A Plant Productivity Measure for High-Tech Manufacturing

By

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A total productivity measure was developed as part of an action research productivity analysis project for a manufacturer of computer peripheral devices. The productivity measure had to be appropriate for a broad range of automation levels, yet resolve the long-standing methodological problems of index construction in a manner intuitive to management. The difficulties encountered in attempting to institutionalize the measure point to the need for a compromise with cost accounting.

Our research objective was to develop a measure of total plant productivity which would satisfy three criteria: that it express the efficiency of the use of all key plant resources; that it meet the academic's requirements for rigor; and that the manager find it simple, practical, and useful in a variety of settings, including highly automated ones. The methodology used was action research: the project was a collaborative effort of a university and a major US-based computer systems manufacturer whom we shall call "Hi-Tech."

Partial productivity measures (of which labor productivity is the most common) are powerful tools when directed at specific problems [Mundel 1983], but are often misleading when used to assess overall efficiency — especially in automated settings [Eilon, Gold, and Soesan 1976].

The effort to establish overall plant productivity measures is not new. Davis [1955] made one of the first systematic efforts to popularize company productivity

measures, and Kendrick and Creamer's work [1965] still serves as a useful guide. Frameworks for the managerial use of overall productivity measurement have reached a high level of synthesis [Hayes 1982].

But while the research use of overall measures at a plant level has been systematically explored (see the survey in Sumanth [1984]), their practical use has barely progressed. Indeed, Sumanth and Einspruch [1980] found that "total factor" or "total" productivity measures were used by only four of the 73 manufacturing and operations functions they surveyed in 90 large companies.

The reason for the slow diffusion of these measures seems to be that they are (1) too sophisticated and therefore vulnerable to subversion by threatened managers, (2) too simple and therefore unreliable in the presence of such common but analytically complex phenomena as product mix changes, or (3) too difficult to implement for lack of available data [Stewart 1984].

The challenge lies therefore in "finding the proper balance between concept and reality" [Stewart 1984]. A growing number of firms seem interested in confronting the challenge in the current climate of a new competition focused on sustaining dynamic efficiency gains [Abernathy, Clark, and Kantrow 1981]. Hi-Tech was just such a company.

The Context

Hi-Tech produced advanced electronic equipment. Its operations varied from simple assembly to highly automated machining and complex electronic testing.

In the past, its competitiveness had been guaranteed by its product technology leadership and its marketing sophistication, but increasing turbulence in the marketplace was threatening the stability of its client relationships, and Japanese competitors were closing the technological gap in broad segments of their market.

In response, Hi-Tech elevated manufacturing competence and productivity to top priority. In the past, manufacturing had not been considered responsible for most of the resources it used; its task was to meet production schedules and reduce

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unit labor hours, even though labor costs were less than 10 percent of total manufacturing costs. Now, its mission had to be broadened, and a new measurement system could serve as an incentive.

Three characteristics that made Hi-Tech a "high-tech" manufacturer were particularly important in defining a new performance measure:

(1) *The importance of new product introduction*: The cost accounting system measured performance against planned (standard) costs. Because of the short product life in this industry, these standards changed monthly to reflect the learning-curve assumptions of the annual operating plan. But to play their strategic role, as distinct from their operating role, manufacturing managers would need a measure that would highlight performance relative to their broader functional responsibility for new product manufac-

turing ramp-up — that is, the ability of the manufacturing organization to move rapidly from prototype to high volume production.

(2) *The importance of knowledge workers*: Hi-Tech's operations were very knowledge intensive; over half its manufacturing personnel costs were generated by indirect personnel (primarily manufacturing engineers and technicians) rather than direct labor. In the past, however, Manufacturing Engineering had reported to Manufacturing only at the highest level of management; it had seemed natural that start-up manufacturing engineering costs be accumulated and combined with current manufacturing engineering expenses to be allocated over the whole year. But if Hi-Tech was to manage and track these crucial knowledge resources, manufacturing engineering expenses actually incurred in a given month would need to be distinguished from allocated expenses.

