

# The Evolution of Supply-Chain-Management Models and Practice at Hewlett-Packard

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Late in the 1980s, Hewlett-Packard (HP) faced inventories mounting into the billions of dollars and alarming customer dissatisfaction with its order fulfillment process. HP produces computation and measurement products whose supply chains include manufacturing integrated circuits, board assembly, final assembly, and delivery to customers. To reduce inventory and improve order fulfillment, HP called on an internal team of industrial engineers and management scientists augmented by academic collaboration. The team used an iterative process, enriched by the interaction of model development and application. HP reaped benefits well beyond its manufacturing operations, extending to diverse functions throughout the organization. Similarly, the academic partners have infused their research with real-life experience. The supply-chain methodology is now mature, and HP is transferring the technology into the product divisions.

The Hewlett-Packard Company (HP) was founded in 1939 by William Hewlett and David Packard. Today, the company's mission is to create information products that accelerate the advancement

of knowledge and fundamentally improve the effectiveness of people and organizations. In 1993, the company employed 96,200 people, 37,300 of them outside the US.

In the past six years, HP has faced spiraling inventory and plummeting customer satisfaction. Solving the latter crucial problem was flagged in 1990 by then CEO John Young as a key objective for the entire company, and one way of accomplishing the objective was through better supply-chain management.

A supply chain is a network of facilities that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through a distribution system. It spans procurement, manufacturing, and distribution. The importance of integrated management of the supply chain cannot be overstated. To fill orders efficiently, one must understand the linkages and inter-relationships of all the key elements of the supply chain. The supply chain for HP's products contains manufacturing, research and development (R&D) sites in 16 countries, and sales and service offices in 110 countries. The total number of catalog products exceeds 22,000.

HP management has recognized that its performance filling orders will cause it to win or lose the competitive battle. In high technology industries, order fulfillment has become a major battlefield in the 1990s [Fuller, O'Connor, and Rawlinson 1993]. Current president and CEO Lew Platt identified successful order fulfillment as one of his top goals for fiscal 1993 and appointed a vice-president to work full time toward that goal.

Grappling with supply-chain issues is a complex and multi-faceted task, especially in a company like HP whose products are diverse and complex. Variabilities and uncertainties can occur at any point along the

chain. Suppliers can be late in their shipments, or the incoming materials may be flawed. The production process may break down, or the production yield may be imperfect. Finally, product demands are also highly uncertain. It is imperative that manufacturing managers understand the effects

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## We discovered data-recording problems.

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of uncertainties. These effects are best understood through analytical modeling. By using analytical techniques, managers can arm themselves with data that enable them to design manufacturing and distribution processes that provide efficient and cost-effective order fulfillment.

HP produces many products whose supply chains include manufacturing and testing integrated circuits, board assemblies, and final assemblies, and distributing the products to customers through a global distribution network (Figure 1). Of HP's product groupings, computers and peripherals provide the largest percentage of net revenue (77 percent) (Figure 2).

The approach HP used to address its supply-chain problems contained an element of serendipity and yielded a host of rewards. Recognizing the need for quantitative-based models to support top management decision making, HP formed a group known as Strategic Planning and Modeling (SPaM) in 1988 and staffed it with industrial and computer systems engineers. HP charged the group with developing and introducing innovations in management science and industrial engineering. By 1989, it had implemented a quantitative-based methodology, the

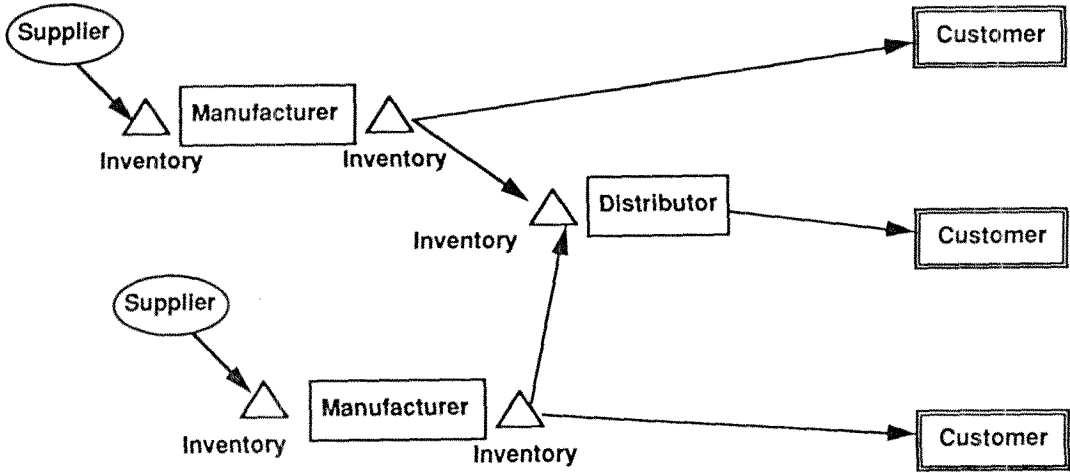


Figure 1: A supply chain includes all the interactions between suppliers of materials, manufacturers, distributors, transportation links, and customers.

bubble model, to assess plant charters by capturing the costs at a site as a combination of fixed and variable costs [Billington and Davis 1992].

While the bubble model was effective in capturing such costs as fixed overhead, equipment, transportation, and other vari-

ables, it did not provide an accurate picture of the effect of uncertainties on inventory investment, customer service, and response time in filling orders. Given the importance of order fulfillment and the rising costs of inventory and logistics, SPaM set out to develop a new methodology that would

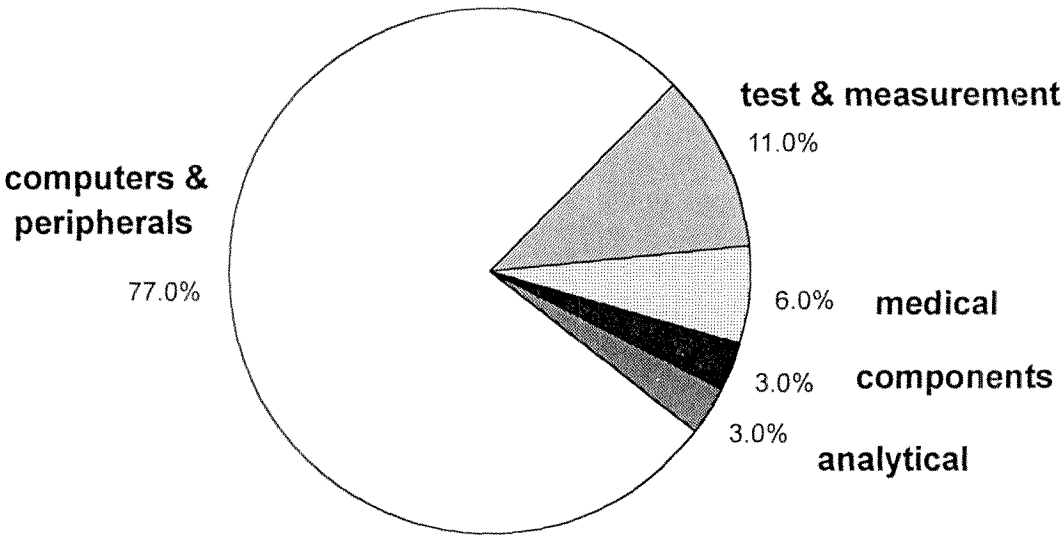


Figure 2: Of Hewlett-Packard's product groupings, computers and peripherals bring in the largest percentage of new revenue (1993).

