Unanticipated Side Effects of Successful Quality Programs: Exploring a Paradox of Organizational Improvement

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Recent evidence suggests the connection between quality improvement and financial results may be weak. Consider the case of Analog Devices, Inc., a leading manufacturer of integrated circuits. Analog's TQM program was a dramatic success. Yield doubled, cycle time was cut in half, and product defects fell by a factor of ten. However, financial performance worsened. To explore the apparent paradox we develop a detailed simulation model of Analog, including operations, financial and cost accounting, product development, human resources, the competitive environment, and the financial markets. We used econometric estimation, interviews, observation, and archival data to specify and estimate the model. We find that improvement programs like TQM can present firms with a tradeoff between short and long run effects. In the long run TQM can increase productivity, raise quality, and lower costs. In the short run, these improvements can interact with prevailing accounting systems and organizational routines to create excess capacity, financial stress, and pressure for layoffs that undercut commitment to continuous improvement. We explore policies to promote sustained improvement in financial as well as nonfinancial measures of performance.
(*Organizational Behavior; Quality; Simulation; System Dynamics; TQM*)

1. Introduction

In 1987 Analog Devices, Inc., a leading manufacturer of integrated circuits, initiated a broad-based Total Quality Management (TQM) program. Led by its founder and CEO, Ray Stata, the company introduced TQM into daily activities. Quality improved dramatically: by 1990 product defects had fallen by a factor of 10, wafer yield had nearly doubled, and manufacturing cycle time had fallen by half. One would expect such dramatic improvements to boost the competitiveness of Analog's products, and lead to superior growth and profitability. Yet during the same period Analog's share price fell from $18.75 to $6.25, return on equity fell from 7 percent to −4 percent and Analog was forced into its first-ever layoff. What happened, and why?

The paradox of large improvements in quality that are not followed by financial improvement is not unique. Ernst and Young (1991) found firms pursuing TQM grew no faster and were no more profitable than comparable firms that hadn't. Interest in the Malcolm Baldrige National Quality Award is falling (Fuchsberg 1993), and press reports skeptical of TQM have appeared (The Economist 1992, Taylor 1992).

The case of Analog Devices is intriguing because it defies all the obvious explanations for TQM's unfulfilled promises. Some argue that TQM is merely another management fad and doesn't really work. Yet TQM often yields significant results. The US General Accounting Office found large quality improvements among Baldrige award finalists (GAO 1991), though the same

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study showed these firms realized negligible gains in profitability.

Another common explanation for the indifferent results of many TQM programs is poor implementation. The literature stresses that improvement programs like TQM must be integrated with the firm's strategy and human resource policies (Kochan et al. 1986, Beer et al. 1990, Kaufman 1992, Lawler et al. 1992). Weak leadership, inadequate training and support, misleading metrics, or inconsistent incentives can surely dash a program on the rocks of organizational resistance and internal politics (Kim 1993 documents many such 'TQM implementation false starts'). Such theories predict that poorly implemented TQM programs will not lead to significant improvement. Yet these theories can not explain the case of Analog Devices—its program produced large improvements in quality and productivity.

An alternative explanation suggests it was the recession in the semiconductor industry beginning in 1989 that caused Analog's profits and share price to fall, masking the benefits of TQM. However, this explanation is not sufficient to explain the magnitude of the decline. During the period after the TQM program was initiated (1987 to 1990) Analog underperformed the semiconductor industry in revenue growth, profit, and net worth (Value Line 1991b).

Analog's experience is paradoxical not because TQM failed to improve operations but because financial results did not improve after the TQM program *succeeded*. The resolution of the paradox must lie in the side effects of successful improvement, not in forces that impede change or external economic events.

This paper explores the causes and consequences of the paradox. How does TQM interact with the organization as a whole? How might initial success lead to unintended consequences that thwart continuous improvement? What policies might mitigate such side effects? Our approach involved three steps. First we constructed a detailed history of TQM at Analog Devices using interview, archival, and statistical data (§2). We then generated hypotheses about the decision processes and feedback structures that created that history. Third, we developed a formal simulation model to test these hypotheses and explore policies (§§3 and 4). We use the model to show how successful improvement created excess capacity, lowered earnings and depressed market value, which in turn fed back to undermine continued improvement (§5). We test alternative strategies for the management of TQM (§6), then discuss the implications of the results for organizational change programs in general.

2. TQM at Analog Devices, Inc.

Analog Devices (ADI) makes integrated circuits that convert between analog and digital data. Their products are used in computers, compact disc players, disk drives, medical instruments and similar equipment. Analog has successfully pursued a strategy of technology leadership, seeking to be the first to market with new products offering superior performance. From its founding through the early 1980s sales grew at an average rate of 27 percent per year. "Then for the first time," as Stata (1989) described it, "we missed our five-year goals—and by a country mile." Stata rejected explanations that pinned the blame on the economy. He suspected "that there was something *about* the way we were managing the company that was not good enough," and concluded, "the bottleneck is management innovation."

Analog designed an innovative quality improvement program (Analog Devices 1991), drawing on the principles espoused by many leaders of the TQM movement (Deming 1986, Feigenbaum 1983, Garvin 1988, Shiba et al. 1993). Stata created the office of Quality VP, on the same level as the heads of functions such as engineering and sales, and hired Art Schneiderman, an experienced quality consultant. Analog provided training for personnel throughout the company. Next they introduced the 'half-life system' (Schneiderman 1988), a method for setting realistic quality targets and monitoring performance against them.

The half-life system was based on Schneiderman's (1988) finding that, in a wide variety of firms, "any defect level, subjected to legitimate QIP [quality improvement processes], decreases at a constant [fractional] rate. . . ." The result is an exponential decline in defects characterized by the 'improvement half-life'—the time required for defects to fall by 50 percent.

The basis for the half-life dynamic is the iterative learning loop at the heart of TQM. Improvement teams identify the root causes of defects, rank them in order of importance, then propose, design, test, and implement solutions using the Shewhart/Deming Plan-Do-Check-Act or 'PDCA' cycle (Shewhart 1939, Analog Devices 1991). The team continues to cycle around the learning loop until the root causes of the defect are corrected, then moves on to the next most important source of defects. The rate of improvement can thus be expressed as:

$$\phi = I \cdot L \quad (1)$$

where ϕ is the fractional rate of defect reduction per month, I is the fractional improvement per learning cycle, and L is the number of learning cycles per month. Defects, D, are then given by

$$dD/dt = -\phi(D - D_{\min}), \quad (2)$$

where $D_{\min} \geq 0$ is the theoretical minimum defect level. Thus $D = D_{\min} + (D_{t_0} - D_{\min}) \exp(-\phi(t - t_0))$ and the half-life $t_h = \ln(2)/\phi$.