(3) *The importance of process and product technologies in driving productivity*: Labor productivity measures can be particularly misleading in machine-intensive processes [Eilon, Gold, and Soesan 1976]. In such contexts, increases in labor productivity will normally be the result, not the cause, of overall productivity improvement (which is primarily driven by improved capital productivity). The performance measurement system should therefore not allocate overhead on the basis of direct labor hours; this established the wrong incentive. Furthermore, much of what had been buried in overhead, in particular, machine costs, had to be made explicit to focus attention on optimizing

fixed assets. Whereas capital accounting had been seen as an exclusively corporate concern, asset management now had to be brought down into manufacturing.

The Approach

The company's objectives were clear in their general orientation and vague as to the specifics. Hi-Tech management wanted a performance measure that could express the new role it attributed to Manufacturing, a measure that would

— highlight the overall efficiency of resource use rather than focusing on direct labor;

— allow more meaningful analysis of a department's performance over the critical start-up period;

— allow comparisons of the various departments producing the same components (sometimes located in different countries); and

— ideally allow comparisons across departments producing different components.

Our goal was thus to establish a rigorous and useful system of monthly productivity measurement, capitalizing on the new competitive importance of manufacturing to overcome objections and resistance.

Our specific challenges were the following:

— To adapt existing research to plant-level (or department-level) analysis, because many of the existing measurement approaches were either too detailed and nonaggregable or too aggregate and insufficiently concrete to satisfy managers.

— To develop a measure that could function equally well in labor-intensive environments and in automated environ-

ments where learning effects were dramatic, where direct labor was minimal, where knowledge work was critical, and where the process was machine-intensive.

— To develop a methodology simple enough to allow effective implementation.

We needed a measure that would track the efficiency of overall resource use. Labor productivity indicators would not be suitable, since they would change with the introduction of more machinery or the subcontracting of components. Hi-Tech managers wanted to know whether the trade-off of better labor productivity for lower output-to-capital ratio (lower capital productivity) or higher purchased materials content (and therefore lower materials productivity) was effective. We needed an overall productivity measure.

The simplest model of total productivity is perhaps that of the American Productivity Center [Ruch 1981]. It makes explicit the connection between productivity and profitability:

$$\text{Profitability} = \frac{\text{sales}}{\text{costs}}$$

$$= \frac{\text{output quantity} \times \text{unit price}}{\text{input quantity} \times \text{unit cost}}$$

$$= \frac{\text{output quantity}}{\text{input quantity}} \times \frac{\text{unit price}}{\text{unit cost}}$$

$$= \text{productivity} \times \text{price recovery factor.}$$

To implement this concept we needed to measure and aggregate output and input quantities and to construct a productivity ratio from these variables.

Measuring Outputs

Monthly cost reports at a detailed

departmental level listed the quantities of each component produced. Inventory adjustments to the output were minor. So the key methodological issue was whether and how to aggregate outputs in departments producing more than one component.

If we did not aggregate, our measurement effort would have remained on the industrial engineering side of a familiar division of turf; this would have kept us out of cost accounting's territory. But our objective was an overall measure of department performance, and several departments encompass more than one cost center, so we needed to be able to aggregate to at least the departmental level.

The standard solution to this problem is to find some dollar value to use as a weight, for example, sales values. But prices were not available for many sub-components; moreover, prices would reflect many market-based forces that are not pertinent to a measure of department resource-use efficiency.

To weight outputs, we thus chose a measure of the resources required for these outputs' production. Standard costs were the best available estimate. This solution would have brought us back to the conventional cost-accounting results, were it not for our definition of input quantities and our treatment of changes in standard costs over time.

These changes in standard costs present particular difficulties when product costs fall rapidly, as they did in the early life of Hi-Tech's products. One Hi-Tech department, for example, produced two successive generations of the same component: the two items were destined to

cost approximately the same amount about two years after the second's introduction, but in the first few months the second generation cost double the first. Which standard cost should be used for the second generation component? The annual operating plan projected the year's standards along a planned learning curve. But using the current month's (sliding) standard would have generated a measure of productivity on a variance-from-budget basis. Such an approach would have suited the traditional objectives of Manufacturing — maintaining shipments and labor hours within budget — but it rendered opaque Manufacturing's new mission of taking charge of the learning process over the whole life of the product.