address the aspect of uncertainty in the supply-chain problem. The quantification of the impact of uncertainties could then be integrated with the bubble model methodology to support strategic decision making. In 1989, we started working together to bring supply-chain-management concepts into HP.

Our collaborative efforts and those of our institutions resulted in an enduring cooperative relationship. Between 1989 and 1994, our partnership has grown, and it is now at the core of a series of joint research and application projects. Its evolution has been iterative, characterized by the interaction of model development and application experiences. We refined our methodology continuously as we accumulated experience with business applications. The work, which began as a manufacturing initiative in 1989, has evolved to span several func-

tional areas: design and engineering, distribution, finance, and marketing (Figure 3). The evolution of supply-chain management at HP follows a dual path of methodology expansion and functional boundary expansion.

**Background and the Identification Phase**

In the spring of 1989, SPaM began modeling the supply chain. The initial project was to investigate the supply-chain problems of the personal computer (PC) and deskjet printer divisions. The project was expected to take one year. We devoted the first six months of that project to identifying and characterizing the problem. We contacted primarily participants from materials and manufacturing groups within the PC supply chain and spent hours talking to production planners, members of the purchasing staff, production control engineers, and managers. We made many

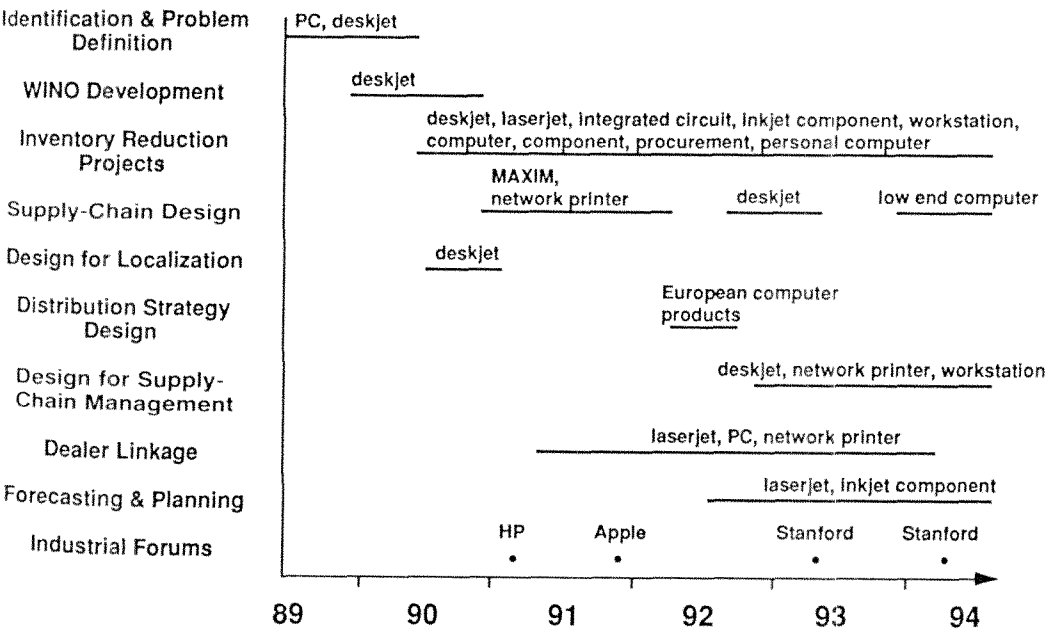


Figure 3: Supply-chain model development parallels project engagements from 1989 to 1994.

site visits. At the sites, the project team came to a clear appreciation of the inter-relationships of all of the processes from integrated circuit (IC) production, printed circuit board (PCB) assembly, PC final assembly, to distribution. The project team also collected massive amounts of data pertaining to manufacturing performance, demand characteristics, and order fulfillment performance. The PC supply chain provided the setting where HP developed

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### HP's peripheral products have been growing at a record pace.

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an understanding of the interactions of different entities in a supply chain, the common pitfalls that operations managers of these entities faced, and the effects of performance measures on supply chains.

Our initial focus was to develop a clear understanding of the business problems faced by supply-chain managers. Having no preconceptions about what modeling work would follow, we were open to any and all ideas as to what we needed to model and what assumptions would eventually be relevant. This explorative approach served us so well on this first project that it has become one of the building blocks of SPaM's philosophy. Now in each project, models are developed only after gaining a thorough understanding of the problem. If one starts with a preconceived model structure before diving into the problem, one risks force-feeding an inappropriate model to the problem or overlooking important elements of the problem that do not fit the model approach.

Supply-chain problems are so complex that even defining and shaping the investi-

gation is a challenge. The initial task within the PC division was to identify and understand the problem. The danger at this stage of a project is spending a great deal of time on something that turns out to be inconsequential. We obtained and analyzed data that we eventually found to be of marginal significance. For example, we collected data related to manufacturing efficiencies, machine breakdowns, change-over times, and so forth at a very microscopic, detailed level, and we collected characteristics of stock-keeping units without any grouping to form summary statistics. Nevertheless, these investigations are important, and, looking back, we can see that this initial phase set the foundation for SPaM's understanding of supply-chain problems. The relevance of the models we subsequently developed was enriched by our efforts to develop a deep understanding of the decision makers' environment.

The project's first data analysis was also a useful exercise. We learned what was available in HP's databases and how reliable those data were. As we analyzed this data, we discovered data recording-problems, for example, order data that were missing or obviously wrong. While this discovery was painful, the exercise itself was fruitful. It illustrated the importance of sound data recording and management and the value of consistent data definitions across different supply-chain models. We learned early on that reliable data is important in formulating models.