Improvement half-lives vary across processes and functions. Simple processes like the functioning of a single piece of equipment were found to have half-lives on the order of a few months. Complex processes like product development had half lives on the order of a few years. Schneiderman (1991) hypothesized that half lives grew with both the technical and organizational complexity of a process. Technical complexity is straightforward: a lathe is simpler than a multi-million dollar numerically controlled machine tool. Organizational complexity refers to the number of different organizational units, functions, and types of people involved in a process. Equation (1) explains why the half-life is longer for complex processes: both the improvement per cycle and the learning cycle time depend on the technological and organizational complexity of the process to be improved. Improvement per cycle will be large and the improvement cycle will be rapid for simple processes where experiments can be performed rapidly and results observed immediately, cause and effect are easily discerned, the process is well understood, and few organizational boundaries are crossed. Conversely, improvement per cycle will be lower and cycle time will be longer for processes where experiments are difficult and time consuming, the process is poorly understood, and problem solving requires cooperation and coordination of many people with diverse skills from multiple organizations within and outside the firm.

Analog used the half-life system to set improvement targets for defects, delivery lead time, on-time delivery and new product development time for the five-year plan beginning in 1987 (Stata 1989). They created a 'balanced scorecard' (Kaplan and Norton 1992) integrating these nonfinancial metrics with financial results. The scorecard allowed management to evaluate progress directly and helped create intense competition to improve among the divisions.

By July 1990 Analog had accomplished remarkable results. Defects in product shipped plummeted from 500 to 50 PPM, on-time delivery (OTD) rose from 70 percent to 96 percent, average yield soared from 26 percent to 51 percent, and cycle time fell from 15 to 8 weeks (Kaplan 1990b). Several indicators, however, did not improve. Product development time had not fallen significantly and the stock price had dropped from $24 in July 1987 to a low of about $6 in November 1990, a larger drop than that for the semiconductor industry or the market as a whole. In 1985 operating income was $46.6 million. In 1990, during the recession, it fell to $6.2 million. A senior manager estimated that, with its depressed market value, Analog could have been acquired for about three years cash flow from operations. Responding to the financial crisis, Analog consolidated some of its operations, changed distribution channels, and began to reorient product development away from the core business of standard linear integrated circuits (SLICs) towards emerging markets for special purpose chips (SPLICs) and digital signal processors (DSPs). Analog also acquired one of its chief competitors, Precision Monolithics, Inc. (PMI). Analog took an $18 million charge for expenses related to the restructuring.

The impact of the consolidation and restructuring on the TQM effort was significant. Responding to the financial crisis, consolidating operations, and managing the acquisition were time consuming. Analog sought to avoid layoffs by transferring people to other operations, but the reorganization disrupted TQM activities. A senior human resource manager noted that during this time "TQM couldn't get the attention it deserved."

Reorganizing operations to take advantage of the productivity gains generated by TQM was not sufficient to alleviate the financial stresses. In 1990 Analog was forced to reduce "worldwide employment by nearly 12 percent, while simultaneously transferring approximately 150 manufacturing jobs to our low cost assembly and test operation in the Philippines and Taiwan" (1991 Annual Report, 1). These layoffs were Analog's first. Despite extensive outplacement assistance for the affected workers, morale suffered. The HR manager recalled, "Morale was low, but we got high marks for our efforts to help people." Nevertheless, the consolidation and layoffs "were confusing and threatening to some people." A divisional TQM manager noted "a lot of [employees in a particular plant] were working their tails off for TQM . . . , and their reward was their [operation] was moved to the Philippines in search of lower cost labor. So [TQM] was another path to a layoff." Schneiderman commented, "Up until the layoff the number of QIP teams was steadily growing. After the layoff, TQM stalled. People didn't want to improve so much that their job would be eliminated." By July 1992 OTD fell back to 89 percent, defects and yield stalled at 50 PPM and 49 percent; and product development time had still not fallen significantly (Schneiderman, personal communication). The stock price had increased to about $9.00.

3. The Organizational Dynamics of TQM

Analog's experience illustrates the complexity of quality improvement programs. It is difficult to test hypotheses to explain the impact of organizational interventions such as TQM because it is not possible to conduct experiments with real organizations. Models provide a means to explore the consequences of alternative policies and environmental circumstances in such settings. Capturing complex interventions such as quality improvement programs in a model requires a methodology that can represent the physical and institutional structure of the firm and its markets, that can portray the decision processes of the actors in the system, including the role of soft variables such as workforce commitment, morale, and fear of job losses, and that can deal with multiple levels of analysis (the shop floor, product development, competitor reactions, the stock market). For these reasons we used the system dynamics method (Forrester 1961, Richardson 1991) to develop the theory and build the model.

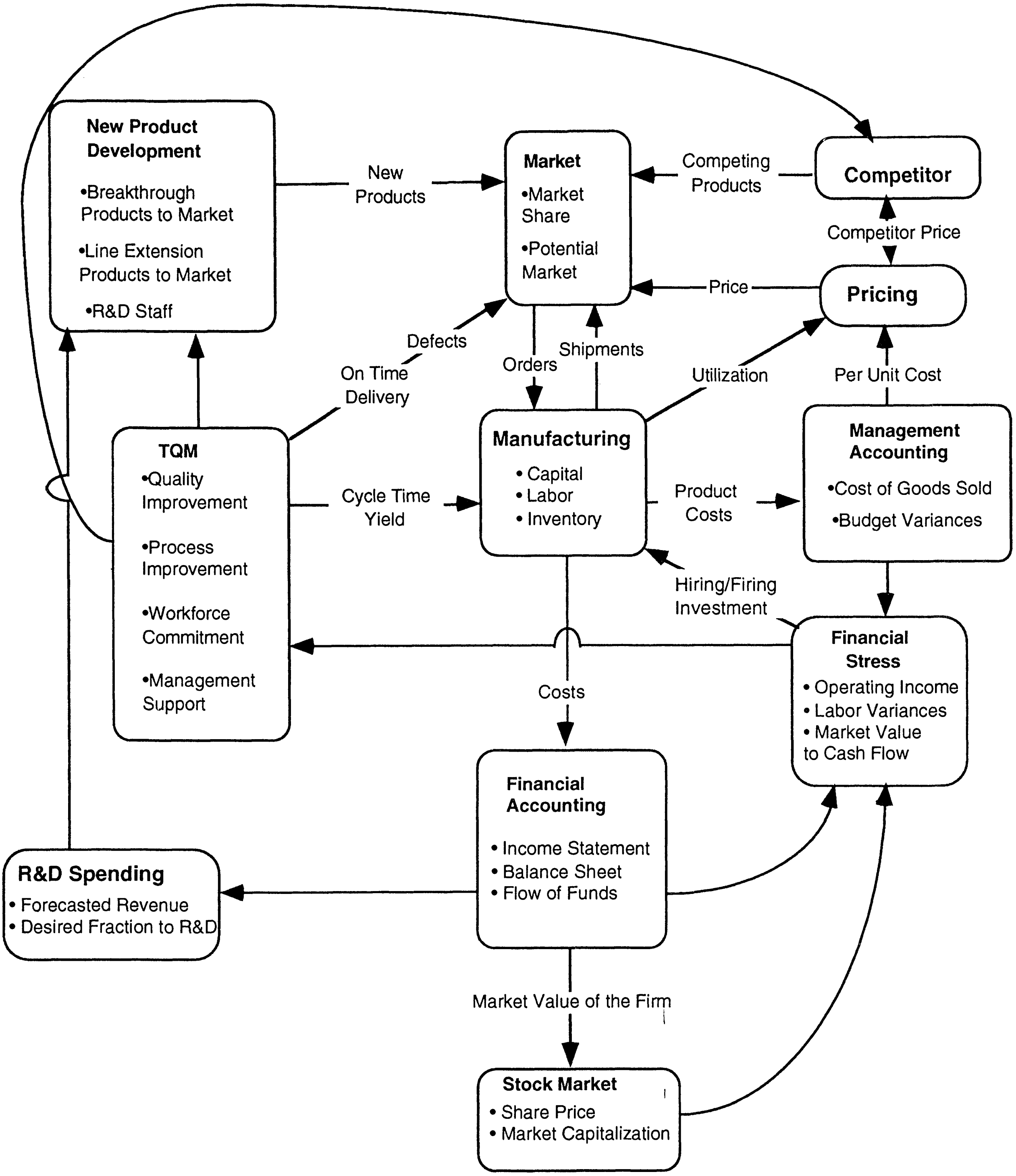
We drew on multiple data sources to develop and test the model. We conducted interviews with key participants in Analog's TQM effort and other personnel. Other primary sources included internal data on quality and product development, and publicly available financial data. Some secondary sources were also available (Kaplan 1990a, 1990b). We drew upon established system dynamics models of the firm (e.g., Forrester 1961, Lyneis 1980, Hall 1976, Morecroft 1985) and experimental studies of managerial decision making (Sterman 1989a, 1989b, Paich and Sterman 1993) to specify model structure and the decision rules for the actors.