The better approach, we felt, was to adopt a constant weight representative of a base period. We decided to highlight performance relative to ultimate product-cost goals, and we therefore used as base weights Cost Engineering's estimates of "ultimate cost." Ultimate cost is the minimum standard cost estimated to characterize the mature process usually attained some two to four years after manufacturing start-up.

This weighting procedure had two key advantages. Ultimate cost was Manufacturing's commitment to Marketing: it served as a basis for pricing decisions. It had therefore a strong managerial content.

With this choice, we also resolved the traditional index number problem. While forced to choose between Paasche, Laspeyres and Divisia-type indices for macroeconomic or industry studies, at the plant level we could construct a procedure which more accurately reflected our objectives and the available information.

A last methodological issue was that of standard costs for international comparisons: Should we use plant-specific ultimate costs, cross-plant average ultimate costs, or perhaps the lowest ultimate cost? These standards varied not just by national currency but also with the efficiency each plant calculated it could attain. The theoretically optimal solution would have been to translate currencies with purchasing power parity exchange rates [Kravis, Heston, and Summers 1978] and then use for each plant the average of the plant ultimate cost and the cross-plant average ultimate cost [Caves, Christensen, and Tretheway 1981]. Our assessment of the costs and benefits of this procedure led us to forego the extra degree of analytic incisiveness; we used plant-specific ultimate costs.

A substantive issue remained: did we want a value-added measure of output (which would have generated a "total factor" productivity measure) or a measure of output which includes materials (generating a "total" productivity measure)? We chose a procedure that gave us the best of both. By excluding from our ultimate cost standards the value of materials (components) coming in from upstream departments, we could aggregate department results into a plant-wide measure. By including the value of purchased materials coming into a given department, we could assess the department's efficiency in materials usage. This last objective seemed particularly important in light of the new manufacturing mission.

Traditional performance measurement left materials usage analysis to separate yield reports, if only because the cost accounting reports did not distinguish materials quantities (Manufacturing's responsibility) from materials costs (Purchasing's responsibiity). We wanted an overall measure of manufacturing performance.

Defining Inputs

More so than output, the monthly input measure was limited by the availability of data. We therefore defined input quantities as follows:

— *Direct labor*: the monthly headcount of direct personnel in each department was available from Industrial Engineering records.

— *Indirect labor*: a monthly headcount of indirect personnel was not available at a departmental level; we therefore estimated a full-time equivalent headcount from the Manufacturing Engineering expenses charged to each department annually. This expense was deflated by the departmental average of manufacturing engineers' annual employment cost (salary plus benefits), and the resultant annual estimated headcount was interpolated linearly to generate a monthly series.

— *Materials quantity*: the sum of purchases and interplant transfers taken from monthly cost-accounting reports gave the dollar value of the materials incorporated into the month's output. A materials-quantity series was derived from these data by deflation, using a company-supplied price index.

— *Capital quantity*: these data were derived from Industrial Engineering reports on the potential output (in units per day) of the department's machines working three shifts per day under optimal technical conditions. The annual data were interpolated.

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— *Inventory quantity*: this series was derived from the monthly accounting data on work-in-progress and materials inventory. To focus on efficiency rather than financial performance, we deflated the value of inventory to correct for the rapidly falling unit costs of many of the inventoried components. We used the same approach as that used for output: we deflated the current value of inventory by the ratio of this month's output valued at current cost to this month's output valued at ultimate cost.

In each of these measures, we focused on manufacturing's efficiency in the use of available resources, rather than adjusting for capacity utilization. This was justified by the large backlog of orders.

Of these measures, the most innovative was that of the capital input. Our approach was based neither on depreciation plus returns [Kendrick and Creamer 1965] nor on total expected returns [Craig and Harris 1973]. Instead, our capital quantity measure had a direct engineering basis in the technical capacity of the manufacturing line. We felt that this would be more relevant for the Manufacturing Department manager whose performance was not measured as a profit center, let alone an investment center. We would need a

measure of the cost of capital, but only to weight the capital input for aggregation purposes. Moreover, this cost weight was a constant, so that movements in the capital input series reflected capacity changes, not financial changes. In this approach, the cost of facilities, as distinct from machinery and equipment, was reflected in the weight, not in the quantity, of the capital input.

A second innovation was the deflation of inventory costs by an ultimate cost index: in a high-tech environment, the learning curve effects experienced by suppliers are often considerable.