We concluded the project with the PC division by identifying the common pitfalls operations managers fall into in the PC supply chain. Drawing on our knowledge from prior research with other companies

in a variety of industries, we summarized the pitfalls and outlined the opportunities they afford [Lee and Billington 1992]. Another member of SPaM [Davis 1993] wrote general discussions of how supply chains can be more effectively managed.

Our effort to identify the problem was augmented by the results of an internal survey of HP's manufacturing managers. This survey, conducted by the manufacturing manager of the disk-memory division, identified the challenges and problem areas manufacturing managers faced. The survey results confirmed our findings that unreliable deliveries of materials by internal suppliers greatly impeded efficient management of the supply chain.

As the PC project neared conclusion, SPaM began work with the Vancouver division. That project called for modeling its supply chain to provide analytical support for manufacturing decision making. In our first meeting with the Vancouver manufacturing management team, the manufacturing manager described four areas in which he wanted analytical modeling support:

- (1) Benchmarking inventory and service trade-offs, that is, identifying the efficient frontier of inventory-service trade-offs;
- (2) Assessing the impact of uncertainties on operational performance;
- (3) Analyzing what-if questions for different scenarios and operating characteristics; and
- (4) Evaluating product design impacts on his supply chain, that is, predicting how his supply chain would perform under different product and process design alternatives.

This request led us to the next phase of developing a supply-chain model for HP

using Vancouver as the test site.

### **The Worldwide Inventory Network Optimizer (WINO)**

Early in 1990, we began to develop a model that would capture material flows and the associated uncertainties of the Vancouver supply chain. In parallel with this modeling effort, SPaM started collecting detailed data at the Vancouver division concerning the deskjet product line. The Vancouver division manufactures printers based on the inkjet technology, sold under the deskjet label. First introduced in 1988, these printers won the 1988 Datek Printer of the Year Award, and sales grew to over 600,000 units in 1990 (\$400 million). The division also manufactures other printer products, but their primary volume is deskjet printers. Since its introduction, the deskjet has been one of the fastest growing product lines at HP. The division has consistently maintained accurate data on supplier lead times, delivery performance, manufacturing lead times, process downtimes, demands, and forecast errors, which facilitated our early investigations. Even with Vancouver's efficient data management system and effective support, the task of gathering the information, analyzing it, and computing the summary statistics needed for the supply-chain model was still tedious.

We used a modeling approach based on developing a single-site inventory model to represent each operation in the supply chain and then integrated all the individual site models to cover the complete supply chain. At each site, we modeled two operations: receiving and production. A receiving operation can be viewed as a production operation in which the "produc-

tion" activities are receiving materials, inspecting incoming materials, and putting them into storage or sending them to the manufacturing line. Thus, one can model a single site as a combination of two separate inventory models, one for receiving and one for production. The sites are all linked in two ways. First, the demand for the end items forms the demand for the intermediate products, which in turn forms the demand for the raw materials, through the bill of materials. Second, the material or production delays of an upstream site result in delays in material receipt at a downstream site. These linkages are the cornerstone of the complete supply-chain model [Lee and Billington 1993], known as the Worldwide Inventory Network Optimizer (WINO).

WINO is basically a network of nodes in which we assume each node operates like a periodic-review, order-up-to-level inventory system. At this time, HP measured the ultimate customer service for final products in terms of fill rates, that is, the percentage of demands filled immediately. The model is therefore applicable to high-volume products for which immediate availability is essential to the customers (make-to-stock products). A model of this type is appropriate for such HP products as personal computers, printers, and other peripherals.

WINO relies on the following inputs:

- (1) Operation characteristics, such as specification of the network structure, operations performed at each node in the network, the bill of materials, the review period for each stock-keeping-unit (SKU), transportation times between nodes (means and variances), and desired service target or inventory levels at a node for

each SKU;

- (2) Supply characteristics, such as supplier lead times (means and variances), supplier delivery performance, and supplier quality (percent acceptable);
- (3) Process characteristics, such as production cycle and flow times (mean and variances), production capacity, downtime characteristics, and yield; and
- (4) Demand characteristics, such as the mean and variance of demand for each final product.

WINO produces a variety of outputs:

- (1) Inventory in different forms (raw materials, intermediate products, and final products), for different functions (as safety stock, cycle stock, and in transit), and in different locations; and
- (2) Customer service in terms of immediate fill rate and response times.

The mathematical specification of WINO was only the beginning of the modeling effort. It took SPaM much longer to program,

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## Management wanted to redesign the distribution strategy in Europe.

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debug, and test WINO for efficient usage. The original WINO was programmed in C++ running on a UNIX workstation, with a spreadsheet interface. We found the spreadsheet interface necessary for data input and result output because it allowed for easy statistical analyses. From 1991 onwards, HP has run revisions of WINO runs on a PC. We validated WINO using the Vancouver supply-chain data [Lee, Billington, and Carter 1993]. We continue to test the effectiveness of the approximation formulae and the robustness of the as-

sumptions in WINO, and we develop new service measure expressions through extensive simulation experiments [Johnson et al. 1995] and empirical testing.

### Inventory Benchmarking and Uncertainties

SPaM's project with Vancouver enabled the manufacturing manager to understand the inventory-service trade-offs for the supply chain and how well the division was performing relative to the inventory-service efficient frontier. In SPaM's subsequent work on supply-chain projects this has been the fundamental first step in supply-chain analysis.

The efficient frontier plots the minimum amount of inventory needed to meet a particular service target, given the current demand, process, and supply characteristics

(Figure 4). Another basic analysis dealt with understanding the impact of uncertainties upon the performance of the supply chain. For Vancouver, successive scenarios were tested. First, supplier delivery lead time uncertainties were reduced to zero, that is, suppliers were assumed to be 100 percent reliable in their delivery performance. Second, the uncertainties of both supplier deliveries and production processes were eliminated. Third, all uncertainties, including demand, were eliminated. Inventories decreased in each of these three cases (Figure 5). This Pareto analysis of uncertainties allowed Vancouver's manufacturing manager to gain a general idea of which source of uncertainty resulted in the highest cost impact to the division. The exact magnitudes of inven-

