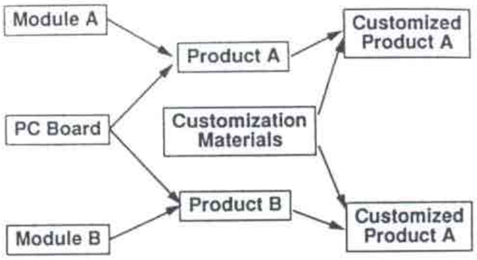

Figure 2. Rainbow product structure.

feasibility of incorporating a universal power supply capable of supporting both 110 V and 220 V standards. There was no doubt that a universal power supply would reduce complexity in the product structure and thus reduce inventory requirements. However, it was not known whether the inventory savings and other supply chain benefits would offset the increase in material and manufacturing costs associated with universal power supplies. A traditional rationale based on design features emphasizing functionality, performance, and narrowly defined material and manufacturing costs would not be sufficient to support standardization of product engines. And yet, HP management was anxious to explore the use of different metrics based on the principles of DFSCM, which include logistics costs and service performance, in determining the cost–benefit trade-offs of incorporating a universal power supply as a design alternative for the product.

3. A model to evaluate standardization/universality

In this section, we describe a model used to evaluate logistics costs and service performance arising from standardization to achieve product universality. This model, coupled with the difference in material and manufacturing cost of standardization, was used by management to determine whether universality was cost effective. To facilitate the discussion, we first present a simplified version of the product design problem. We discuss additional features of the analysis in subsequent sections.

Our model is based on certain specific assumptions. The product being analysed requires a key module. To sell the product in market A, module A is required; to sell the product in market B, module B is required. The demands per period in these markets are stationary as well as independent across time periods, and they may be correlated between markets. The lead time for obtaining the module from the supplier, including transit time, is T time periods for both market A and market B. In each market, there is a manufacturing centre (MC) that receives and stocks the modules, integrating them with other subassemblies to produce the final product. The MC uses a built-to-stock, periodic review, order-up-to S inventory system for monitoring the modules. Order-up-to levels are set to meet a target service level, which is defined as the percentage of demand met from stock, and unfilled demands are backordered. At the beginning of each period, each MC orders an amount from the supplier that would bring its inventory position (on-hand inventory plus inventory on-order) to the target level. Hence, if x is the on-hand inventory, y the inventory on order, b the backorder level, and q the order amount, then: $q = S - x - y + b$.

Using the inventory of the modules, the final products are configured to order. Figures 1 and 2 describe simplified versions of the supply chain and product structure for Rainbow. Such a 'configure-to-order' approach means that inventory is held in the module form, and so the module is the 'de-coupling point' of the total supply chain (Hoekstra and Romme 1992). Jones and Riley (1985) have long recognized the importance of the optimal positioning of inventory along a supply chain as a means to design for manufacture, a concept similar to our model here.

At this point, we need to understand what would happen if module A and module B were standardized. With standardization, the supplier no longer has to manufacture two unique models. Instead, at the beginning of each time period, the total amount of a common module required to bring the inventory position to the target level at each MC is requested from the supplier, who then begins manufacturing this quantity of the common module. The total lead time of the module is still T time periods, of which t time periods constitute the manufacturing lead time, and $T - t$ time periods constitute the transit times from the supplier to the two MCs, again assumed to be equal for the two markets. We can view standardization as a means of delaying the point of product differentiation. Using two dedicated modules rather than one common module is equivalent to having $t = 0$. Note, however, that with a standardized module, the geographical dispersion of the two markets and the non-zero transit times make complete inventory pooling infeasible. Further, if the supplier needs preparation time to get the modules ready for

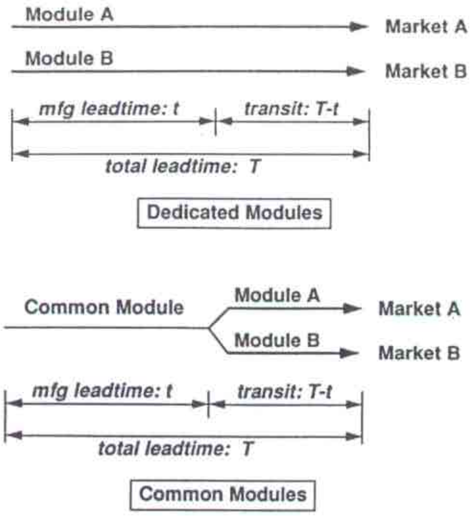

Figure 3. Model for dedicated versus common modules.

shipment, then the point of product differentiation can actually occur before t. This was the case with Rainbow.