The weakest element was the materials deflator. Consistent with the old functional division of responsibility, Hi-Tech plants had not developed department-specific price indexes: Purchasing's mission was simply to keep the total materials bill as low as possible. The US plant therefore used the US Producer Price Index; one of the overseas plants did develop a plant-specific, but not department-specific, index.

The monthly interpolation of indirect labor and capital was also a limitation. Monthly actuals never made the transition to the status of usable information in the company records.

We next needed a weighting system with which to aggregate these heterogeneous input quantities. It seemed most appropriate to weight inputs by some price indicator of relative marginal productivities.

It is standard practice to use market prices as weights, on the principle that a competitive market equilibrium generates prices proportional to marginal productiv-ities. This approach has three difficulties: factor markets may not be fully competitive; factors are not always fully substitutable; and it is often meaningless to attempt to identify individual productivity contributions in a synergistic whole. These problems can be circumvented by an econometric estimation of the weights simultaneously with that of the overall productivity measure. However, this would have been impossible to implement on a regular basis at a department level.

Taking each input in turn, our approach was the following:

— *Direct and indirect labor*: we used the sum of wages and benefits to generate a total employment cost for each department and each personnel category.

— *Materials*: materials needed no weighting since they were already in deflated currency units.

— *Capital*: the appropriate weight for the capital input was a total cost of capital. We used the Kendrick-Creamer approach to estimate this weight, calculating the cost of a unit of capital (capacity) by adding the return *of* capital — depreciation — to the return *on* capital — its opportunity cost. The former was not readily available on a department level; we adapted data culled from the minutes of Hi-Tech's capital appropriations committee. These gave us a series of appropriations for machinery and equipment as well as facilities (structures and fittings). We used this data in a model of the appropriation-to-installation lag developed by the Hi-Tech staff to estimate the installed asset value. Based on staff estimates, we assumed an average useful life of five years for machinery and equip-

ment and 10 years for facilities. Depreciation was calculated on a linear basis. To these depreciation costs, we added the return on capital measured as the real cost of financial capital, which we set at seven percent, reflecting the long-run average inflation-corrected cost of a typical mix of debt and equity [Kaplan 1985]. We ignored real estate costs on the principle that manufacturing managers were not responsible for their location in high or low land value areas.

— *Inventory*: this was valued at a 10 percent annual cost, reflecting the seven percent foregone return on capital and an estimated three percent storage and handling cost. We left our model open to revise this cost upward, as Hi-Tech managers became more conscious of the cost of inventory in hiding operations problems.

We had to decide whether to let these price weights evolve relative to each other or to adopt a fixed-base weighting scheme. The former approach would have reflected a very strong interpretation of the new manufacturing mission, since it would reward or penalize managers for the speed with which they adapted to changes in relative prices. But during ramp-up, process debugging was much more important than fine-tuning, and during on-going operations, department managers had to follow rather tight process recipes and to respect a corporate no-lay-off policy. We thus used the simpler fixed-weight system.

The base period was the most recent month. This way, build-up costs and the indivisibilities of early, small-scale operations would not cloud the results over the whole period. We thus had a Paasche-type aggregation of inputs to compare to our ultimate-based output aggregation.

The Total Productivity Ratio

Any approach to measuring productivity implies a certain model of production: Do the factors combine additively? Multiplicatively? In the economic analysis of industry productivity, a more complex but more flexible function — the transcendental logarithmic function — is often preferred [Christensen, Jorgenson, and Lau 1973].

Our focus on developing a measure with some hope of implementation led us to adopt an elementary, additive model. (In any case, the correlations between the different measures proved to be very high.) In this approach, we followed the examples of the American Productivity Center and such practically oriented researchers as Kendrick and Creamer, Craig and Harris, and Sumanth. The additive model has the advantage of giving a productivity measure that is the inverse of an inflation-corrected unit cost. Our measure of total productivity was thus a simple ratio of total output to total input:

$$TP_t = \frac{\Sigma w^{ui} Q_{it}}{\Sigma s^{dj} X_{jt}}$$

where

t	= time period,
TP	= total productivity,
Q_i	= quantity of output i,
w^{ui}	= unit cost of output i at "ultimate" (a constant),
X_j	= quantity of input j,
s^{dj}	= unit cost of input j at base-period d (a constant),

and where the base period d is the last period under study.