The model has a broad boundary (Figure 1). The endogenous elements include a detailed representation of Analog's manufacturing process; a complete set of financial accounts; managerial accounting data such as overhead absorption and labor variances; quality metrics; and motivational variables such as the commitment to TQM of top management and the workforce, and the workforce's perceived job security. The model contains only five exogenous inputs: two price indices to capture inflation; an index of the industry demand for electronic components; the yield of the S&P 500 (a determinant of the discount rate investors use to value ADI's expected earnings); and an index of the diffusion of TQM throughout US industry (a determinant of how quickly Analog's competitors improve as a result of their own TQM efforts). While the model is too large to describe fully here, we discuss two important formulations: the market demand for ADI's products (a hard variable for which good numerical data exist) and the commitment of the workforce to the TQM program (a soft variable for which numerical data do not exist). Complete documentation (Repenning and Sterman 1994) is available from the authors.

3.1. Modeling the Product Life Cycle

The dynamics of demand were critical to the impact of TQM on Analog. Improvements in product development can speed the introduction of new and better products, creating new markets. Market demand is therefore endogenous to the model. ADI's share of the total demand for products in the markets in which it competes is determined by the attractiveness of ADI's

Figure 1 **Overview of Model Structure**



products relative to those of competitors. For a product of given functionality, customers are assumed to judge the attractiveness of ADI's products by considering the price, defect rate, delivery lead time, delivery reliability, and the extent to which the customer depends on ADI as a sole source (indicated by Analog's market share). These attributes are weighted nonlinearly. Attractiveness falls if any of the attributes is particularly poor, for example, if product lead times become excessive, attractiveness plummets even if price remains below the competition.

Following ADI's own practice, we disaggregate the product portfolio into two categories: 'breakthrough' products, those focused on entirely new market segments; and line extensions, incremental improvements to existing products. We describe the formulation for breakthrough products here; we model line extensions analogously.

The number of breakthrough products on the market, B, increases as Analog releases new products and decreases as Analog discontinues old products. The product development subsystem determines introductions and the average product life, τ, determines discards:

$$dB/dt = b^i - b^d, \tag{3}$$

$$b^d = B/\tau, \tag{4}$$

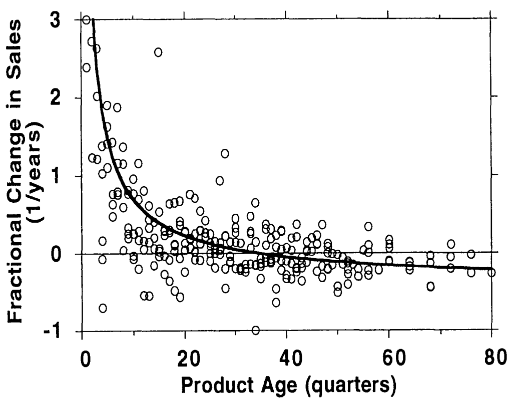
where b^i is the rate of product introductions and b^d is the rate of product discontinuation.

The total demand for breakthrough products, M, increases by an amount μ each time a new product is introduced. Industry demand for those products then grows at a fractional rate g, reflecting the rate of economic growth and the stage of the products in their life cycle. Sales of new breakthrough products typically rise rapidly, then peak and decline as new products and new technologies supersede them (Gort and Klepper 1982). We assume that each time a product is discontinued the total potential market decreases by the average sales per product, M/B. Thus:

$$dM/dt = b^i\mu - b^d(M/B) + gM. \tag{5}$$

The fractional market growth rate, g, is a decreasing function of the average age of the product portfolio, A, and rises with the rate of growth of the computer/electronics industry. We assume

Figure 2 **Dependence of Sales Growth on Product Age**



Model: $g_{i,A,t} = \alpha + \beta(A_{i,t})^{\gamma} + \delta g^e_t + \varepsilon_t$ for product i of age A in year t

Parameter	Estimated Coefficient	Asymptotic Standard. Error
α	-.465	.178
β	6.413	.407
γ	-.743	.088
δ	.052	.914

$\bar{R}^2$ = .51, N = 270.

$$g = \alpha + \beta A^{\gamma} + \delta g^e \tag{6}$$

where g^e is the fractional growth in the index of industrial production of electronic components, our proxy for industry demand. We estimated Equation (6) by nonlinear least squares using a data set ADI provided consisting of annual unit sales for every product introduced between 1970 and 1991. The effect of product age is highly significant, while the economic growth term g^e is not.[1] Sales of typical new products grow at about 100% per year during the first several years (Figure 2). The fractional growth rate slows as the products mature. After six to eight years sales peak and gradually decline until the product is discontinued. While some products enjoy steady sales for a decade, vigorous demand growth requires the continual introduction of new products.

[1] The economic growth index was not significant because of its low variance. Nevertheless, because the economy must influence the demand for ADI's products, we retain g^e in the model with an income elasticity of unity, which is not significantly different from the estimated value.

