Integrating Cost, Capacity, and Simulation Analysis

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1. Introduction

In this article, we discuss the integration of cost, capacity, and simulation analysis. Cost analysis is often treated as a separate task from capacity and simulation modeling activities. Several important factory-level cost performance measures, however, rely on detailed capacity analysis calculations. In fact, much of the difficult groundwork for making these calculations has already been completed in existing capacity and simulation analysis tools. We argue that these activities fit quite naturally together, and give a more complete picture of factory performance than isolated analyses. Also, capacity and simulation analysis tools are increasingly used to support strategic and tactical business decisions. These decisions are most often framed in terms of their impact on the bottom line. Therefore, effective decision-support tools must speak not only in terms of capacity and cycle time, but also in terms of dollars.

In the spirit of *The Goal*, by Eli Goldratt and Jeff Cox [2], we focus on three factory-level cost and revenue performance measures, namely dollar-valued throughput, dollar-valued inventory, and operating expenses (Section 2). In Section 3, we describe the input parameters added to Factory Explorer™, an existing factory analysis tool, to support estimation of these performance measures. With one additional parameter, it is also possible to perform detailed product cost analysis. In Section 4, we present some sample uses for this integrated analysis framework. On a cautionary note, we also present an example where the use of product cost to the exclusion of factory-level measures can lead to sub-optimal results. We close by discussing the advantages present in an integrated cost, capacity, and simulation analysis framework.

2. Outputs

Early in *The Goal* is a scene in which Alex, a plant manager, talks with Jonah, a scientist. Alex mentions that the use of robots has increased productivity by 36 percent in his plant. Jonah is skeptical. After questioning Alex about various performance measures, Jonah concludes “if your inventories haven’t gone down ... and your employee expense was not reduced ... and if your company isn’t selling more products ... then you can’t tell me these robots increased your plant’s productivity.” To Jonah, productivity is “the act of bringing a company closer to its goal.” And the goal of a manufacturing organization, of course, is to make money. The three performance measures outlined by Jonah, dollar-valued throughput, dollar-valued inventory, and operating expenses, provide a means of

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measuring the daily operations in the factory in terms of the goal. They allow a plant manager like Alex to tell whether or not a change in procedure will actually help his company to make more money. The specific goal of a manufacturing organization, then, is to simultaneously reduce operating expenses and inventory while increasing throughput. These are all factory-level measures, as defined in more detail below.

Dollar-Valued Throughput (Annual Basis): This output measures the revenue generated by finished goods leaving the factory. In the discussion that follows, we make the important assumption that *products exiting the factory model are actually sold, and generate the revenue indicated in the model*. If this assumption is not justified, then the model must accurately represent any post-production inventory loss or price reductions. In essence, the factory model (and factory modelers) must account for the fact that goods leaving the factory are not automatically sold at top dollar. In Factory Explorer™, dollar-valued throughput is based upon the results of capacity analysis, and hence requires no simulation.

Dollar-Valued Inventory (Snapshot Basis): This output measures the average value of inventory (work-in-process) in the factory at any given time. To compute this measure, the average inventory level for each product is multiplied by the product's per-unit value. Two logical choices for the per-unit value are a raw-cost basis and an absorbed-cost basis. Under a raw cost basis, the per-unit value is the simply the cost of a unit when it is released into the factory. Under an absorbed-cost basis, the per-unit value is the raw unit cost plus the cost of all labor, equipment, and material and consumable costs absorbed by the unit as it is travels through the production line. The current release of Factory Explorer™ values inventory on a raw-cost basis. Future releases will also value inventory on an absorbed-cost basis. Due to its reliance on estimated inventory levels, dollar-valued inventory requires execution of Factory Explorer™'s simulation engine.

Operating Expenses (Annual Basis): This output measures the annual operating expenses for the factory. In *The Goal*, operating expenses are defined as all the money the system spends to turn inventory into throughput. Included are line items such as raw materials, depreciation, tool recurring costs, labor, materials, and consumables. All of these items are calculated directly from Factory Explorer™'s capacity analysis results, thus no simulation is required to estimate operating expenses.

