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Manufacturing Strategy Analysis: Models and Practice

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In this paper we examine the relationship between manufacturing strategy and cost modeling. Combining activity-based accounting and mathematical programming concepts, we define a structure and specific production cost functions for use in quantitative facility strategy models. The cost functions explicitly consider economies of scale and diseconomies of scope. We incorporate these cost functions into optimal facility network design formulations, and we use the resulting models as a basis for assigning individual facility charters and supply chain network structures. This modeling process has been used extensively at Hewlett–Packard Company. A case study is included.

Key words—cost models, decision making/process, electronics industry, manufacturing, strategic planning

INTRODUCTION

IN RECENT YEARS, the Hewlett–Packard Company (HP) has undertaken the realignment of its manufacturing and distribution network to enable more effective execution of its manufacturing strategy. The situation has been complicated by the interaction of the company's strong culture, its diverse product structure, and its long-standing tradition of manufacturing flexibility and quality [10].

Increasing product complexity and cost competition initially dictated the change in manufacturing structure. More precisely, a change was required in the company's supply chain network structure and the associated facility charters. At HP a manufacturing facility's *charter* defines the set of products that the facility will produce. HP's global facility *strategy*, on the other hand, defines the supply chain network and the product flows through the chain of independent facilities.

Managers desired detailed cost models to help them determine the best facility strategy for the changing business environment. The fundamental question was how to incorporate both economies of scale and diseconomies of scope into the models. This paper details how Hewlett–Packard's Strategic Planning and Modeling group formulates facility location models that explicitly include scale and scope effects in ways useful to and used by middle and senior level managers. We also show how this formulation can be used with the existing optimal supply chain formulations [3–6].

LINKING MANUFACTURING STRATEGY TO COST MODELS

Many models have been developed to support manufacturing strategy analysis [3]. However, most of them are limited, as they ignore diseconomies of scope and complexity. Moreover, real applications of these models are rare, due in part to the difficulty of obtaining the necessary data by traditional cost accounting methods. One of the greatest obstacles to employing highly analytical models, though, is the fact that they alienate senior managers unfamiliar with the intricacies of the modeling technology. In this paper, we recognize these limitations and build a model to address these concerns.

At Hewlett–Packard the decision-making council that ultimately decides to change the charter of a facility normally comprises a senior manager from each division in the group. This council, though empowered to set strategic direction for the group, typically lacks appreciation for the tactical implications of the various scenarios for change under consideration. (In the HP parlance, a *division* is an autonomous—and physically isolated—business organization with profit and loss responsibility. Divisions traditionally have their own R&D, manufacturing, and marketing. A number of divisions with similar product lines are organized into *groups*. Groups, in turn, are organized into *sectors*. Most decisions about facility charter and facilities strategy are made at the group level at HP.)

The models described here were developed specifically to support HP's group-level decision making. Used in this way, the models serve as filters for senior management and bridge the gap between them and the tactical managers at divisions' factories. Figure 1 shows the role of analytical models in the communication of information between different layers of management.

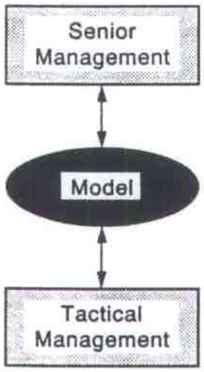
Our strategic models share three characteristics. Each is critical to the successful use of a model as a communication tool between senior and tactical management. First, the models allow any proposed scenario to be examined in detail. The open format does not obscure alternative solutions behind a single optimal solution. Among other things, this allows each decision maker to study the relative merits of his or her initial solution (i.e. his or her hunch or preference). Not surprisingly, their tentative solutions usually have their respective divisions assuming a dominant role in the group. Open models provide a clear window through the fog of emotion.

Second, our models use data available from existing cost accounting systems. This is critical because of the great expense of gathering additional data. More importantly, it means that the model's calculation of the *status quo* scenario will be consistent with the management reports familiar to those reviewing the work. This is necessary for establishing the model's credibility [1, 7, 8].