3.2. Building Commitment to TQM

A hallmark of TQM is employee involvement: improvement teams consist of the same people who do the work (Shiba et al. 1993). Thus the improvement half-life depends not only on the complexity of the process but also on the skills, efforts, and commitment of the workforce. Generalizing Schneiderman's half-life model, Equation (2), we assume the rate of improvement is proportional to both the potential half-life and the commitment of the workforce, C. Because changes in product mix, equipment, or employees may render prior improvements obsolete and introduce new defects, quality also decays towards the initial level D_0 at a fractional rate η:

$$dD/dt = -\phi \cdot C[D - D_{\min}] + \eta[D_0 - D]. \quad (7)$$

The current commitment of the workforce to TQM is defined as the fraction of the workforce currently applying TQM methods at a high level of commitment and competence. Commitment varies from $0 \leq C \leq 100$ percent of the workforce. We model commitment as a diffusion process driven by both a management-led 'push' and a results 'pull' (Shiba et al. 1993):

$$dC/dt = \theta(C^* - C) + wC(1 - C). \quad (8)$$

The first term in Equation (8) captures management's 'push'. When management initiates TQM workforce commitment rises gradually, at a fractional rate θ, towards C^*, the commitment and competency achievable through the leadership and training management provides. The effectiveness of management's efforts to promote TQM, C^*, depends on how much attention management can devote to TQM: C^* falls below 100 percent when, for example, financial stress demands more of management's attention. The second term represents the 'pull' effect generated by results. As more people become involved in TQM, the more they communicate their enthusiasm and successes to others through word of mouth and presentations. Thus the pull effect depends on the current commitment level and the word of mouth effect, w. As commitment approaches its maximum value of 100 percent, the impact of word of mouth necessarily falls; this is captured by the term $(1 - C)$. The pull effect creates a positive feedback loop through which commitment can be self-generating—provided word of mouth is favorable.

Word of mouth can have a positive or negative impact on commitment. We model the sign and strength of the word of mouth effect, w, as depending on the perceived improvement resulting from TQM ('does it work?'), the adequacy of the support for TQM provided by management ('is help available; will TQM effort be rewarded?'), and the security and stability of the workforce ('if we don't move product I might lose my job, so I don't have time for TQM', or 'with this reorganization going on, I don't have time for TQM'). Thus

$$w = f_r\{r\} + f_a\{a\} + f_s\{s\} \quad (9)$$

where $f_r\{r\}$ is the impact of results, r, on word of mouth; $f_a\{a\}$ is the impact of the adequacy of management support, a, on word of mouth; and $f_s\{s\}$ is the impact of perceived job security and stability, s, on word of mouth. The nonlinear functions $f\{\cdot\}$ may be positive or negative.

Sufficiently strong evidence of improvement causes positive word of mouth, but if TQM is perceived to be ineffective word of mouth is negative, so $f_r\{0\} < 0$: employees require evidence that a new program works before undertaking it. Thus $f_r' \geq 0$, and $f_r'' \leq 0$ for $r > 0$.

TQM initiatives require management support in the form of training, assistance, rewards, and release time from normal responsibilities. The adequacy of support, a, is the ratio of the support available to that required. Support requirements are proportional to TQM effort and thus to commitment. Support resources depend on management's focus: if management shifts its attention to financial firefighting or organizational restructuring, support for TQM falls. The assumed relationship is an s-curve such that $f_a\{1\} = 0$ and $f_a'\{\cdot\} > 0$.

Finally, if workers are threatened by layoffs, overburdened by reorganization, or preoccupied by financial crisis, commitment to improvement will fall. We define job security and stability from 0 (financial stress, consolidation and/or layoffs cause severe turmoil) to 1 (workers are confident their jobs are secure). Thus $f_s\{1\} = 0$, and $f_r\{\cdot\} < 0$ for $0 \leq s < 1$.

The interplay of leadership, results, support, and job security determines the dynamics of commitment. The introduction of TQM stimulates a few initial improvement efforts. If support resources are adequate and job stability is high, early results of the improvement effort will encourage others to participate, leading to still greater results. Commitment will grow rapidly and defects will fall. However, if participating in TQM takes too much time away from people's primary responsibilities, or if the productivity gains created by improvement lead to reorganization or layoffs, the effects of inadequate support and low morale can overwhelm the effect of results and cause commitment to fall. Thus the feedbacks from the diffusion of commitment to the rest of the organization are critical. These feedbacks are captured endogenously in the full model and, as will be seen, play a crucial role in the dynamics of TQM at Analog.

4. Comparison to Historical Behavior

Model testing in system dynamics emphasizes a wide range of tests, including tests of model structure as well as correspondence with historical behavior (Forrester 1961, Forrester and Senge 1980, Barlas 1989). The structure and parameters were verified through a series of meetings with various Analog executives. The broad model boundary helps ensure important feedback effects and possible reactions to policies are captured. We assessed the robustness of the model through extreme conditions tests. We conducted tests for both parametric sensitivity and sensitivity to the level of aggregation. We used partial model testing (Homer 1983) to test each major subsystem in the model. In partial model testing the endogenous inputs to each subsystem are replaced with the corresponding historical data. Significant deviations from historical behavior in the output of the subsystem reveal formulation or parametric errors.

We then assessed the ability of the full system to replicate the data. We consider various goodness-of-fit measures including the mean absolute percent error (MAPE) and the Theil inequality statistics (Theil 1966). The Theil statistics partition the mean square error between model output and data among three components: bias (different means); unequal variation (different variances); and unequal covariation (imperfect correlation between the two series). These components of error can be used to diagnose flaws in simulation models (Sterman 1984).

The simulation begins in 1985; most of the historical data run through 1991, when Analog acquired PMI. The acquisition is not incorporated in the model, so comparisons after 1991 are not meaningful. We assess model behavior against twelve variables for which time series data were available (Table 1, Figure 3). The fits for unit sales, revenue, cost of goods sold, R&D budget, and cumulative new products introduced are excellent, with $R^2 \geq 0.91$, mean absolute percent errors ≤ 7 percent, low bias and low unequal variation. The operational measures of performance have more variation than the aggregate measures, so the MAPE tends to be larger. Yield, cycle time, and OTD have MAPE ≤ 13 percent and $R^2 > 74$ percent, and the majority of the error is unsystematic. The MAPE for defects is 22 percent, but $R^2 = 0.91$ and there is negligible bias (the comparatively large error is due to the assumption that TQM starts at the same moment in all activities, while actual start times differed). Model fits for share price and market value/cash flow, a measure of vulnerability to takeover, are good, and most of the error is unsystematic. The largest error is in operating income. Operating income is the small difference of two large numbers (revenue less cost); small errors in either create much larger percentage errors in income. Overall the model's ability to replicate Analog's experience endogenously, from the factory floor to the financial markets, is good.

5. Results: Base Case

TQM in the simulations begins in 1987 with the creation of the office of the VP for Quality, the introduction of the balanced scorecard, and training in TQM methods for managers and the workforce. These activities raise commitment (Figure 4a), leading to initial improvement efforts in various divisions. At first, job security and stability are high and resources are ample to support them (Figures 4b, 4c). The improvements flowing from these initial efforts are widely publicized throughout the company, leading to positive word of mouth that increases commitment still further. As more employees jump on the TQM bandwagon defects begin to fall throughout the manufacturing organization (Figure 3).