3. Inputs

"What can be done with fewer is done in vain with more" — William of Ockham [1]

Naturally, to compute factory-level cost measures using a capacity analysis and simulation tool, some additional input parameters are necessary. In deciding which inputs to include in Factory Explorer™, we have followed the principle quoted above, commonly referred to as *Ockham's razor*. This principle argues for the smallest possible set of explanatory (input) variables in any scientific model. That is, we wish to estimate throughput, inventory, and operating expenses, as much as possible, in terms of the input parameters already present in the model. Table 3-1 displays the minimum set of additional input parameters we feel are necessary for this purpose.

Factory Entity	***Additional Input Parameter***	***Used to Calculate…***
Product	Raw Unit Cost	Operating Expense, Product Cost
	Revenue Per Good Unit Out	Dollar-Valued Throughput
Tool	Fixed Cost	Operating Expense, Product Cost
	Depreciation Life	Operating Expense
	Useful Life	Product Cost
	Annual Recurring Cost	Operating Expense, Product Cost
Operator	Hourly Wage Rate	Operating Expense, Product Cost
Process Step	Per-Unit Material and Consumable Cost	Operating Expense, Product Cost

Table 3-1: Cost Input Parameter Summary

In addition to the three factory-level performance measures discussed above (throughput, inventory, and operating expenses), detailed product costing information can be useful. Product cost estimation requires only one additional input parameter beyond those needed for factory-level performance measures – the useful life for each tool. Product costing also requires an assumption about the allocation of shared resource expenses (tool and operator-related expenses) to individual products. Factory Explorer™ allocates shared resource expenses on a time-used basis. For example, if 50% of the processing time at a machine is due to one product, and 50% to a second product, half of the annual cost of the machine will allocated to each product.

Other factory-level costs exist, of course, such as facility depreciation, research and development costs, and marketing expenses. These may be needed to give a complete picture of the cost environment in a factory. The capability to include such costs will be included in future releases of Factory Explorer™. Even without this extension, however, we believe that in many cases more informed decisions can be made by using an integrated cost, capacity, and simulation analysis tool than by using separate, stand-alone applications.

4. Sample Uses

The most obvious use of an integrated cost, capacity, and simulation analysis framework is for evaluating different scenarios on the basis of throughput, operating expense, and inventory. For example, we might want to decide whether an investment in an additional machine is justified. The change would result in increased operating expense, but might lead to increased throughput and decreased inventory expense. Other alternatives, ideally, might be identified that lead to decreased operating expenses and inventory expenses, and increased throughput. By looking at these alternatives in terms of factory-level cost measures, we can perform interactive optimization to identify the best solution. In the following sections, we describe several possible uses for such integrated analysis.

4.1 Evaluating Process Changes

One area where this cost/capacity framework may be particularly useful is in evaluating the impact of process changes. For example, suppose that the engineering department wants to increase the length of a heat-treating operation from 30 minutes per lot to 40 minutes per lot. A capacity analysis will determine whether or not this change decreases factory throughput (if the machine is not a bottleneck, and does not become a bottleneck because of the change, then throughput should not be affected). However, even if overall throughput is not affected, the change will most likely increase inventory, and correspondingly increase cycle times. There could also be an increase in the cost of consumables. By measuring the impact of all of the various changes in terms of dollars, management can understand the true impact of the change, and perhaps work with engineering to find a compromise if the impact is too great. Ultimately, the ability to assess the direct impact of process changes on the profitability of the factory may help drive integration of product design and manufacturing.

4.2 Quantifying Procedural Changes

Another potential use of an integrated framework is in justifying changes in manufacturing for which the benefits are difficult to directly quantify. For example, by altering preventive maintenance (PM) schedules, equipment engineers may be able to decrease variability in the factory. Seven short daily PM events in a week are considerably less disruptive than one long one, particularly if the machine is the only one of its kind. There is no immediate cost justification for this change, and the overall capacity (if the short events take one seventh the time of the long event) does not change. However, by simulating the system to quantify the expected decrease in average cycle times and WIP, the engineers may be able to compute the decrease in dollar value of inventory, and the corresponding increase in cash flow.

4.3 Avoiding Local Optimums

“We are not concerned with local optimums” — Jonah, in The Goal [2]

An additional benefit to the use of factory-level cost measures in decision-making is that they keep us from getting trapped at local optima. Using product cost analysis without considering factory-level performance measures can lead to sub-optimal decisions. For example, suppose a highly automated factory produces two products, AlphaWidgets and BetaWidgets. Raw AlphaWidget and BetaWidget units cost $35 and $25, respectively. AlphaWidget units require 4 hours of production time on the factory’s single milling machine, while BetaWidget units require 6 hours of production time. The milling machine has a fixed cost of $500,000 and a useful life of five years. The current annual sales volume is 800 AlphaWidgets (average sales price $160) and 100 BetaWidgets (average sales price $175). Assume there is no scrap in the production process and that in-process material and consumable costs, tool recurring costs, and operator costs are negligible. The product costing results are summarized in Table 4-1.