Finally, each model's interface to decision makers clearly communicates the relative merits of alternative scenarios. We use spreadsheets, like Lotus 1-2-3, as the interface with management and as our link to commercial optimization packages like VINO. Spreadsheets are commonly used by all tactical managers and most senior managers. Thus, they allow efficient communication of the data, algorithms, and solutions of the mathematical programs to the managers. In fact, managers can quickly learn to explore the solution space manually, which helps to improve their insight to the subtleties of the problem at hand. Heightened understanding also increases their support of the model and the modeling process.

PARTITIONING WORK

The models we've developed attempt to quantify the total cost of different manufacturing *scenarios*. Typically, the scenarios are defined after partitioning the group's total work into logical *work buckets*. Then the work buckets are assigned to the facilities; different assignment combinations define the different scenarios.



Solicit consensus on a manufacturing strategy. Empower team to study problem, review options. Select best choice in face of qualitative factors.

Clarify and summarize key issues in concise, analytical format. Use to study relative effectiveness of alternative strategies.

Provide insight and data required to create and validate model. Ensure effectiveness of adopted strategy.

Fig. 1. Roles in decision making.

The group's work is partitioned into work buckets by using critical distinguishing *features*. Work typically can be segregated along many mutually exclusive dimensions; a *feature set* is the finite set of possible values or elements in one such dimension. For example, one feature set might simply be the different R&D laboratories in a group (the characterizing *feature* being a product's laboratory of origin).

Work buckets, in turn, are defined by the permutation of the feature sets. A work bucket is characterized by a value in each of the critical dimensions. Note that a work bucket is *not* simply an aggregation of similar products (though product line might be one distinguishing feature). The physical work required to satisfy a product's demand might be partitioned into several different work buckets, which might in turn be assigned to several different facilities. Also, some permutations of the feature sets may not have real meaning. Those work buckets should be ignored.

The partitioning of work is a critical step in the modeling process and must be carefully considered by the model builders. The feature sets limit the scenarios that can be studied using the model. It is necessary to limit the number of features because the number of work partitions grows with the product of the work features. Thus, the trade-off between model complexity and accuracy must be considered, as with other modeling techniques.

One Hewlett–Packard business group examining its printed circuit and final assembly strategy satisfactorily described its work with three features: process technology, facility location, and product test requirements. The group divided work into one of three process technologies: through-hole (THT), surface mount (SMT), and final assembly (BOX). Likewise, they distinguished work on the basis of the four locations where work was currently performed (D1, D2, D3, D4). Finally, two levels of testing requirements—high (H) and low (L)—were used to break up work into representative parcels. Thus there were 24 possible work buckets to be assigned to the four divisions. However, since D4 did not have SMT capability (and none would be added, per one of the financial constraints from management), the work buckets with that combination were ignored. An assignment matrix, known as the *steering wheel*, was used by the modeling team to input scenarios by assigning work buckets to divisions. The assignment matrix defining the *status quo* (no change) scenario for this example is shown in Fig. 2.

	Manufacturing divisions			
Work buckets	D1	D2	D3	D4
D1-THT-H	1			
D1-THT-L	1			
D1-SMT-H	1			
D1-SMT-L	1			
D1-BOX-H	1			
D1-BOX-L	1			
D2-THT-H		1		
D2-THT-L		1		
D2-SMT-H		1		
D2-SMT-L		1		
D2-BOX-H		1		
D2-BOX-L		1		
D3-THT-H			1	
D3-THT-L			1	
D3-SMT-H			1	
D3-SMT-L			1	
D3-BOX-H			1	
D3-BOX-L			1	
D4-THT-H				1
D4-THT-L				1
D4-BOX-H				1
D4-BOX-L				1

Fig. 2. *Status quo* work assignment matrix.

MODELING MANUFACTURING COSTS

A number of costs must be considered when reviewing alternative manufacturing strategies. Of course, the costs are context dependent, and different situations call for increased or decreased focus on specific cost elements. A good example is material cost. In many cases, material cost is of no consequence. Corporate contracts and domestic production (and sales) obviate the need to model the impact of volume purchases, tariffs, and local content laws. Particularly when modeling manufacturing for a world market, though, these same factors can have considerable impact.