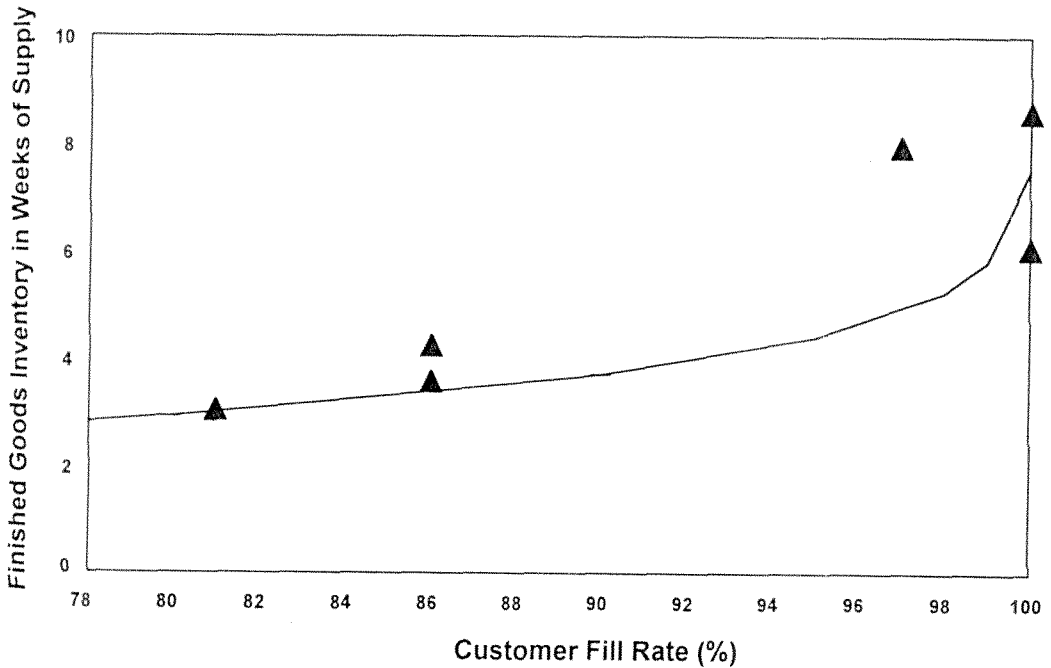


Figure 4: The amount of inventory and customer service are measured by the percentage of customer orders filled immediately for the deskjet products over time. They are quite close to the inventory-service trade-off curve.



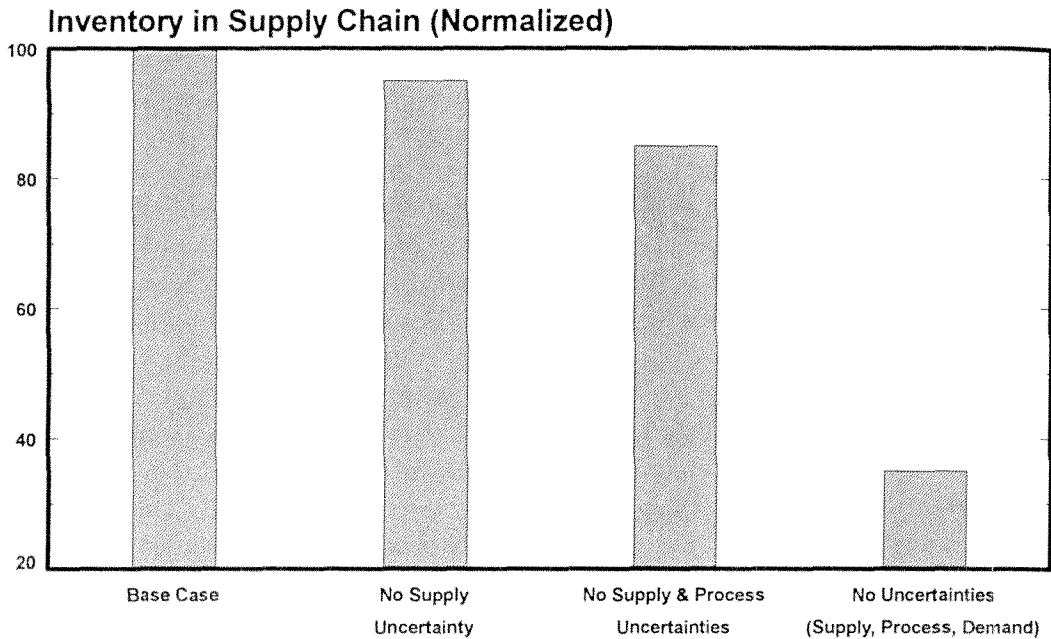


Figure 5: Inventory can be reduced by successively eliminating the uncertainties in a supply chain.

tory reduction would depend on the sequence in which the uncertainties were eliminated. Nevertheless this analysis helped managers to prioritize the investments needed to improve the performance of the supply chain. We found that demand uncertainties had the greatest impact on inventory. This prompted the division to consider redesigning products and processes to lessen the impact of demand uncertainties on its supply-chain performance.

From 1991 to 1994, SPaM did similar analyses for the laserjet printer division based in Boise, Idaho; the inkjet component division based in Corvallis, Oregon; the integrated circuit division based in Fort Collins, Colorado; and the computer manufacturing division based in Cupertino, California. The supply chains of all these divisions contain multiple sites inside and

outside the United States. In all cases, the basic analysis was effective in identifying opportunities for operational improvements. For example, in one case, the project team found that shortening review periods was effective and important. In another case, the team discovered that safety stocks were being held at two locations (one HP and the other non-HP). In a third situation, the team observed products routed through many sites before completion; the resulting long cycle times necessitated high inventories and resulted in poor response time to the customers. For another group, SPaM explored alternative transportation options and frequencies of shipments as means to improve the efficiency of the supply chain.

It became apparent during the early applications of WINO that we could improve supply-chain performance by employing a

variety of fine-tuning techniques, including more frequent reviews of inventory; balancing inventories in component, subassembly, and finished product forms properly; using different means of transportation; and reducing manufacturing cycle times. Inventory reductions by 10 to 30 percent were identified. More important, SPaM found that, by using a more radical approach, it could make genuine breakthrough improvements. Three avenues offer this type of high payoff:

- (1) Realignment of manufacturing and distribution strategies;
- (2) Improvement in forecasting processes and methods; and
- (3) Product and process redesign for supply-chain management.

**From Inventory Modeling to Manufacturing and Distribution Strategy**

In a logical progression, SPaM and its partnering divisions have moved from examining manufacturing processes to evaluating the methods HP uses to deliver the resulting products to customers. HP distributes most of its personal computer products and peripherals through its own distribution network. This network consists of two major distribution centers (DCs) in the US, several in Europe, and one in the Asian-Pacific region. Manufacturing sites are located all over the world. HP's peripheral products—laserjet printers, deskjet printers, and inkjet components—have been growing at a record pace. For example, the deskjet printer volume has grown from 600,000 units per year in 1990 to over 400,000 units a month today, an 800 percent increase. The inkjet components division has grown from a \$200 million business a few years ago to over \$1.2 bil-

lion today. Because product mixes are diverse and the distribution channel in Europe is complex, the cost of distribution is a large part of the product cost. Consequently, management wanted to redesign the distribution strategy in Europe. Inventories can be targeted to serve clusters of customers. Savings can be realized by optimizing freight and delivery mechanisms.