As the number of improvement teams grows, management support becomes inadequate. At the beginning Schneiderman and his small staff could provide guidance, support, and cheerleading to the small number of initial projects. As TQM spread, however, line managers

Table 1 Historical Fit of Model, 1985–1991

Variable	MAPE	Bias	Theil Inequality Statistics Unequal Variation	Unequal Covariation	R^2	*N*
Unit Sales	0.04	0.11	0.12	0.77	0.94	6
Sales Revenue	0.03	0.01	0.08	0.91	0.94	24
Cost of Goods Sold	0.05	0.08	0.11	0.80	0.92	24
Operating Income	0.18	0.11	0.25	0.64	0.70	24
R&D Budget	0.07	0.19	0.01	0.81	0.91	24
Cum. Products Introduced	0.04	0.00	0.50	0.50	0.99	24
Manufacturing Yield	0.10	0.16	0.00	0.84	0.82	72
Outgoing Defects	0.22	0.06	0.01	0.92	0.91	24
Mfg. Cycle Time	0.13	0.11	0.02	0.87	0.82	24
On Time Delivery	0.05	0.31	0.05	0.64	0.74	24
Market Value/Cash Flow	0.19	0.16	0.02	0.82	0.82	6
Share Price	0.13	0.21	0.00	0.79	0.81	24

Note: MAPE = Mean Absolute Percent Error between simulated and actual variables. Bias, Unequal Variation, and Unequal Covariation are the Theil Inequality Statistics showing what fraction of the mean square error between simulated and actual series is due to unequal means, unequal variances, and imperfect correlation, respectively. Low bias and unequal variation fractions indicate the error is unsystematic. *N* is the number of data points in the historical series. Theil statistics may not add to 1.00 due to rounding.

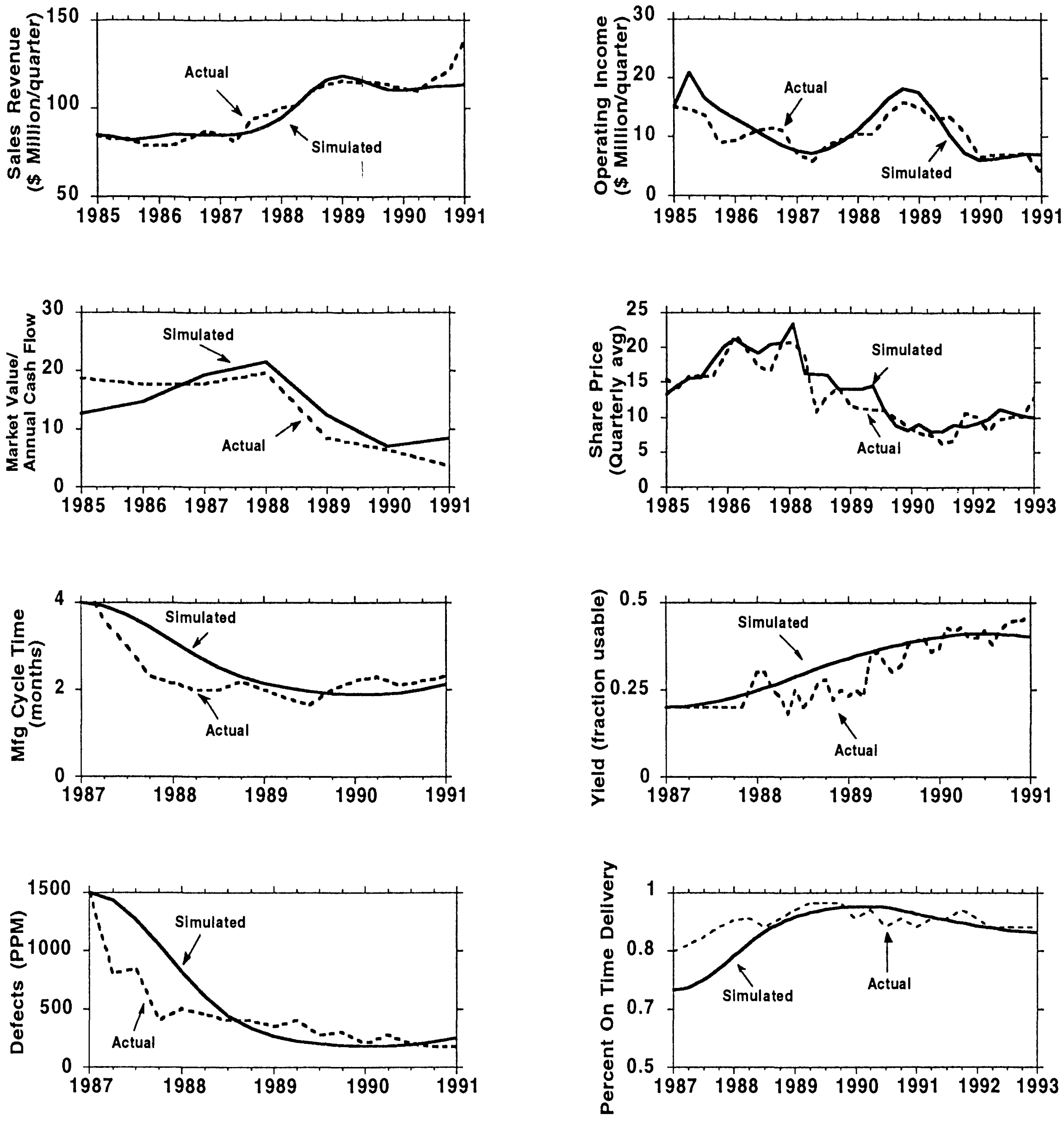
were called on to provide support for their improvement teams. However, their training, experience, and available time were not always adequate, and the quality of support fell (Figure 4c).

Management attention is limited and must be allocated among competing demands. The Quality VP said, "We needed to demonstrate that TQM worked for Analog to bring the skeptical majority on board, so we spent a lot of our time on projects we thought would succeed early on." Thus, we assume managers turn their attention towards areas in which improvements become visible quickly. The result is a pair of positive feedback loops which reward the areas improving faster with the support they need to improve still more, while starving the slow improving areas of resources, further impeding their progress. In the model, as in reality, improvement comes first and quickest in manufacturing, and is slower in product development and other management functions. Thus the manufacturing area receives the lion's share of support resources from 1987 through 1990 as it demonstrates the quickest results (Figure 4d).

In addition to improving operations, Analog had to restructure its strategy and capabilities to align itself better with changes in technology, competition, and customer needs, including a shift of R&D towards SPLICs and DSPs and changes in distribution channels. However, intrinsically greater complexity means improvement half-lives for these activities are long. Worse, commitment to improvement in the product development area lags behind manufacturing, because results have not yet been observed and inadequate support leads to frustration. Schneiderman said, "Many engineers didn't think TQM could improve product development and thought it interfered with their autonomy. The requests for help we received came primarily from the operations side." Stata was more blunt: "There is some closeted cynicism about quality in the company. Among the engineers, it isn't even closeted. They think it's crap" (Jacob 1993). Due to poor support and low commitment, product development times do not exhibit appreciable improvement, despite a potential half-life of 24 months (Figure 4e).