At the most elemental level, costs can be divided into two categories, direct and indirect (manufacturing overhead). Direct costs change principally with the volume of work, having relatively small fixed cost components, and they are generally well understood. Overhead costs are more difficult to quantify. Particularly onerous is the task of separating fixed from variable indirect costs. Activity based accounting methods greatly facilitate this effort.

Fixed costs determine economies of scale, since consolidating work to a single facility eliminates redundant fixed costs. But complexity —observed as number of products, number of processes, and similar measures of scope—leads to substantial fixed overhead costs, too. Consequently, the fixed cost structure driving manufacturing overhead must be analyzed carefully.

The fixed costs are determined by the amount and type of *physical resources* required by a facility to complete its work. The resources typically include things like floorspace, equipment, maintenance labor and materials, and supervision. Resources are general categories, and the definitions of a resource as it applies to each particular feature must be worked out by the modeling team.

It is important that cost models for the physical resources be developed consistent with the accounting system so that meaningful data can be readily collected. Hewlett–Packard uses an activity based accounting system that makes accurate cost modeling especially straightforward. Under this system, the cost of each resource is a function of some corresponding physical *cost driver*. For example, supervisory costs are most closely related to span of control. Direct labor headcount is the cost driver for supervisory cost. Cost drivers are ultimately tied back to some measure of demand (product volume, part volume, etc.).

Accounting and manufacturing experiences have shown that linear variable cost relationships are sufficiently accurate for strategic modeling purposes. These *cost driver rates* include fixed and variable elements of resource cost. However, the rates can change with time, and they can change differently from facility to facility depending on local operating and business conditions. Thus, local rates must be used. Typically, HP's planning models have a horizon of many years (4–10), so the impact of changes over time can significantly affect decisions.

For modeling purposes, we consider four broad categories of cost, which break up the problem along conventional lines. Constructing the model in this way, we have found, assures the modeling team of completely capturing all pertinent costs. *Build costs* are most significant, including both fixed and variable production costs. *Logistics costs* account for the cost of buffering and transporting goods between remote facilities. *Linkage costs* must be modeled because of the need for physically remote facilities to work together and exchange information, too. Finally, *implementation costs* are incurred when change takes place. More formally,

C_{build} = total build cost over the model's horizon;
C_{log} = total logistics cost;
C_{link} = total linkage cost;
C_{imp} = total implementation cost.

Each of these elements of cost will be explained in greater detail in succeeding sections.

Our models are designed to minimize the sum of these costs over the time period of study. The decision variables are:

$x_f = 1$ if facility f is open, 0 otherwise;
$y_{fb} = 1$ if facility f builds work bucket b, 0 otherwise;
$z_{fk} = 1$ if feature element θ_k exists at facility f, 0 otherwise.

A rigorous formulation would include the possibility of opening and closing facilities from year to year. We recognize the practical limitations of such a dynamic strategy, though. In the face of the prohibitively high implementation costs that would make such a solution unlikely, we simply remove that dimension of the solution space. In essence, we assume that plant charters will not be changed during the planning horizon, apart from any changes at the onset.

The resulting objective function is:

$$\text{minimize: } C_{\text{build}} + C_{\text{log}} + C_{\text{link}} + C_{\text{imp}}$$

subject to the following constraints:

facilities must be open if they are to do any work
feature elements must be available to do work at a facility
work buckets are built at only one facility

Build costs

In the course of developing several facility strategy models at Hewlett–Packard, we have observed three principal types of fixed divisional manufacturing overhead costs: *business core*, *product specific*, and *process specific* costs. In our experience, these three categories adequately encompass all of the pertinent costs of scale and complexity that are affected by a facility's charter. (Note that many real costs are ignored in the model if they do not vary from one scenario to the next, like the material costs mentioned earlier.) During the normal course of business the elements of these costs are truly fixed, and they are reported as such by both traditional and activity based accounting systems. Since they are a function of facility charter, though, *they are treated as variable costs* in our facility strategy formulations because their magnitudes change with the scenario.

Core costs include those associated with the infrastructure necessary for a facility to be in business—*any* business. They include things like an information technology support group, a facilities maintenance group, etc. The core costs must be included because the costs can vary greatly from one location to the next.