Delayed product differentiation, as depicted in Figure 3, was analysed by Lee (1994). Table 1 gives a glossary of the notation used in this paper.

Assume that the coefficients of variation for the demands per period for modules A and B are equal. This is a commonly used assumption in multi-echelon inventory systems (Eppen and Schrage 1981, Schwarz 1989, and Lee 1994). Given this assumption, we can set

$$\mu_i/(\mu_A + \mu_B) = \sigma_i/(\sigma_A + \sigma_B) = R_i$$

where $i = A, B$. At the beginning of the first period (period 0), the stockpile for module i is brought to the target position S_i. At this time, the total inventory position for modules A and B is $S = S_A + S_B$. After t periods have elapsed, this inventory position for both modules is reduced to

$$S - \sum_{i=A,B} \sum_{j=1}^{t} D_{ij}$$

At this point, the differentiation of the common inventory into the distinct modules would ordinarily occur. The optimal way to allocate the common inventory to the two modules is to apply the 'equal fractile' allocation (Eppen and Schrage 1981, Schwarz 1989). This rule attempts to achieve an allocation so that the resulting inventory level would be such that both modules would have the same safety factor. Note that, because of random demands, it is possible that the stocks for the modules are in great imbalance so that equal fractile allocation is not feasible. In that situation the allocation would be done so that the resulting inventory levels would have as nearly equal safety factors as possible. In practice, the likelihood of such an imbalance is very small. For tractability the equal fractile rule is often assumed to be feasible as an approximation in the literature. From our assumption of equal coefficient of variation it is easy to verify that the equal fractile rule, when feasible, would result in module i having an inventory position of

$$R_i\Big(S_i - \sum_{i=A,B} \sum_{j=1}^{t} D_{ij}\Big)$$

where $i = A, B$. After the remaining $T - t$ periods have elapsed, the inventory level for a module would now be

$$R_i\Big(S_i - \sum_{i=A,B} \sum_{j=1}^{t} D_{ij}\Big) - \sum_{j=t+1}^{T} D_{ij},$$

Table 1. Notation.

T = the total lead time of the module
t = the manufacturing lead time. ($T - t$ = transit times from the supplier to the two MCs)
μ_A, μ_B = mean demands per period for module A and module B, respectively
σ_A, σ_B = standard deviations of demands per period for modules A and B, respectively
ρ = covariance of demands per period between modules A and B
β_i = service target (fill rate) for module i, $i = A, B$
D_{ij} = demand for module i in period j, a random variable
R_i = fraction of mean demand of module i to total mean demand, $i = A, B$
S_i = target inventory position for module i, $i = A, B$
S = sum of the target inventory positions for the two modules
K_i = safety factor for module i that enables the service target to be met, $i = A, B$
I_k = safety stock in phase k
h_k = unit holding cost per period in phase k
d_k = mean demand per period in phase k (total over both regions)
μ_{ik} = mean demand per period for region i in phase k, $i = A, B$
p_k = per unit stockout cost per period in phase k
r_k = unit cost of rework + trans-shipment cost in phase k
β_{ik} = service target in phase k for region i, $i = A, B$
x_k = expected trans-shipments per period in phase k
f_k = fraction of the duration of phase k over the total product life cycle
τ = length of the product life cycle.

where $i = A, B$. This inventory would be available to satisfy demand in the next period. Hence, the ending inventory level for a module (where a negative quantity denotes backorders) is equal to

$$R_i(S_i - \sum_{i=A,B} \sum_{j=1}^{t} D_{ij}) - \sum_{j=t+1}^{T+1} D_{ij}$$

where $i = A, B$. The expected value and the variance of the ending inventory level for each module at each period, respectively, are

$$E(I_i) = S_i - (T+1)\mu_i$$

$$Var(I_i) = R_i t(\sigma_A{}^2 + \sigma_B{}^2 + \rho) + (T - t + I)\sigma_i{}^2$$

where $i = A, B$. The target inventory position value for module i to support a specified service target would therefore be

$$S_i = (T + I)\mu_i + K_i\sqrt{Var(I_i)}$$

where $i = A, B$, and K_i is the safety factor that enables the service target be met. The term $K_i\sqrt{Var(I_i)}$ can be viewed as the safety stock of the inventory system.