Table 4-1: Product Cost Summary

Cost Driver	***AlphaWidgets***	***BetaWidgets***
Raw Unit Cost	$35	$25
Tool Fixed Cost	$105[1]	$158[2]
Total	$140	$183
Sales Price	$160	$175
Item Margin	$20	($8)

From this summary, it appears that AlphaWidgets are a reasonable moneymaker, but every BetaWidget sold results in a $8 loss for the factory. Should the factory continue to produce BetaWidgets and sell them at a loss? From the viewpoint of product cost, it appears the answer is no. However, consider the question from the viewpoint of factory-level performance measures, as summarized in Table 4-2 (assuming a five year depreciation life for the milling machine).

Table 4-2: Gross Margin Summary

Production Volume	***(A) Throughput***	***(B) Operating Expenses***		***(A) - (B) Gross Margin***
		Raw Cost	***Depreciation***	
800 Alpha, 100 Beta	$145,500	$30,500	$100,000	$15,000
800 Alpha, 0 Beta	$128,000	$28,000	$100,000	$0
800 Alpha, 200 Beta	$163,000	$33,000	$100,000	$30,000

Dropping the BetaWidget product does decrease operating expenses, but it causes a larger decrease in dollar-valued throughput. The net result is a decrease in annual gross margin of $15,000. This drop is due to the fact that shared resource costs are not a linear function of production volumes. In this case, even though the production of BetaWidgets falls from 100 units to 0 units, the milling machine fixed cost does not decrease at all. Unless the resulting idle time on the milling machine can be used to make revenue-producing products, the factory is better off continuing with the current production volume of 800 AlphaWidgets and 100 BetaWidgets. In fact, if the annual sales volume of BetaWidgets could be doubled to 200 units, gross margin would increase to $30,000.

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[1] [$500,000 / 5 Years * [800 Units * 4 Hours/Unit / (800 * 4 + 100 * 6)]] / 800 Units per Year

[2] [$500,000 / 5 Years * [100 Units * 6 Hours/Unit / (800 * 4 + 100 * 6)]] / 100 Units per Year

This simplified example shows that local optimization can sometimes lead to globally sub-optimal results. In this case, making a decision to discontinue BetaWidget production on the basis of product cost (a local performance measure) leads to sub-optimal results in terms of gross margin (a global performance measure). Factory gross margin would be better served by an *increase* in sales of BetaWidgets, not a *decrease*.

4.4 Product Mix Optimization

Identifying the 'best' product mix to run in a factory can be very difficult. Focusing on product cost alone, as shown in Section 4.3, can lead to sub-optimal results. If instead we evaluate different mix scenarios in terms of their overall gross margin (calculated from the factory-level performance measures), we can identify as the optimal mix the one that makes the most money for the company. To do this requires having an accurate assessment of available system capacity. For example, suppose that in the widget example above we know that the milling machine has 5000 hours of available capacity per year. Figure 4-1 shows the gross margin that results from considering mix scenarios where the volume of AlphaWidgets is decreased from 900 units per year to no units per year, and the volume of BetaWidgets is chosen to use up all of the remaining capacity (so that the total processing time required remains less than 5000 hours). For this example, the company is better off producing only AlphaWidgets. These are the more profitable part when all of the capacity is being used. However, if AlphaWidget demand decreases, using the remaining capacity to produce BetaWidgets helps make up some of the lost profit.