HP has considered several factors in developing a strategy for distributing peripheral products in Europe:

- (1) Many products are shipped from a single European DC to customers on the continent. However, some products (both peripherals and computer products) can be distributed from multiple DCs in France, Germany, and the Netherlands.
- (2) HP distributed some products, such as laserjet printers, out of two different DCs. One location specialized in bulk packed, pallet movements for customers with large order volumes, while the other location served customers with small order volumes. While it gained some economies through this specialization, HP lost the benefits of pooling safety stocks and incurred additional overhead expenses and other fixed costs.

In designing a new European distribution network, SPaM used a combination of cost modeling (the bubble model) and supply-chain-inventory model (WINO) methodologies. For a specific distribution network strategy, it used the bubble model to evaluate the costs of transportation, customs, duties, fixed and variable processing, and implementing changes to the existing network. It used WINO, on the other hand, to analyze the trade-offs between inventory investment and customer service

and to augment the bubble model with a more accurate estimate of inventory carrying costs.

HP's general manager of worldwide distribution initiated the European distribution network strategy project. The project team was led by a member of the worldwide distribution organization and con-

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## Supply-chain analysis is much more than inventory modeling.

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sisted of representatives from the European DCs and from the key product divisions that supplied them: deskjet, laserjet, and inkjet components. For two months the team worked intensively, collecting and validating data, and debating and evaluating alternative strategies. Team members traveled to all the sites, since they could obtain some information only by talking directly to people at the sites. In early 1992, the executive vice-president of the computer products operation used the data from this investigation to make the decisions that resulted in the realignment of the distribution network. This realignment reduced the total distribution cost in Europe by \$18 million a year.

The European distribution network strategy project was very successful and validated many of our beliefs. First, it quantified many cost elements. Historically, management had often made such decisions subjectively or intuitively. Second, we validated the importance of integrating the supply-chain-inventory (WINO) and fundamental cost models. Third, this effort convinced us that the composition of a project team greatly affects management

receptivity and the implementation success of modeling projects. Because the project team comprised representatives from all the sites concerned, it obtained the appropriate data and information, assessed and interpreted the analyses properly, and validated the output. Finally, it is clear to us that supply-chain analysis is much more than inventory modeling. It can be extended to distribution strategy analysis and to other types of supply-chain problems.

As the European market grew, HP considered expanding manufacturing capacity on the continent. In particular, deskjet printers experienced explosive growth. In 1992, HP's deskjet orders doubled in Europe in a single month! The need for a European plant became apparent. Yet HP needed to consider its manufacturing and distribution strategies jointly and coordinate them. Management asked SPaM to evaluate these strategies for the deskjet expansion into Europe.

In reality, HP's manufacturing activities were often not completely decentralized. For example, boards were often assembled in one location to serve all of the company's requirements worldwide. Consequently, we could not isolate the European manufacturing strategy from that of the rest of the world. Therefore, when SPaM embarked on the European manufacturing and distribution strategy, it had to model the worldwide deskjet supply chain. Even though our focus was the European strategies, we analyzed the worldwide manufacturing and distribution strategies of the deskjet printer division. With global data, HP could align the European strategy with the worldwide strategy and avoid less effective strategies.

HP has relied on supply-chain modeling in introducing new products as well. In late 1990, SPaM worked with a product development team from Vancouver to analyze alternative manufacturing strategies for a new product that involved a Japanese partner. The project team discovered that the expected cost-service efficient frontier was much worse than that for Vancouver's existing products. Declaring this unacceptable, the team explored alternative supply-chain networks based on different manufacturing locations for both HP and the Japanese partner. As a result of the analysis, both companies decided to redeploy their existing facilities so that they could produce this new product with optimal efficiency. Performing this kind of analysis before the new product was launched was extremely valuable [Lee and Billington 1993].

SPaM made a similar evaluation in 1991 when HP introduced the network printer in Europe. We assessed alternative strategies that looked at relocating various HP facilities in Europe and the US. The supply chain of the network printer involved an Asian partner that manufactured the key engine. The engine was integrated with HP's printed circuit board to form the end product. The locations of this Asian partner's factory, HP's board factory, and the DCs could affect the costs and inventory performance of the supply chain. HP's management used the results of our investigation during its negotiations with its Asian partner to determine the manufacturing and distribution plan for the new product.

### **Design for Supply-Chain Management**

The concept of supply-chain manage-

ment had begun to grow as projects proliferated throughout the company. In the early supply-chain projects that dealt with inventory and service trade-offs, we treated the bill of materials and the production process as known a priori. We focused on how to improve the performance of the chain. Our involvement with a number of divisions led to the emergence of a concept known at HP as "design for supply-chain management." The key point of this concept is that the design of products and the design of the associated production processes can produce big payoffs.

The Vancouver division provided the first instance of such payoffs. The division used to make all models of their printers in the factories and then ship them to the DCs for distribution. The uncertainties of different countries' demands had resulted in inventory imbalances: the DCs had excess inventories of some printers, and shortages of others. Since printers are shipped by sea from the factories to the overseas DCs, the DCs had trouble responding quickly to variations in customer demands. Despite a large investment in inventory, they could not provide good customer service.

SPaM used WINO to analyze what payoffs were possible from redesigning the product. The project team quantified the savings that HP could realize if the remote DC performed the final localization step (customized the printer for the local country) instead of the factories. This concept is known as "design for localization." A change as far reaching as this required the collaboration of all of the division's major functions: engineering, manufacturing, and distribution. Engineering had to redesign

the product so that the power supply module could be plugged in externally instead of being internal to the product. Buy-in from manufacturing was imperative because the tasks performed by the factories and DCs would change. Distribution also had to support the change because it would now be responsible for procuring parts, power supply modules, and manuals, performing final localization operations, and ensuring quality, functions that had not been part of its normal routine. In addition, we expected that these activities would be more expensive when performed *at the DC instead of at the factories*. However, the Vancouver division was considering the entire system, not just isolated activities.

For this project, we used WINO to assess the risk-pooling benefits in the form of inventory savings that would result from Vancouver making one model of the printer, instead of multiple country versions. On the other hand, with DC-localization, the localization materials would need to be stocked at all DCs, instead of in one central location. Hence, in terms of inventories of localization materials, we have a "reverse risk-pooling" phenomenon, and WINO was used to quantify those differences as well.