The product and process specific costs relate closely to the work features described earlier; usually the work features used to partition work can be easily categorized into one of these two general classes of cost. Product and process costs tailor a facility to participate in specific businesses. The nature of the costs varies from situation to situation, but a surprisingly high proportion of the total product and process specific costs accounts for *knowledge* that an organization must have in order to utilize a particular technology or to participate in a specific market. The knowledge is typically embodied in engineers; the balance of the costs include more routine equipment and supplies.

Figure 3 shows the "bubble model", which clearly communicates these concepts. Different scenarios are easily presented in this format by simply redrawing the arrangement of the bubbles. Each "bubble" in the illustration represents fixed cost elements. In this generic illustration, the two facilities are process focused, and supplemental product specific costs are incurred to tailor each-process center to the requirements of the product lines supported. Product focused factories can be modeled just as easily, but in either case the core costs are inescapable.

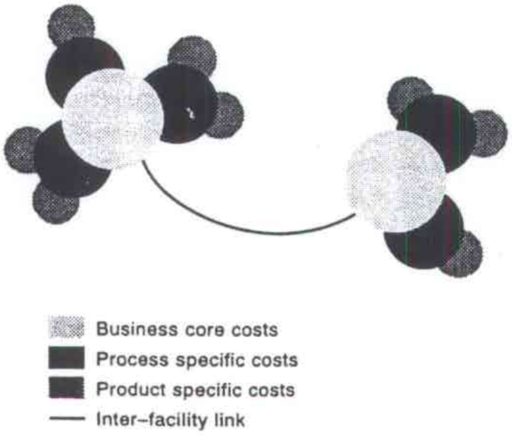


Fig. 3. Graphical representation of the "bubble" model.

We have found this representation immensely valuable as a teaching and communication tool. The visual model makes it easy to communicate concepts like redundant fixed costs. It is also useful for illustrating the possible realignment of work and the concept of features characterizing work. It is especially useful for introducing the mathematical modeling approach to senior managers who are relatively unfamiliar with the problem at hand. It provides a simple language to use with them.

We do not explicitly include plant capacity in our models. Because of Hewlett–Packard's human resource and physical plant policies, capacity can be inexpensively altered from year to year to any practical limit. Also, models like these provide broad guiding principles for the assignment of work to plants, essentially answering the question of where to have capacity. Modifications to a general implementation plan are considered using the selected strategy as a point of departure. Specific considerations like capacity adjustments are relegated to this level of planning.

The build cost is the sum over time of the different core costs, the fixed costs related to the specific work done at each facility, and finally the variable costs related to the total volume of work. Build costs typically account for over three quarters of the total cost modeled. Consequently, considerable effort has been devoted to the accurate and useful treatment of these costs. The remaining categories of cost receive a simpler treatment.

Linkage costs

Linkage costs account for the glue that holds together different organizations. Linkage costs bind geographically remote facilities that must work together to design, manufacture, and distribute a product. However, there can be significant costs to link organizations within a single facility, too.

Generally speaking, communication links between organizations are necessary to ensure sound "customer–supplier" relationships between internal operations. People are required, especially engineers, buyers, and logistics experts. Travel and electronic communication expenses must also be considered.

Generating consensus on the costs to include in this category can be difficult. At HP, where products have traditionally been designed, manufactured, and distributed on the same site, there is a reluctance to separate the functions. High linkage costs are anticipated for remote manufacturing, especially to ease new product introduction. The jury is still out at HP on this point; many feel that separating functions will necessitate more formal design transfer practices that will actually improve performance. One way or the other, linkage costs should account for comparable product introduction schedules, product quality, and manufacturing flexibility from scenario to scenario (or adequately account for differences).

The driver used for linkage costs is simply the number of connections between organizations. The linkage cost for each work bucket for each possible assignment location and resource-type must be determined independently to adequately model the total cost.

Logistics costs

Logistics costs stem from the uncertainties encountered when manufacturing a product (i.e. inventory costs) and the need to transport products from one facility to the next. Our drivers for logistics costs are the number and size of physical products moving to their final destination with the customer.