Thus, efforts to speed product development and reorient Analog's capabilities to meet changing customer needs could not stimulate demand fast enough to absorb the capacity created by faster cycle time, higher yield, and fewer defects. However, if

Figure 3 **Selected Comparisons of Simulated and Actual Data**



Note: The last data points show the impact of the PMI acquisition, raising Analog's revenues and expenses above the simulated levels for 1991 because the acquisition is excluded from the model.

higher quality allowed Analog to capture additional market share, sales might rise enough to match the increase in capacity. This was not the case. TQM knowledge is not privately appropriable, and Analog's competitors were not standing still. Analog's simulated market share rises slightly until early 1988

Figure 4a Base Case: Fraction of Workforce Committed to TQM

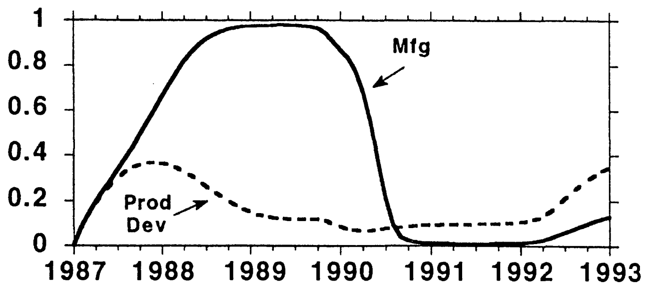


Figure 4b Base Case: Perceived Job Security (0 = No Security; 1 = No Layoffs Believed Possible)

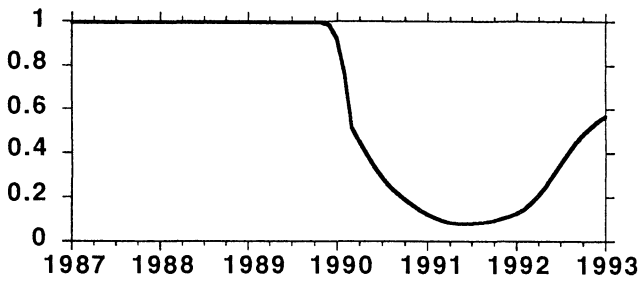


Figure 4c Base Case: Adequacy of Resources to Support the TQM Program

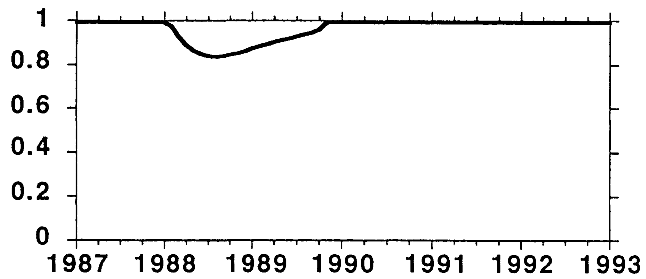
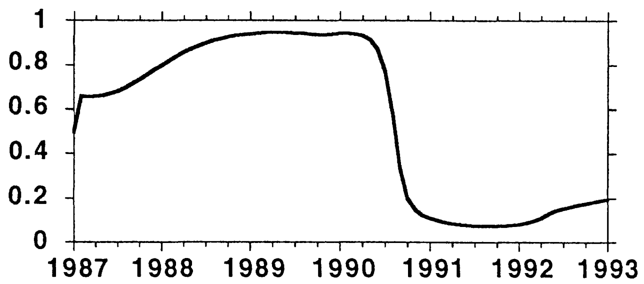


Figure 4d Base Case: Fraction of TQM Support Resources Allocated to Manufacturing

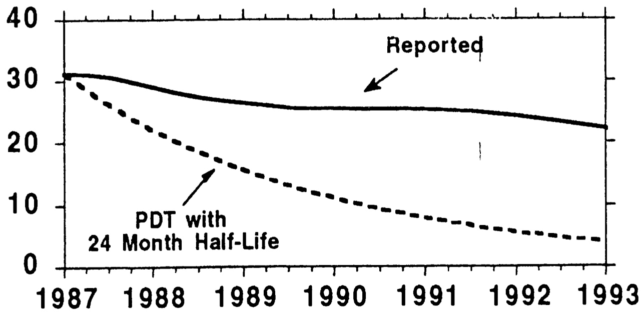


but then falls back despite the large increase in product quality. Through benchmarking, conferences, training, and consultants TQM knowledge diffuses rapidly, so competitor quality improves and prices fall (though with a lag). The industry-wide improvement in quality generated benefits captured by Analog's customers rather than rents or market share advantage for Analog.

As TQM boosted capacity and productivity, Analog's direct costs dropped. Our interviews indicated that Analog used unit direct costs as a key input to the pricing decision. Because Analog offers many hundreds of products, they did not have the ability to allocate indirect costs fully to each product. Instead, as in many firms (see Cyert and March 1963/1992), unit direct costs were marked up by a standard percentage to yield a base price level, which could be adjusted on the margin to reflect market conditions. The traditional markup ratio, a little over 200 percent, was historically sufficient to cover indirect costs and provide a reasonable return. The traditional markup changed only slowly. Between 1985 and 1989, unit production costs fell by about 16 percent, and average selling prices fell by just over 17 percent (Table 2). However, indirect costs per unit fell only slightly. R&D, sales, marketing, distribution, and administration, the drivers of indirect costs, all have high technical and organizational complexity. They have intrinsically longer improvement half lives than the manufacturing activities driving direct costs. And as discussed above, commitment to TQM in these areas was low, further slowing improvement. By 1989 unit indirect costs had fallen only 9 percent. Analog's traditional gross margins were no longer sufficient. Operating income per unit fell by 45 percent (Table 2).

It might be argued that the decline in prices was due entirely to market pressures outside of Analog's control. If so, the drop in profits was not a side effect of TQM but the inevitable result of increased competition. Clearly competition intensified. Business began to shift from defense-related applications towards more competitive consumer markets, and competitors began to produce 'pin compatible' substitutes for some of ADI's products. Note, however, that despite these changes the markup ratio remained remarkably constant (Table 2).

Figure 4e **Base Case: Reported and Target Product Development Time (Months)**



If ADI did not adjust the traditional markup at all, prices would have fallen by exactly 15.8 percent, the decline in unit production costs. Average prices actually fell 17.2 percent, implying intensifying competition and shifting product mix caused prices to fall 9 percent beyond the decline in costs. If prices had fallen only as much as unit costs, operating income per unit would still have fallen 35 percent.

As earnings dropped investment analysts criticized the rising indirect cost fraction and what they took to be ADI's lack of cost control. Value Line's reports were typical:

> ". . . we caution our readers that this company has a history of frequent earnings disappointments." (Value Line 1991a)

> "Sales may be difficult to predict, but it is hard to understand why Analog can not cope with this problem by adjusting expenses accordingly." (Value Line 1991b)

> "Analog needs to develop cost control ability to match its technological skill and sales growth. The company has enjoyed fairly steady revenue increases. . . . Its earnings record has been inconsistent enough, however, to make one think that Analog's priorities are not what investors seek." (Value Line 1992)

Between 1987 and 1990 both actual and simulated stock prices fall (Figure 3) as earnings decline and growth slows. The drop in market value makes Analog vulnerable to takeover (an acquirer could pay off the cost of gaining 51 percent control with just three years of cash flow; Figure 3). Pressure to boost share prices by cutting costs and trimming excess capacity leads to the layoff. The simulated layoffs occur in mid-1990, roughly the same timing as in reality. Job security and stability plummet (Figure 4b) and commitment to TQM falls (Figure 4a): managing the consolidation takes time away from TQM, and the anxiety and disruption caused by the layoffs hurt morale. Improvement stalls, and on time delivery falls (Figure 3), eroding Analog's competitive position. Schneiderman recalled: "In 1989, thanks to our TQM program, we made it to number one on H[ewlett] P[ackard]'s list of top ten suppliers. After TQM stopped in 1991, we became number two on their list of ten worst suppliers."