This project gave SPaM its first taste of the impact of organizational issues in supply-chain management. To convince all three groups to work together on this redesign, the project team had to quantify the costs and benefits of the change.

The Vancouver division implemented the DC-localization strategy successfully, improving both cost and service. It is now fully committed to the design-for-localiza-

tion concept and currently designs all its new products to be localized at the DCs [Lee, Billington, and Carter 1993].

This project convinced us that supply-chain performance can be greatly improved by concurrently redesigning a product and its production process. Such traditional design concepts as design for manufacturability are inadequate to capture these logistics and distribution aspects. At the conclusion of this project, we began working on other projects where product designs can affect supply-chain performance. Localization is only one of many *options within the design-for-supply-chain-management* concept. Another is the use of common parts so as to delay the differentiation of products during manufacturing. This strategy of delaying product differentiation has gained momentum at HP. We have interviewed individuals in a number of divisions who have changed designs to gain flexibility, and as a result, we have developed a more formal structure of the *design-for-supply-chain-management* concept [Lee 1993].

SPaM's work in designing for supply-chain management also included strategies that involved strategic partners, expanding the scope of its work over company boundaries to include key suppliers. We have discovered tremendous economic potential. In a 1993 project to introduce a peripheral product, we found we could reduce the unit cost of the product (based on the traditional supply-chain structure) by as much as \$80 by appropriately aligning the supply-chain structures of the strategic partner. Peripherals have thinner margins than complex computers and instruments, and this reduction in unit cost goes directly

to the bottom line.

### **Postponement**

In general, the production of multiple versions of a product (for different geographical markets or different user segments) generally begins/can begin/could begin with a single engine. Throughout the production process, different subassemblies are added, leading to multiple versions of the end product. By delaying product differentiation one delays as much as possible that moment when different product versions assume their unique identities, thereby gaining the greatest possible flexibility to changing customer demands. Flexibility can improve the cost-effectiveness of the supply chain, because inventories are stocked in the predifferentiation forms. At HP, the concept of delaying product differentiation is known as "postponement" [Lee and Billington 1994].

The Vancouver division's printer family proliferated as the division tried to satisfy many different customer segments, each requiring different functionalities. We adapted the basic supply-chain model to analyze the potential benefits of using alternative process designs so that the division could delay product differentiation [Lee forthcoming, Lee and Tang 1994].

Increasingly SPaM is asked to work on delayed-product-differentiation projects. Another printer division was a recent candidate. Traditionally, printers destined for the European market use dedicated engines with 220V power supplies and those for the North American markets use 110V power supplies. Reworking the engines to switch the power supply is not a trivial task and would incur some significant labor and material costs. Using such a design

for printers would not provide HP with the flexibility to use the printer inventory to satisfy both markets. Imbalances in the inventories of the two types of printers could cause serious problems during two stages of the product life cycle: early introduction and end of life. In 1993, SPaM analyzed the cost implications of switching to a design that specifies engines with a universal power supply. We examined such costs as materials, inventory, rework, shortages, and transshipments from one region to another to correct imbalances.

The costs are quite dependent on the lead times from the supplier for the engines with dedicated and universal power supplies. With dedicated power supply, product differentiation for the two markets effectively starts at the beginning. With universal power supply, differentiation does not occur until the engines are transported to the two continents. The value of this postponement, in the form of inventory reduction, can be quantified [Lee and Sasser 1995]. With product life cycles that are becoming shorter and shorter, the benefit of postponement with universal power supply outweighs the additional material cost.

### **Expanding into Distribution Channel**

SPaM's supply-chain projects at HP have progressed from considering material management to considering manufacturing and ultimately distribution partners. We have expanded their scope across divisional and functional boundaries and beyond the corporate structure. We now include suppliers on the upstream side and, on the downstream side, HP's salesforce and dealers. In expanding the distribution channels, we cross a frontier, because HP

does not usually own these agents. They are, however, an integral part of the overall supply chain of HP products. HP's expanded view of its supply chain has led it to try to create win-win situations for HP and its dealers [Mullich 1993]. HP is now much more responsive to the requirements of its distribution channels and more flexible in satisfying their changing needs.

The interdependencies between HP dealers and HP were the subject of a study early in 1991. We began with a survey of dealer needs. We sent out teams to a number of major dealers in the US. The divisional marketing managers coordinated these visits. This was marketing's first involvement in the supply-chain efforts. During these visits, the teams tried to understand the dealers' operational environments, their crucial needs from HP, their past experience with HP, and the improvements HP could make to enhance their competitiveness. HP manufacturing managers used this survey as a springboard for greater involvement with their downstream external customers as supply-chain partners. The survey provided HP with factual information and also generated a spirit of collaboration with the dealers.

We found, first, that the dealers are much more concerned about the reliability of delivery than the length of delivery lead times. Second, dealers depend upon having accurate and timely information on delivery dates, order status, revisions of delivery dates, and product availabilities.

The make-to-order environment has important implications. In make-to-stock systems, customers expect products to be available on the shelf. In make-to-order systems, customers expect products to ar-

rive within a delivery time window, known as the promised lead time. When a customer requests a product and expects the order to be filled within a time window, the order reliability is the probability that the order will be filled within this target lead time. At HP, some computer products—personal computers, computer peripherals, and consumable units like toners and inkjet cartridges—operate like a make-to-stock system, because immediate avail-

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Immersing themselves in an industrial setting is recommended to all academics.

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ability is a critical competitive factor. However, other products, such as minicomputers, workstations, medical instruments, and other test and measurement products, operate like make-to-order systems. Because of the needs of these other product divisions, HP eventually extended WINO to handle make-to-order situations.

In 1991, HP started a project to extend a division's supply chain to include the key dealers' inventory systems. The project revealed the existence of duplicate safety stocks throughout the supply chain. Finished products were stocked at both HP DCs and the dealers. HP used WINO to quantify how much inventory could be reduced at these two locations, while maintaining the same service target for the customers. Quantifying this duplication was useful to management.

HP and the dealers have worked closely to improve the performance of the overall supply chain [Mullich 1993]. In another

initiative, HP has collaborated with its dealers in applying the postponement strategy. Possible postponement strategies range from dealers performing only distribution functions, to performing distribution plus some localization operations, to performing distribution, localization, and customization tasks. Postponement strategies involving dealers must be carried out in close collaboration with them. We cannot emphasize too strongly the importance of interactions and empirical studies. To assess the capabilities of dealers to perform some of these operations and to develop operational relationships, HP visited a number of US and European dealers. Before modeling the situation in which dealers customized and configured end products, HP had to find out if they were equipped to perform these operations, if they were willing to do so, and if they had adequate incentives. Managers considering postponement strategies should conduct detailed analyses before making such decisions. These analyses should include visiting and negotiating with dealers, quantifying the costs and benefits, assessing the marketing implications, and considering government regulations and local content laws, environmental requirements, and organizational impacts.