Previously, we have modeled logistics costs in a manner completely analogous to our treatment of linkage costs. Because optimal supply chain design formulations exist, we are currently expanding our strategic facility modeling formulations to include an optimal logistics cost formulation [6]. The combined formulation is given in the Appendix.

Implementation costs

Implementation costs are the one-time, up-front expenses incurred when making changes to a facility's mission, for such changes often result in the need to relocate and train people and to outfit floor space. Also, there are direct costs associated with planning changes from the *status quo*. While there is considerable detail to consider when modeling implementation costs, the costs are relatively straightforward to quantify.

The implementation model is unique to each situation depending on the current situation and the type of changes contemplated. Implementation costs can be tremendous for changes affecting a large number of people. Implementation costs are typically calculated based on the changes that result in the first period in the significant drivers, particularly labor and space.

Model validation

Validation of the cost model is essential if it is to be used by decision-making senior managers. The complete model must be tested and verified by experts at each facility. Typically they use the *status quo* and specific test scenarios that are costed in detail using standard targeting and business techniques.

Identifying current costs is relatively easy; agreeing on a model to estimate costs under extreme conditions (like tripled volume with increased mix) is more difficult. This is typically achieved by polling experts at the facilities in what might be described as an informal Delphi approach. Sometimes these experts are actively involved with the modeling process, and this exercise amounts to a structured "sanity check". In other cases, specialists who are not involved with the modeling team provide a more thorough validation (at least in their respective fields of expertise).

Several iterations on both cost driver algorithms and parameter values are normally required before the model is acceptable to all parties. The final results of HP cost models to date have agreed with results from standard business planning exercises to within about 5%.

ROBUSTNESS AND OPTIMALITY

The facility strategy models described here do not dictate decisions. They merely help provide a basis for decision. It is assumed that (in most instances) no one scenario can be unequivocally identified as the "optimal" solution to the business problem at hand. While much of the modeling effort focuses on highly quantifiable data, there remains a significant body of qualitative issues that simply cannot be cast adequately into analytical form. These include concerns about the flexibility and morale of the work force, among others. Risk, while potentially quantifiable, is often treated qualitatively, too. In short, the best decision may not be the lowest cost solution as identified by a cost model.

We use a more robust "short list" to present a handful of scenarios that stand up well in the face of unquantifiable assumptions and polluted accounting data bases. A quantitative model can identify many different "good" scenarios, and it can even make a close estimate of cost. Distinguishing between the different appealing options—the short list—is left to the judgement of the experienced upper management team charged with resolving the qualitative and quantitative issues. The true objective of the model, then, is to provide sufficient clarity of understanding to allow the management team to determine the "best" overall manufacturing strategy, and to take action on it. As one senior manager at HP put it, "There is no such thing as an optimal solution. We need understanding and we need to make good decisions."

Even among the quantifiable elements of cost, there remains a question of just how much accuracy is needed. The trade-off is simple: accurate, capacitated, nonlinear cost models can be achieved, but at the expense of time, energy, and resources dedicated to the collection and validation of the data. Given the natural discrepancies in the data and the resulting expected error, along with the relative importance of more qualitative issues like flexibility of the resulting strategy or the ability to "focus" the factories, high precision for the cost model seems inappropriate. For our purposes in supporting the development of manufacturing strategy at HP, linear, uncapacitated models capture accurately enough the salient characteristics of cost.

CASE STUDY: APOLLO-HP

In the spring of 1989, Hewlett–Packard purchased Apollo Computer for approximately $500 million. The modeling that was done to support the development of a joint Apollo–HP workstation manufacturing strategy was one of the most challenging applications of the "bubble model" to date.

Three characteristics of the situation created challenges. First, the accounting systems of the two companies were different and required careful reconstruction to provide suitable data for modeling purposes. Second, the time frame for the creation and analysis of the model was very short, only four months, due to legal and labor considerations. The third challenging aspect of the situation was the international scope of the problem. Duties, taxes, and government relationships, like government grants, needed to be included in the model.

The modeling team included representatives from each of the affected facilities, generally either a materials manager, production manager, or engineering manager. Data was provided by representatives from both companies' accounting and manufacturing engineering organizations under the direction of their respective modeling team members.