To determine the safety factor, we use the approximation as reported in Nahmias (1989) which has been used in several HP applications (Lee *et al.* 1993, and Lee and Billington 1993) and has been found to be quite accurate for high service targets (Johnson *et al.* 1994). This safety factor is computed either using approximations or determined exactly using table-lookups when demands are normally distributed (see the Appendix in Lee *et al.* 1993 for details).

Safety stocks for the universal module can be computed by letting t represent the production lead time of the common module, whereas the safety stocks for the dedicated modules can be computed by letting $t = 0$.

4. Trans-shipments, rework, and product life cycles

The preceding section describes the basic framework in which the safety stocks under the two design alternatives can be evaluated. Besides inventory there are other significant factors that need to be considered in a comprehensive evaluation of the design alternatives. The basic model can be expanded for that purpose.

The basic model assumes that demand is stationary. In reality, however, products go through life cycles that can usually be separated into three distinct phases: the introductory, mature and end-of-life phases. The duration of each phase is different for different product types. For durable goods, the length of the mature phase is much longer than the other two phases. This allows one to approximate the cost associated with a total life cycle by using the mature characteristics only, since they dominate over the introductory and end-of-life characteristics. For high-technology products, on the other hand, the life cycle durations are continually decreasing, and it is not uncommon for the mature phase of the products life to be so brief that it is equal in duration to the sum of the other two phases. Each phase has unique demand characteristics and cost structures. Hence, for this type of product, it is essential to model each phase explicitly. In the introductory and mature phases, the cost of holding inventory is the usual inventory cost, i.e. warehousing, storage, and opportunity cost of capital. At the conclusion of the product life cycle, the cost of excess inventory is the cost of obsolescence. The cost of obsolescence depends on the several ways by which the product can be handled then: (i) a fire sale, i.e. sale of goods at a deep discount; (ii) the salvage value of the product that results from dismantling the product and returning its components as spare parts for service support; (iii) the salvage value from recycling some parts of the product, such as plastics and sheet metal; and (iv) the cost of disposal. Furthermore, it is typical for mean demand rates to be lower and standard deviations of forecast errors to be higher in the introductory and end-of-life phases than those of the mature phase. These differences can have a significant impact on safety stock targets.

In module stockout situations, production delay of final products can lead to stockout presented to the final customers. The actual final assembly of the finished products at the MCs takes relatively short times, and therefore, in periods when stockouts of the modules occur, stockouts of finished products also occur. In the introductory phase of the product life cycle, it is crucial for such stockouts to be minimized, since the unavailability of the product at this time can significantly reduce the chance of a successful product introduction into the marketplace. Even with high safety stocks, it is still possible that some imbalance of the two modules may occur. For example, we might have a situation where module A in region A is out of stock, and module B in region B has excess. To ameliorate the stockout situation in region A, it might be worthwhile to trans-ship modules in region B to region A. Such trans-shipments are usually carried out by air, incurring significant transportation cost. In addition, some handling and rework costs might be incurred to reconfigure the module in region B for region A. With dedicated modules, this rework cost could be very high, depending on labour requirements for reconfiguring a product and the material value of parts that might have to be retrofitted or discarded. With universal modules, any required rework cost should be much lower. As made evident from this discussion, trans-shipment is not always a sound strategy. The economics work in the following way. If we have a stockout in one region while excess inventory exists in another, a unit of trans-shipment would incur transportation, handling and rework costs. If trans-shipment was not carried out, the economic consequence would be the cost of stockout in one region combined with the corresponding cost of inventory in another. Therefore, a trans-shipment should only be carried out if the sum of the unit costs of stockout and inventory holding is greater than the sum of the unit costs of trans-shipment (transportation, handling, and rework).