### **Engaging Marketing and Finance**

As SPaM's supply-chain-modeling work progressed, a shift took place within HP. Some heretofore isolated and internally focused groups began to move to a broader perspective and started to work together to improve the performance of their supply chains. SPaM saw that beyond engineering, manufacturing, and distribution, the next functional area it needed to involve

was marketing. A number of projects have revealed that demand uncertainty resulting from forecast errors was the key source of inefficiency in a supply chain. Design changes, such as common parts, delayed product differentiation, and other postponement strategies, helped lessen the impact of forecast errors. Nevertheless, SPaM felt that it should address the fundamental problem of forecasting processes and methods.

In 1992, HP's Boise Printer Division formed a major team to tackle this problem. The project team members came from SPaM and from the divisional marketing and material departments. At the outset of this project, SPaM was convinced that forecasting was much more than a statistical tool for projecting demand into the future. It also embodied the analysis of the impact of forecast errors on the efficiency of the supply chains. We believed that a forecasting project should also include the process in which the firm used forecasts to generate production, inventory, capacity, and financial plans. As a result, the project team was expanded to include representatives from production planning, finance, product marketing, process engineering, and materials management. In fact, the project name FLAP (forecasting, logistics, and planning) indicates the expanded scope of this project.

The FLAP project unveiled interesting information, such as the importance of installing a measurement system to track forecast accuracy, the importance of carefully and completely documenting the forecast processes that translate basic customer needs into production requirements, and the need for forecasters and planners



to communicate in a timely and accurate manner.

Another extension to our supply-chain modeling considers the financial implications of a worldwide supply chain. As the supply chains for most of HP's products are global in nature, HP must evaluate cost and revenue implications in light of fluctuations in exchange rates. We need to account for currency exchanges in the global supply chain, value-added activities in the global manufacturing and distribution network, and the revenues generated from sales in a worldwide market. Financial hedging strategies and their associated costs can affect where HP should locate plants, how it should deploy its resources, and how it should add capacity. We must model exchange rate uncertainties explicitly, or perform extensive sensitivity analyses. In recent projects which dealt with supply-chain designs, the divisions involved dedicated a financial analyst to the project, along with the controller of the division who oversees the development of the project, and members of the manufacturing staff.

With marketing, finance, manufacturing, engineering, and distribution all involved in its projects and with recent supply-chain modeling developments, SPaM has entered a mature phase of supply-chain work at HP.

### **SPaM and Academic Collaboration**

It is worthwhile to describe the events that led to the working relationship of the two authors. In 1989, Hau Lee took a sabbatical leave from Stanford and expressed an interest in using that time to work on industrial projects. Prior to that, he had been working on supply-chain-related

problems with Booz-Allen-Hamilton, IBM, and Apple Computer [Cohen and Lee 1988, 1989]. Integrating an academic partner into a corporate research and development effort at HP required both skillful positioning and high-level champions. To bring him into HP, Corey Billington had to convince the executives of the value of such an undertaking. He approached two vice-presidents: Hal Edmonson, then vice-president of corporate manufacturing, and Lew Platt, then executive vice-president of computer peripherals, and they approved of the plan. In addition, the team secured the support of the manufacturing managers of the divisions that produce personal computers and deskjet printers as pilot project sites. In this way, we launched a highly successful, ongoing collaboration.

SPaM values its close ties with academic research and teaching. Hau Lee spent his sabbatical year at HP in 1989. Initially, we expected to introduce rationalized supply-chain inventory models into HP during that year. Over the last five years, our relationship has continued, and its scope has expanded. This relationship is collaborative, not consultative. Hau Lee is a full participant on such issues as organizational design and assists in technology development for the group. On a reciprocal basis, the members of SPaM have availed themselves of his expertise. As a result, the amount of learning that has taken place within the group has been tremendous.

Academia has benefited from this relationship by virtue of the mandate for relevancy within a working corporate environment. Priorities must be clearly defined, and that very ranking, in turn, helps to identify industrial trends that can yield

topics for future research. Immersing themselves in an industrial setting is highly recommended to all academics who can arrange such an opportunity.

SPaM's work in supply-chain management has also contributed to the curricula at Stanford University. One of the projects with the Vancouver division has been developed into a teaching case for classroom discussion [Kopczak and Lee 1994], and the case is now being used at supply-chain training workshops for HP employees.

SPaM has continued to host academic researchers who fit SPaM's research needs. In 1992, when SPaM began its forecasting work, it enlisted a statistician from the University of Texas to spend half of her sabbatical year with SPaM to develop forecasting methodologies. In the same year, SPaM brought in a professor from the Graduate School of Business at the University of Chicago for six months to explore financial hedging problems. In the summer of 1993, SPaM hosted a professor from the Graduate School of Business at Vanderbilt University to help the group with the simulation testing of some key assumptions and approximation formulae of WINO. In 1994, SPaM began working with a faculty member from the Graduate School of Management at UCLA on the impact of product-line structuring on supply-chain performance.

SPaM contributes to the academic community through its strong ties with specific research programs. For example, HP is an industrial partner in the Stanford Integrated Manufacturing Association (SIMA), a consortium of industrial corporations that are partners to the teaching and research programs on manufacturing at Stanford.

HP has suggested areas of work and offered direction to SIMA researchers. As a result, SIMA has initiated projects that are supply-chain related. These projects have received strong support within the company in terms of advisory assistance from HP managers. Just as HP has begun expanding the involvement of multi-functional teams in supply-chain modeling efforts, Stanford has expanded its involvement in supply-chain research. Professors from industrial engineering, the design division of mechanical engineering, and the school of business who specialize in operations, incentives, and information systems have been involved in the SIMA supply-chain projects.

In the last few years, other divisions within HP have also funded Stanford doctoral students doing research on supply-chain management. These doctoral students worked as summer interns at HP and have used the problems they studied to motivate their thesis research.