The modeling team settled on four critical work features to characterize the situation: current work location, customer location, process technology, and relative product complexity. The first two features, work and customer location, most strongly influenced linkage and implementation costs. Build costs were more strongly affected by the last two features. Logistics costs, mainly freight and duty costs, were relatively small, regardless of the scenario.

At the onset, "current work location" meant the same site as the R&D lab responsible for the product. Thus, scenarios moving work from one facility to another meant introducing substantial linkage costs for the first time in that group. It also meant sharing unfamiliar manufacturing processes. That was a substantial emotional hurdle that the modeling team—and the two companies and their different cultures—had to clear.

Using physical drivers like part volume rather than, say, labor or machine hours as the basis for modeling resource consumption facilitated the development of a cost model that represented both companies quite well. Both accounting organizations felt that the use of cost drivers was critical to the development of the data and the validation of the model. The manufacturing managers felt that the analysis using cost drivers resulted in much clearer understanding of the strengths and weaknesses of each organization.

The model was used as a key part of the analysis in forming a joint HP–Apollo manufacturing strategy. The model provided crucial support for the decision to close two facilities and drastically change the charter of two others. The cost model allowed senior managers to trade off cost consequences of "organizational pain and confusion" for quantifiable benefits in reduced manufacturing cost. The model's optimal solution was not selected, but one option on the "short list" was; it was valuable to have a benchmark for comparing different scenarios.

The management team reported that the decision resulting from the modeling efforts would save HP more than $15 million dollars per year in manufacturing costs, net of implementation costs. It is also interesting to note that the path ultimately chosen was not one initially considered by any of the senior managers before the modeling team became involved.

CONCLUSION

In this article we described a modeling framework to assist in the formation of manufacturing strategy. Mathematical programming models—and a practical method for using them—were developed that exploit readily available accounting data. Also, they explicitly consider the effects of economies of scale and diseconomies of scope. The resulting facility cost models have been folded into available supply chain network design models to support the development of multisite manufacturing strategy.

Each modeling exercise requires careful consideration of the peculiar attributes that make each business situation different. In our models, we routinely characterize ostensibly similar work (electronics manufacturing) in different ways, using different feature sets and cost drivers. Despite the specific differences between situations, though, the "bubble model" approach described here has been tremendously valuable to Hewlett–Packard. The approach has been used several times, and the facility strategies for different HP business groups have been successfully modified in response to the information brought to light in our models. Execution of strategic change has followed in the wake of a practical, rational, data-driven decision making process.

APPENDIX A: SUPPLY CHAIN OPTIMIZATION

Here we integrate our build, linkage, and implementation costs with more advanced logistics costs concepts [6]. While we have yet to implement this extension in our practice at Hewlett–Packard, we view it as the natural extension of our earlier work.

Specifically, we add two new ideas in defining a more thorough logistics cost function. First, consider an additional type of facility, the distribution center, which can be opened and closed like a manufacturing facility. Distribution centers can be remote from or co-located with manufacturing facilities. Second, break up the customer base into geographic zones, each with a known demand for products. Each distribution center can ship to any of the zones—for a price.

Two new decision variables are introduced, which are analogous to the decision variables for facilities:

$\underline{x}_d = 1$ if distribution center d is open, 0 otherwise;

$\underline{y}_{dc} = 1$ if distribution center d serves customer zone c, 0 otherwise.

A number of additional constraints are also necessary:

the number of open facilities and distribution centers may be restricted
some facilities and distribution centers may be forced open
ship only to open distribution centers, and only from open facilities
all customer zones must be served, but only from open distribution centers
ship an adequate supply of raw materials to each facility
ship from a facilitry no more than has been received
ship from a distribution center no more than has been received
meet all customer requirements

With this approach, the complete cost of managing a supply chain is captured, including transportation costs and the cost of running distribution facilities. Decisions on distribution center charter are made independent of manufacturing facility charters, yet the entire system is considered in the total cost formulation. Of course, inventory investments can be included in the distribution center cost. One additional change that affects the complete formulation is the constraint on minimum and maximum number of open facilities.

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