During the product introductory phase, stockout costs can be quite high. In the case of Rainbow, the cost of stockout includes not only the lost profit from unsatisfied customers, but the potential loss of the customer for future products from this or any other HP division. Stockout costs were high enough to justify trans-shipment during this phase of Rainbow. At the end of the product life cycle, while stockout costs might not be as high anymore, the cost of the obsolescence of excess inventory might also make trans-shipments worthwhile. Table 2 describes the comparisons of the various cost and demand characteristics in different phases of the product life cycle, as well as under the two design alternatives.

The cost model used to deal with the three phases of the product life cycle and with the issue of trans-shipment is a heuristic. No doubt, the exact analysis of the transient behaviour and operating characteristics of trans-shipments are very complex. Our heuristic offers an approach whereby these complicating issues can be analysed. We do not claim that this heuristic approach is perfect. Our justification of our approach is as follows: (1) the trans-shipment analysis (shown below) was motivated by the early work of Lee (1987), and seemed to compare well with simulation results in that same study; (2) real case results based on the heuristic had been examined closely by engineers and division management at HP, who together had tremendous experience with these complex issues, and the results passed their 'intuition' test; and (3) the approach has since been applied to other products and situations at other HP divisions, and similarly satisfactory results have been obtained.

We now present this heuristic approach. Denote the three phases of the product life cycle by $k = 1, 2, 3$. We refer to the notation of Table 1 in the following discussion. Note that I_k is computed from the safety stock formula in the previous section, where the appropriate parameters (including β_{ik}) related to the respective phase k are used. The total demand d_k is the same as $\mu_{Ak} + \mu_{Bk}$, for the appropriate phase k.

To compute the amount of trans-shipments in a particular phase, we use the following approximate analysis. First, we proceed as in the previous section to compute the respective S_{ik}s for the two regions under each phase k. Next, if trans-shipments are not allowed, then the expected stockouts in both regions per period are

$$\sum\nolimits_{i=A,B} (1 - \beta_{ik})\mu_{ik}$$

Suppose the inventory for the two regions can be completely pooled. This is equivalent to a standard inventory system with lead time T periods, and a target inventory position of S_k, which is the sum of the respective S_{ik}s from the individual systems. We can then compute the service level achieved, from which the expected stockouts can be obtained. Let β_k be the resulting service level, then the expected stockouts per period is $(1 - \beta_k)d_k$. Hence, if trans-shipment is economically justifiable, then the amount of trans-shipment in a period can be estimated as

$$x_k = \sum\nolimits_{i=A,B} (1 - \beta_{ik})\mu_{ik} - (1 - \beta_k)d_k$$

Of course, if trans-shipment is not economically justifiable, then the amount of trans-shipment is zero, and the stockout situations in both regions would not be affected. With trans-shipment, the expected stockout after trans-shipments is $(1 - \beta_k)d_k$. The excess end-of-period inventory will thus be reduced by the amount of trans-shipment. In the cost analysis, the transit inventory is ignored, as we have assumed that the lead time and transit times are the same for both design alternatives.

When trans-shipment is used in all phases, the total cost is

$$\sum\nolimits_{k=1}^{3} f_k[(I_k - x_k)h_k + x_k r_k + (1 - \beta_k)d_k p_k]$$

If trans-shipment is not used in some phases, then the above cost function would have to be adjusted accordingly. Since that would be quite obvious, we omit the detailed presentation of that case here.

At this point, we can compare the total cost functions under the two design alternatives. It is useful to express the cost

Table 2. Cost and demand characteristics.

	Product life cycle			Design alternatives	
	Introductory	Mature	End-of-life	Dedicated modules	Universal modules
Mean demand	Medium	High	Medium	Same	Same
Variance of demand	High	Low	High	Same	Same
Stockout cost	High	Medium	Low	Same	Same
Rework cost	Same	Same	Same	High	Low
Inv. holding cost	Low	Low	High	Slightly lower	Slightly higher
Safety stock for same β	High	Low	High	High	Low

difference between the two design alternatives in terms of the cost difference per unit. Let Δ be the cost difference per period, and τ be the length of the product life cycle. The total demand over the product life cycle is $\tau\Sigma_{k=1}^{3} f_k d_k$. Hence, the cost difference per period is $\Delta\tau/\{\tau\Sigma_{k=1}^{3} f_k d_k\} = \Delta/\{\Sigma_{k=1}^{3} f_k d_k\}$.