The base case shows that TQM unquestionably benefited the company. Rapid improvements in yield and cycle time boosted productivity, lowered unit costs and roughly doubled Analog's production capacity. Schneiderman commented in 1992 that "When I arrived we were expecting to have to build a new wafer fab for about $100 million. We still haven't had to build it because yield doubled." But TQM also created unanticipated side effects. Management's desire to build commitment rapidly by demonstrating early results focused attention on operational issues and slowed progress in new product development, contributing to excess capacity. TQM created excess capacity and disrupted the historic relationship between direct and indirect costs, a relationship embedded in organizational norms for

Table 2 **Changes in Cost Structure Caused by TQM Interacted with Pricing Policy to Yield Lower Profit**

	Historical Data		
$/unit	1985	1989	%Δ
Avg Selling Price	16.32	13.51	−17.2
− Cost of Goods Sold	7.61	6.41	−15.8
= Gross Profit	8.71	7.10	−18.5
− Indirect Costs	6.35	5.80	−8.7
= Operating Income	2.36	1.30	−44.7
Markup Ratio (%) = 100* (ASP/COGS)	214	211	−1.7

Note: All figures expressed per unit sold. %Δ column shows the change as a percent of the 1985 value.

Source: Sales Revenue, COGS (Cost of Goods Sold), and Operating Expense Data from 1987 and 1989 Annual Reports. Unit Sales Data provided by ADI. Indirect costs include General, Sales, Marketing, R&D, and Administrative expenses.

price setting. Because unit production costs fell faster than indirect costs, the traditional markup was no longer adequate, leading to lower operating income, lower stock prices, financial stress, and ultimately, to layoffs.

5.1. Analog Devices Since 1992

Though the side effects of successful improvement were severe, by mid 1993 Analog had recovered significantly. With lower costs, the economic recovery, and the 1990 acquisition of Precision Monolithics, operating income had grown to $101 million on sales of $773 million in 1994. The stock price rebounded to about $21/share by the end of 1994, a rise of more than 230 percent from the 1990 level, compared to a rise of about 40 percent for the S&P 500 as a whole.

TQM at Analog rebounded as well. Our interviews show that morale among employees has recovered significantly from the lows of 1990–91. A second wave of TQM activity is underway. Unlike the first wave, current efforts emphasize improvements in product development and the other drivers of indirect costs. Stata is personally involved in many of these quality efforts, chairing the quality steering committee and attending the annual 'QIP-fests'—gatherings where TQM successes and methods are shared.[2] These meetings have attracted growing numbers of teams since they began in 1990, and a growing fraction of these teams come from engineering, sales, and administration. In 1993 market research firm Dataquest named Analog "the best midsize semiconductor supplier for the second year in a row" (Jacob 1993, 67).

Most of these developments were predicted by the model. Figure 4b shows simulated job security recovering after 1991 as improving financial results boost morale. As morale recovers, a second wave of TQM begins in the model around 1992 (Figure 4a). The second wave, as in reality, stresses improvement in product development and the other drivers of indirect costs (Figure 4a, 4d). Both the simulated and actual stock price rebound from the 1991 lows (Figure 3). These developments arise endogenously in the simulation and emerged from the model before the evidence for the rebound of TQM activity and financial improvements was available.

[2] Schneiderman left Analog at the end of 1992 and became an independent consultant.

6. Policy Tests

6.1. Analog Does Not Implement TQM

The base case shows Analog's success in improving operations led to unanticipated side effects that contributed to financial stress, downsizing, and consequent collapse of commitment to TQM. The obvious question is 'what would have happened if Analog had not implemented TQM?'. We ran a simulation identical to the base case except that TQM is never implemented. Without the productivity gains stemming from TQM, Analog's costs and investment needs remain high, reducing competitiveness. And though ADI's success spurs the competitors to pursue TQM in the base case, they eventually adopt TQM on their own even when Analog does not. As competitor quality outstrips ADI's, and as customers demand their suppliers meet higher standards, the simulated no-TQM Analog quickly loses market share. Revenues fall 80 percent from base case levels by the beginning of 1991 and the stock price plummets. The simulated Analog is forced into layoffs in 1989, earlier than the base case. Without TQM the company would most likely have been taken over or forced to exit the industry. While the speed of the decline in the simulation is sensitive to the assumed rate at which competitors adopt TQM, there is little doubt that competitors and customers would have pursued TQM even if Analog did not. Though TQM caused unanticipated stresses, the alternative was worse.

6.2. Maintaining the No-Layoff Policy

One of Deming's (1986) precepts for success is to "drive out fear." Since the 1990 layoffs eroded commitment to TQM, we test a policy in which Analog maintains its traditional no-layoff policy. The goal is to keep commitment and morale high so that improvement continues—employees know that ADI will never lay them off, regardless of any excess labor capacity.

Guaranteeing job security intensifies the tradeoff between short and long term effects. In the short run

Table 3 Policy Analysis

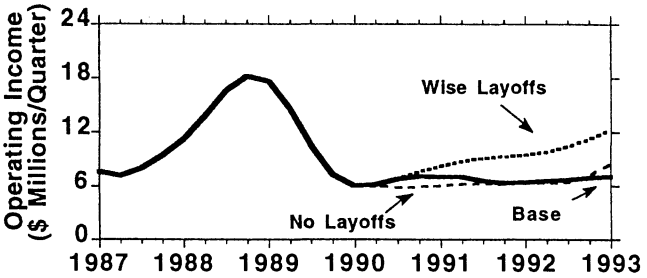
	1991							1993						
Variable	Base Case	No-Layoff	%Δ	Wise Layoff	%Δ	Increase Margin	%Δ	Base Case	No-Layoff	%Δ	Wise Layoff	%Δ	Increase Margin	%Δ
Revenue ($ Million/qtr)	113	114	1	114	1	114	1	124	132	6	137	10	134	8
Operating Income ($ Million/qtr)	6.9	5.9	−14	8.2	19	10.9	58	7.0	8.5	21	12.2	74	17.8	154
R&D Expenditure ($ Million/qtr)	17.6	17.7	1	17.7	1	17.8	1	18.7	19.6	5	20.1	7	19.7	5
Work Force in Mfg (people)	1465	2225	52	1467	0	2074	42	1357	1879	38	1248	−8	1697	25
Comm to TQM in Mfg (dimensionless)	0.01	0.50	0.49*	0.52	0.51*	0.92	0.91*	0.13	0.35	0.22*	0.46	0.33*	0.72	0.59*
Comm to TQM in PD (dimensionless)	0.09	0.08	−0.01*	0.09	0.00*	0.22	0.13*	0.35	0.40	0.05*	0.50	0.15*	0.41	0.06*
Breakthrough Products on the Market	279	278	0	279	0	295	6	315	319	1	323	3	328	4
Manufacturing Yield (%)	0.40	0.42	5	0.42	5	0.44	10	0.37	0.41	11	0.43	16	0.46	24
Outgoing Defects (PPM)	250	193	−23	192	−23	170	−32	432	277	−36	235	−46	180	−58
Mfg Cycle Time (months)	2.11	1.94	−8	1.93	−9	1.85	−12	2.64	2.22	−16	2.10	−20	1.88	−29
OTD (dimensionless)	0.94	0.96	2	0.96	2	0.97	3	0.89	0.93	4	0.94	6	0.96	8
Product Development Time (months)	27.0	26.9	0	26.9	0	26.2	−3	26.1	26.0	0	25.0	−4	24.3	−7
Stock Price ($/share)	7.96	7.32	−8	8.91	12	15.06	89	9.93	10.26	3	19.80	99	28.40	186