Implementation Difficulties

Hi-Tech's principal use for this methodology has been a historical analysis of the performance of the eight departments contributing to the production of a new generation machine [Adler 1985; Hayes and Clark 1985a, 1985b]. The statistical results were discussed with department managers and staff in order to identify the key determinants of their performance difficulties.

An example of the type of result that gave rise to useful discussion was the surprising evolution of some of the total productivity ratios themselves: the total-productivity learning-curve effect was diminishing in intensity in two of the eight departments studied. On closer examination, this appeared to reflect the negative evolution of the materials partial productivity index. A blind spot in Hi-Tech's information and management control systems became apparent when department managers had to admit that they did not know whether the declining materials productivity was due to increased subcontracting or to uncorrected changes in the unit costs of purchased materials.

But the idea of incorporating productivity analysis into Hi-Tech's regular measurement system has not taken hold. After 18 months' research effort I have a hypothesis as to why.

Productivity measurement is based on an extensive set of conventions. Often, a variable has more than one theoretically correct definition, and limits on data availability force compromises that are necessarily debatable. The key problem for productivity measurement is therefore legitimacy, and it is naive to believe that theoretical validity automatically generates legitimacy and acceptance.

Moreover, productivity analysis wants to occupy a place in the firm that is already taken by cost accounting. As Hopwood [1985] has written:

Operating, as it does, in organizations where the elucidation of both the ends and the means of organized endeavor resides in a contested domain rather than in one which is subject to the dictates of a pregiven rationale, accounting can be seen as having the characteristics of an interested practice which is concerned with creating and quite actively mobilizing, rather than merely facilitating the context that it is used to regulate.

Established measurement practices are difficult to dislodge if only because managers have limited information-processing abilities. The last thing they want is another report to read. A second measurement system living in peaceful co-existence with cost accounting is thus extremely unlikely unless it has some extraordinary demonstrable value. One potential contribution that many managers would value is the ability to compare performance across different products and companies. Productivity measurement, however, has yet to demonstrate any advantages over cost accounting in this regard.

Towards a Compromise with Cost Accounting

If the difficulties of implanting productivity accounting persist, cost accounting might be encouraged to adopt conventions that better express the new manufacturing mission and the new conditions of automation.

Three axes of development appear most encouraging:

(1) A number of cost accounting varia-

bles can be redefined to advantage. First, pooled overhead costs can be broken into components that can be assigned to specific manufacturing departments. As automation levels rise, it becomes increasingly important that each department's capital costs be identified. Second, overhead can be allocated to reflect incentives management wants to highlight. In particular, where labor costs are a very small proportion of total costs, it may be more appropriate to burden products or machine hours rather than labor hours.

(2) The presentation of cost reports could be revised. First, materials costs could be broken into their quantity and unit cost components; variances could be broken into their quantity and cost factors. Second, the cost report could be broken into layers to reflect the levels of authority exercised by the cost center managers over the individual items: items over which they had full authority — like labor and machine hours — would appear in the top part; items over which they had virtually no authority — like corporate overhead — could appear in the bottom part; and the middle zone could contain items — like some indirect staff — over which authority was shared.

(3) The system of performance measurement can be broadened to include some noncost accounting data. Typically, data on yields, field failures, machine utilization, labor force attitudes, and so forth are not incorporated into the core monthly reporting package. Such data are collected but discussed in separate meetings. One of productivity measurement's objectives is a synthetic measure of performance; cost accounting could respond at least in part to this need by opening its reports to a broader variety of data, even if they remain heterogeneous [Kaplan 1984].

Conclusion

Were cost accounting to adapt aggressively to the challenge of measuring performance in the new competitive conditions so clearly exemplified in high-tech firms, the need for a second measurement system would be dramatically attenuated. Productivity measurement would still be useful in the planning department, for example in testing the coherence and plausibility of planning projections for the individual cost elements or for occasional studies that serve to highlight specific problems. But someone somewhere will need to respond to the new measurement needs of manufacturing.

Labor productivity measures can be particularly misleading in machine-intensive processes.

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