5. Rainbow analysis

Our inventory and cost model was used to evaluate the two design alternatives for the power supply in the Rainbow product. The objective of the analysis was to quantify the cost difference on a per unit basis between universal and dedicated power supplies, and compare this amount with the increase in material and manufacturing costs incurred for the universal power supply. The power supply in the engine of Rainbow will be manufactured by an Asian-Pacific strategic partner, and they provided HP with the material and manufacturing cost estimates.

A DFSCM team, of which the authors were a part of, was assembled to perform the analysis. This team consisted of members from different functional areas including finance, marketing, manufacturing, distribution and engineering. Through teamwork and collaboration the necessary demand and cost parameters for the two design alternatives during different phases of the product life cycle were obtained. However, because this product has not yet reached the market, many variables had to be estimated. To compensate for those estimates having the least reliability, the team performed extensive sensitivity analyses. Our evaluation was based on the lower limit, the most likely, and the upper limit of some key parameters, as shown in Table 3.

One of the parameters for sensitivity analysis is the lead time required by HP's partner to prepare the engines for shipment to each region. In our model, T denotes the total lead time from the strategic partner to the HP division, and $T-t$ denotes the transit time from Asia to each MC. As it turns out, however, an unknown time is needed for the partner to prepare the engines for shipment to the two destinations. Hence, $T-t$ is likely to be longer than the transit time by at least a week, and in the extreme case, by a month.

Another parameter is the duration of each phase of the product life cycle. Rainbow will enter a market where technology changes rapidly and product life cycles are extremely short and unpredictable. We used 6 months as the duration of the introductory and end-of-life phases of the product life cycle. The mature phase can be 12 or 18 months.

Finally, we examined the cost of reworking a dedicated power supply from one voltage to another. Reconfiguring an engine from one power supply voltage to another is feasible with some finite cost of labour and material. However, the team was not sure if the quality and reliability of the reconfigured engines would be acceptable to HP's high standards. Since the product was still in the design stage, an accurate reliability picture was not available. It is possible, however, that reconfiguration of the engines to meet HP's standard might not be feasible, and therefore trans-shipments would not be an option in that case. This is equivalent to saying that the rework cost is prohibitively high.

Several observations were made from the sensitivity analysis. It was found that, even under conservative assumptions, the cost benefits from universal power supply are significantly greater than the increase in material and manufacturing costs incurred. Most of the cost benefits in the introductory and mature phases of the product life cycle result from lower inventory investments. During the end-of-life phase, the savings result from significantly lower rework cost and, consequently, lower trans-shipment costs required to correct for stock imbalances. Demand variabilities for the two regions and the reconfiguration cost were found to be the key drivers of the cost–benefit analysis.

6. Conclusion

Product universality or standardization has become a powerful concept in DFSCM. Nevertheless, because this design principle often results in higher material and direct manufacturing costs, there is a need to use analytical models to quantify the complex impacts and benefits of cost drivers like stockouts, reconfiguration, logistics and inventory. Our experience with Rainbow shows that the exercise is highly worthwhile. Along with helping management determine which design is most effective, the analysis puts HP management in a more knowledgeable position when negotiating prices and design requirements with strategic partners.

Table 3. Sensitivity of key parameters.

Parameter	Lower limit	Most likely	Upper limit
Demand variabilities	Base* (0·5)	Base	Base* (1·5)
Demand rate	Base* (0·5)	Base	Base* (1·5)
Shipment preparation leadtime	1 week	2 weeks	1 month
Ratio of mature to other phases		2:1	3:1
Rework cost		Base	Infinity

Beyond consideration of using a universal power supply, Rainbow has adopted other design concepts that facilitate DFSCM. Although not presented in this paper, we are gratified to report that the new product development team working on Rainbow has performed many analyses related to DFSCM concepts—further evidence that DFSCM has become one of the most important design approaches at this division. The universality model described in this paper is not confined to the consideration of power supplies. There are many other product components in which such a model can be used to gain key insights and understandings. Continued application of this methodology in other product settings is being promoted and pursued actively at HP.