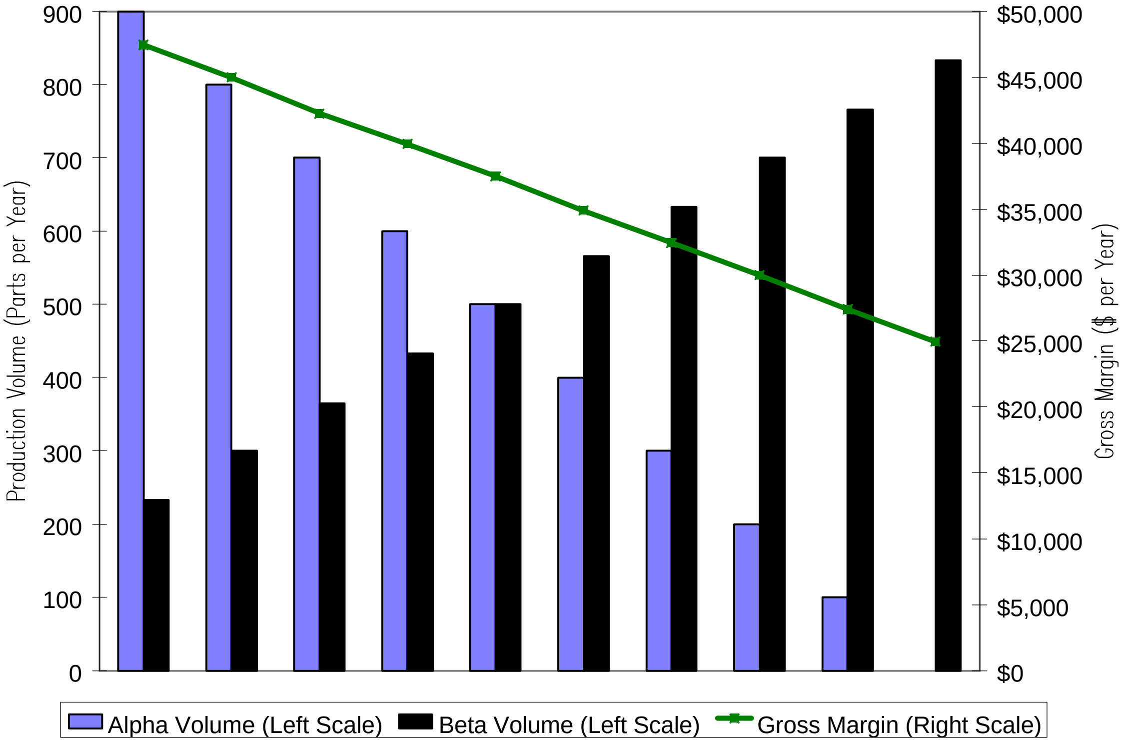

Figure 4-1: Impact of product mix on gross margin.

For this example, if the capacity of the milling machine is known, the calculations to find gross margin can be easily accomplished in a spreadsheet. However, for even slightly more complex scenarios, a spreadsheet quickly becomes cumbersome. For example, suppose that a sequence-dependent setup is required when changing between AlphaWidgets and BetaWidgets. Not only does this setup time reduce the available hours of capacity on the milling machine, but how much the capacity is reduced depends upon the particular mix scenario chosen. When a factory has multiple machines, the situation becomes even more complicated. In some cases the capacity of the bottleneck may be used to approximate the capacity of the system. However, when the product mix changes, the bottleneck often shifts from machine to machine. If the process flow in a factory includes re-entrant flow, batch processing, or rework, the problem quickly becomes difficult to solve with spreadsheet methods. Understanding the effect of different product mix scenarios requires accurate capacity analysis, sometimes accompanied by simulation. Factory Explorer™ provides these capabilities, along with the ability to perform batch analysis of many different mix scenarios. Future releases will extend upon these capabilities and provide more direct cross-scenario output analysis.

4.5 Cycle Time Optimization

As discussed previously, an integrated framework can help make decisions regarding capital acquisition. A logical extension to this is the ability to run an optimization to determine where a limited budget for capital expansion should be best spent, to maximize factory capacity while meeting certain cycle time goals. For example, Factory Explorer's capacity analysis can be used to find a minimum cost toolset for any given process model and product mix. The cycle time for the minimum cost toolset, however, may be quite high. If cycle time is an important customer performance measure, it may be worthwhile to explore the purchase of additional capital equipment to lower cycle times. Using Factory Explorer™, it is possible to interactively optimize cycle time by purchasing additional capital equipment. The end result will likely be a chart similar in form to that shown in Figure 4-2. In future releases of Factory Explorer, this optimization process will be automated as part of the overall system.