### **Industrial Interactions**

We are aware that supply-chain problems are not unique to HP. An increasing number of reports and articles describe how other companies are wrestling with the same issues [Interactive Information Services 1994]. To improve the methodologies that SPaM has developed, we wanted a broader perspective than that available solely at HP. In March 1991, HP hosted an industrial forum on supply-chain management, not a public conference, but a gathering of SIMA industrial partners interested in research on supply-chain management. The forum's objectives were to share common problems and best practices, and to generate ideas and directions for the

Stanford research team. Hal Edmonson, former vice-president of corporate manufacturing at HP, was very supportive. He presented the opening address in which he said that, "although we are fierce competitors, the sharing and interactions at this forum will make us better competitors." The same idea was echoed by Bill Hansen, the former vice-president of manufacturing and logistics at Digital Equipment Corporation. The participants at the first forum included HP, Apple Computer, Digital, Ford Motor Company, and Stanford University. Each participating company was required to give a presentation on the challenges and problems it faced, the methods or approaches it used, or the lessons learned from implementation experiences. The forum was a great success. Representatives from all the participating companies felt that the forum provided a very useful exchange and agreed that there should be a follow-on forum.

For HP, the forum was a means to conduct a first-level benchmarking on industrial practices in supply-chain management. It also provided a means to build up industrial relationships and networking. There are always some areas in which HP employees can learn from its peers.

Apple Computer hosted the next industrial forum in November 1991. In addition to the first year participants, the 1991 attendees included IBM, Xerox, AT&T Bell Labs, Raychem, and SUN Microsystems. Returning participants reported on their progress with the supply-chain issues they had identified in the preceding forum. For example, Apple Computer had gone through the problem definition phase, and it reported on the redesign of its distribu-

tion strategies. Digital Equipment Corporation described how it had integrated supply-chain management with its learning organization concept. HP shared with the participants its first success in design for localization.

SIMA hosted the third industrial forum, in April of 1993, focusing on design for supply-chain management. New participants included General Motors, General Electric, Seagate Technologies, Quantum, Silicon Graphics Inc., Lockheed, and Advanced Micro Devices. We began to see more companies working on the design and organizational aspects of products and processes to improve their supply-chain performance. At two separate panel discussions, participants reiterated the importance of multi-disciplinary research and coordination. Moreover, they suggested that supply-chain research has not yet focused on the accounting and financial aspects of supply chains.

The 1994 forum was again hosted by Stanford. This time participants came from industries beyond the high technology area, such as pharmaceuticals (Eli Lilly), distribution (McKesson), fast food (Jack-in-the-Box), general (Siemens, Texas Instruments), and consulting (Andersen Consulting, PRTM). Companies began sharing information on how they carried out supply-chain education internally.

### **Current and Next Steps**

SPaM plans to continue its supply-chain efforts in the future. One major goal is to transfer the analytical supply-chain methods to HP divisions. It has initiated several steps toward this end already. They include enhancing the analytical tools and educating users.

We originally developed WINO as an internal tool for SPaM analysts to use in their consulting work at HP. We designed the user interface for use by highly trained analysts. The divisions in Computer Products Operations need a tool to aid material planners with inventory and service management. SPaM engaged professional systems programmers to rewrite WINO into a more powerful tool, named the Supply-Chain-Analysis Tool (SCAT). This tool enhances WINO in three ways. It has a better graphical interface, supports more help functions, and is more user-friendly. SCAT was implemented on a PC. We have completed pilot projects using SCAT, and so far, the divisions' reaction has been very positive. We hope that SCAT will make analytical supply-chain analysis more accessible to HP divisions.

In 1994, SPaM launched a major initiative to develop an education program for HP managers and engineers on supply-chain management. It developed the material for the program in collaboration with the corporate education group. We intend to design and offer a workshop that highlights the importance of supply-chain management, teaches the basic methods involved, and illustrates some case examples. Formalized education should hasten the diffusion of supply-chain competence throughout the company. In 1994, SPaM conducted close to two dozen workshops. The demand for such management education programs has continued to grow, and we have plans for many more workshops in the future.

Recognizing the importance of supply-chain management, several key divisions at HP have now formalized such positions

as supply-chain project managers, supply-chain analysts, or supply-chain coordinators. These individuals work closely with SPaM to ensure that supply-chain models are used effectively at the divisions and to identify new problem domains that feed SPaM's research and development efforts.

## Reflections

Supply-chain modeling has entered its sixth year at SPaM. Over the years, the SPaM projects have produced tremendous value for HP. SPaM has often identified cost savings of 10 to 40 million dollars per year from a single project. SPaM's role is in helping the divisions to identify the problems, to structure the decision process, and to provide support in management decision making related to supply chains. The accountability, decisions, and the final implementation of the decisions still rest with the divisions. While SPaM's projects have resulted in great dollar savings, another measure of SPaM's success is the increasing demands for SPaM's service. In 1988, the group size was only two. In 1994, the group, including part-time contractors, had risen to about a dozen. Even with this growth, the demand for SPaM's service continues to exceed what the group can handle.

We've learned a great deal over the past six years:

- (1) Supply-chain management is a business fundamental. As SPaM examined many of its customers, it often found that very basic changes in operations (for example, installing a performance measurement system) would improve supply-chain performance. Sophisticated inventory models were not always required. Identification of such problems and developing

Supply-Chain Problems	Material	Manu- facturing	Distri- bution	R&D	Marketing	Finance
Inventory/Service Improvement	X					
Operational Efficiency	X	X				
Chain Structure, Distr. Strategy	X	X	X			X
Distribution Channel		X	X			
Global Financial Hedging		X				X
Forecasting & Planning		X	X		X	
Design for Supply Chain	X	X	X	X	X	X

Figure 6: Supply-chain development has been tied to functional boundary expansion, with increasing involvement and collaboration of cross-functional areas.

plans to address them are the first steps towards effective supply-chain management.

(2) Interactions with the academic and industrial communities are of tremendous benefit. In particular, having a professor spend a sabbatical or internship with a company is a valuable means of technology transfer and mutual education.

(3) It is very important that research and model developments do not happen in a vacuum. All our model developments happened while SPaM was working with HP divisions on real projects. Real projects and interactions with managers and relevant decision makers are the motivating forces that guide SPaM's development work.

(4) Supply chain is not just a problem for manufacturing or for distribution. All functional areas of the company must even-

tually be included, and these areas must participate in improvement projects (Figure 6). In a parallel fashion, research at universities on supply-chain management cannot continue as a problem just for operations management groups but instead must be tackled by multi-functional teams.

(5) Without sound analysis and quantitative data support, management may settle for the status quo, and engineers may avoid making substantive engineering changes. Our analytical work has provided different functional teams with bases for their negotiating and deliberating on strategies. They have helped management see the costs and benefits of implementing changes in their policies.

(6) Great payoffs can be achieved by taking an expanded view of the supply chain

and, in particular, including the key suppliers and customers in supply-chain decisions.

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