Acknowledgements

The authors gratefully acknowledge the support of the following individuals from Hewlett-Packard Company: Everett Bailey, Corey Billington, Roxanne Ditlevson, Craig Fix, Jeff Larsen, Steve Rockhold and Michael Stillman.

References

CHILD, P., DIEDERICHS, R., SANDERS, F.-H., and WISNIOWSKI, S., 1991, The management of complexity. *Sloan Management Review*, **32**, 73–79.

COHEN, M. A., and LEE, H. L., 1988, Strategic analysis of integrated production–distribution systems: models and methods. *Operations Research*, **36**, 216–228.

DAVIS, T., 1993, Effective supply chain management. *Sloan Management Review*, **34**, 35–46.

EPPEN, G., and SCHRAGE, L., 1981, Centralized ordering policies in a multi-warehouse system with lead times and random demand. In L. B. Schwarz (ed.) *Multi-Level Production/Inventory Systems: Theory and Practice* (North Holland, Amsterdam), pp. 51–67.

FULLER, J. B., O'CONOR, J., and RAWLINSON, R., 1993, Tailored logistics: the next advantage. *Harvard Business Review*, **71**, 87–98.

HOEKSTRA, S., and ROMME, J., 1992, *Integral Logistic Structures Developing Customer-Oriented Goods Flow* (Industrial Press, New York), Section 1.5.

JOHNSON, E. L., LEE, H. L., DAVIS, T., and HALL, R., 1994, Expressions for item fill rates in periodic inventory systems. *Naval Research Logistics*, in press.

JONES, T. C., and RILEY, D. W., 1985, Using inventory for competitive advantage through supply chain management. *International Journal of Physical Distribution and Materials Management*, **15**, 16–26.

LEE, H. L., 1987, A multi-echelon inventory model for repairable items with emergency lateral transshipment. *Management Science*, **33**, 1302–1316.

LEE, H. L., 1993, Design for supply chain management: concepts and examples. In R Sarin (ed.) *Perspectives in Operations Management* (Kluwer, Boston), pp. 43–65.

LEE, H. L., and BILLINGTON, C., 1992, Managing supply chain inventory: pitfalls and opportunities. *Sloan Management Review*, **33**, 65–73.

LEE, H. L., and BILLINGTON, C., 1993, Material management in decentralized supply chains. *Operations Research*, **41**, 835–847.

LEE, H. L., BILLINGTON, C., and CARTER, B., 1993, Hewlett-Packard gains control of inventory and service through design for localization. *Interfaces*, **23**, 1–11.

LEE, H. L., 1994, Effective management of inventory and service through product and process redesign. *Operations Research*, in press.

LEE, H. L., and BILLINGTON, C., 1994, Designing products and processes for postponement. In S. Dasu and C. Eastman (eds) *Management of Design: Engineering and Management Perspectives* (Kluwer, Boston), pp. 105–122.

LEE, H. L., and TANG, C. S., 1994, Modelling the costs and benefits of delayed product differentiation. *Management Science*, submitted for publication.

NAHMIAS, S., 1989, *Production and Operations Analysis* (Irwin, Homewood, IL).

SCHWARZ, L. B., 1989, Model for assessing the value of warehouse risk-pooling: risk-pooling over outside-supplier leadtimes. *Management Science*, **35**, 828–842.

Obituary

John L. Burbidge

With sadness we have received news of the death of John L. Burbidge on 10 January 1995, just a few days before his 80th birthday. Those of us who came to know him will miss an enthusiastic and warm person with an unusual ability to inspire younger researchers in the field of production planning and control. He really was the grand old man in PPC with an enormous production of publications spread throughout the world. He was enthusiastic about promoting the industrial and applied aspect of PPC. Having worked both in industry and academia, he spoke with insight into this field.

He was, over the years, a significant contributor to this journal. It was a natural choice to ask him to write the very first invited paper. Since the beginning he contributed both research and industrial application papers as well as a number of notes and discussion letters.

John Burbidge's memory will stay with us forever and will inspire all of us to further achievements in bridging the gap between academia and industry in production planning and control.