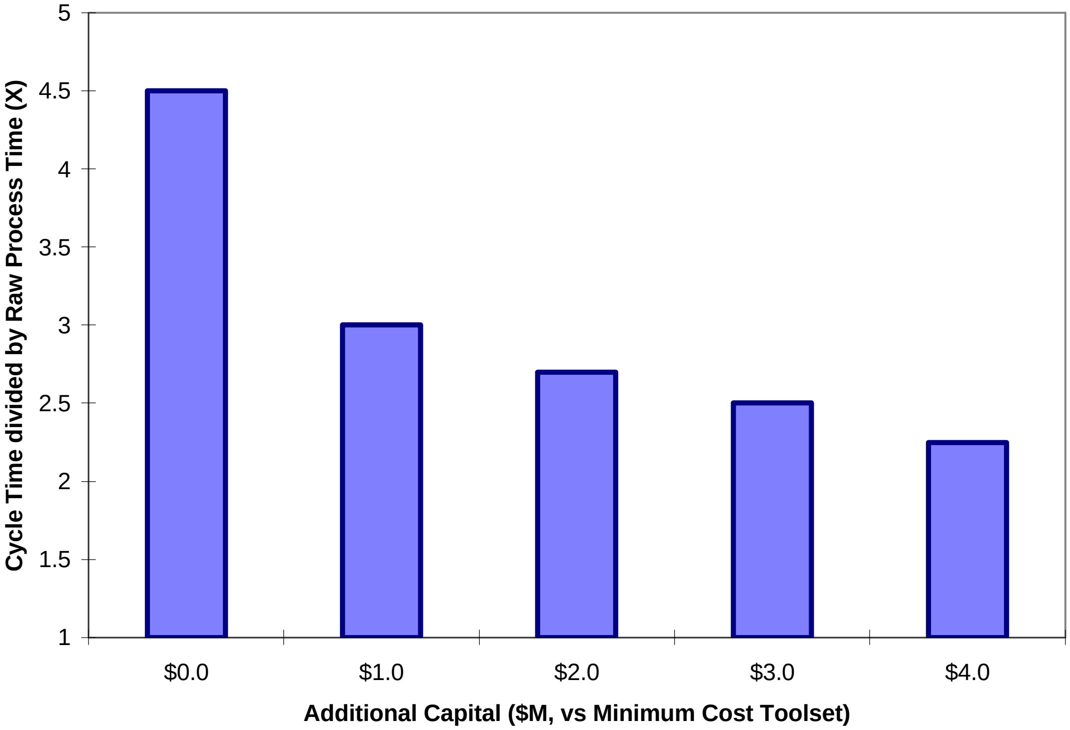

Figure 4-2: Optimizing cycle time with additional capital expenditures.

5. Conclusion

There are a number of advantages to an integrated capacity/cost/simulation framework. The most obvious of these is the ability to make decisions regarding changes in capacity, both large and small, based on their impact on the bottom line. Including the capacity and simulation analyses allows the cost analysis to be conducted based on more accurate, detailed information than can be included in pure static models. Including the cost analysis provides a rational framework for making comparisons between alternatives. Another advantage to an integrated framework is that data maintenance is significantly decreased when working with one model instead of two or three. A single model saves time, money, and effort spent on data entry, and sharply reduces the likelihood of inaccuracy. With an integrated model, there is no need to write conversion programs to move data from one model to the next. The ability to quickly perform analysis based on multiple performance measures opens the door for interactive optimization, especially in the arena of strategic planning. With tight project deadlines and a multitude of options to explore, integrated decision support tools can make the difference between finding a marginal answer and finding a highly profitable one.

6. References

[1] Charles Van Doren, *A History of Knowledge*, Ballantine Books, NY, 1991.

[2] Eliyahu M. Goldratt and Jeff Cox, *The Goal: A Process of Ongoing Improvement*, North River Press, Inc., Croton-On-Hudson, NY, 1986.

7. Author Biographies

Dr. Frank Chance is president and co-founder of FabTime Inc., a provider of cycle time reduction software and associated services for the semiconductor industry. He is a specialist in the modeling and simulation of complex manufacturing facilities. He is the author of the Delphi and Factory Explorer™, integrated capacity, cost, and simulation analysis tools. He was the founder of Chance Industrial Solutions (CIS), which distributes products and consulting services through Wright Williams and Kelly. During 1994-1995, he was a member of the SEMATECH MIMAC (Measurement and Improvement of Manufacturing Capacity) team. Dr. Chance holds M.S. (1991) and Ph.D. (1993) degrees in Operations Research from Cornell University. He has taught at Cornell University and was a visiting assistant professor at the University of California, Berkeley.

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