No Layoffs: Layoffs prohibited; workforce can fall through attrition.
Wise Layoffs: The function $f_s\{s\}$ is set identically to zero (see eq. 9), so that layoffs have no impact on commitment to TQM.
Increased Margin: 5% Increase in target margin phased in from 1988–1989.
* The values in the '%Δ' column for Commitment to TQM in Manufacturing and Product development are absolute differences.

performance is worse (Table 3, Figure 5). Maintaining the no-layoff policy does keep commitment to TQM from collapsing. Nevertheless, quality improves only slightly by 1991 compared to the base case. The main near term effect is to keep ADI's costs from falling, reducing profit and the stock price further below base case levels. By 1993, however, the policy outperforms the base case, yielding higher quality, revenue, profits, and stock price.

The no-layoff policy does little in the short run because Analog's problems arise from the side effects created by the success of TQM before the layoff. TQM stalled after the layoff, but by then the 'damage'—the excess capacity, under-absorbed overhead, and reputation for poor cost control—was done. Maintaining job security does nothing to prevent these pressures from arising; rather it intensifies them. Note that despite the no-layoff policy, commitment to TQM in operations falls from nearly 100 percent in 1988 to 50 percent by 1991 (Table 3). With higher labor expense and a lower stock price, the ratio of market value to cash flow falls below the already dangerous levels of the base case, intensifying the threat of takeover. Even more of management's attention is diverted to short-term financial firefighting, further eroding commitment to TQM. Job security is no guarantee of TQM success, and may be self-defeating.

Figure 5 A No-Layoff Policy Causes a Long-Term/Short-Term Tradeoff in Financial Results
The 'Wise Layoff' Policy, Where Job Cuts Have No Impact on Morale or TQM Effort, Moderates the Tradeoff



6.3. Maintaining Morale While Downsizing

The no-layoff case illustrates a strong tradeoff between short and long run effects, a tradeoff Analog might not have survived. We now test a policy of 'wise layoffs' to consider how commitment to improvement can be maintained while still cutting costs. We test a perfect, costless policy in which layoffs have no effect on employee commitment to TQM (the function $f_s\{s\}$ is set to zero). Though unrealistic, the perfect policy provides a benchmark to assess the potential of policies that might reduce the turmoil and low morale associated with downsizing.

The wise layoff policy mitigates the tradeoff (Table 3, Figure 5). Employment in 1991 falls by as much as in the base case, but because commitment to TQM remains high there is further quality improvement, leading to higher profit and share price. By 1993 the policy outperforms the no-layoff case. Nevertheless, the company still experiences severe financial stress: profit and market value fall between 1989 and 1991, forcing Analog to lay off a significant number of workers. Note that because the policy leads to even greater improvement in productivity, simulated 1993 employment is 8 percent lower than the base case despite a 10 percent increase in sales. While policies addressing employment security and morale speed Analog's recovery from the crisis, even perfect management of human resources does not prevent it.

6.4. Maintaining Operating Margins

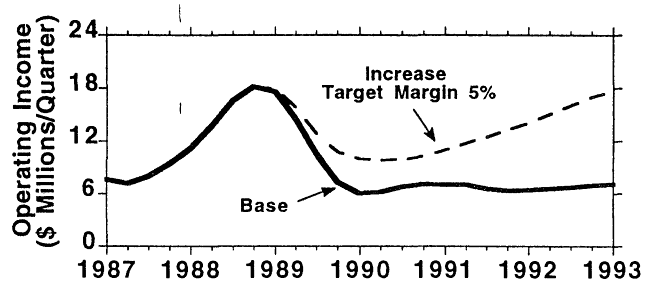
The unbalanced rate of improvement caused two critical side effects at Analog. First, productivity grew faster than demand, creating excess capacity. Second, direct costs per unit (driven by progress in manufacturing operations) fell faster than indirect costs per unit (driven by progress in R&D, sales, and administration). Price-setting, however, continued to reflect the traditional cost structure, eroding operating profit as indirect costs, though falling, became a larger share of unit costs. The inadvertent erosion of profit margins contributed significantly to the financial stress that led to the layoff, in turn causing the TQM effort to falter.

To maintain the 1985 ratio of operating income to sales (on a per unit basis), the markup ratio in 1989 should have been 223 percent, about 5 percent higher than the actual value (Table 2). We test this policy by assuming Analog increases the markup ratio 5 percent between 1988 and 1989. Prices still fall from the 1985 level, though more slowly, to compensate for the slower rate of improvement in indirect costs compared to direct costs.

The policy leads to superior performance (Table 3, Figure 6). The higher price policy has little effect on revenues in 1991 compared to the base case, but operating profits and the share price rise more than 50 percent. By 1993 the higher margin policy yields a substantial increase in revenue and boosts operating profit and the stock price by over 150 percent compared to the base case.

The higher margin policy is effective even though we assume the long-run elasticity of demand with respect to price is greater than unity. Under the higher margin policy Analog does trade off volume for improved profitability. However, because higher margins improve operating profit, the share price does not fall as much as in the base case, easing the pressure to cut costs and

Figure 6 Raising Markups to Compensate for the Slower Reduction in Indirect Costs Improves Financial Performance



reducing the threat of takeover. Better financial results allow the simulated Analog to avoid layoffs. Without the disruption and morale effects of downsizing, commitment to TQM remains high and quality continues to improve. By 1991 the higher margin policy produces higher yield, lower defects and cycle time, and improved delivery performance compared to the base case, boosting product attractiveness and further lowering unit costs, partially offsetting the effect of higher margins. The increase in revenue caused by higher margins also leads to higher R&D spending and thus a greater number of new products. More new products increase total demand, offsetting the reduction in market share caused by higher prices.

The higher margin policy illustrates the complexity of the feedback processes governing the dynamics of quality programs. Because we assume demand is more than unit elastic, higher margins would reduce revenues and hurt the firm—if all else remained constant. Instead, higher quality, lower unit costs, and the introduction of additional new products offset the effect of higher margins so that the number of units shipped is nearly the same as the base case despite higher prices. Most important, higher profits reduce the pressure from Wall Street to cut costs, so commitment to improvement remains higher.

The results of the higher margin policy are contingent on a variety of assumptions, particularly customer preferences and competitor behavior. Sensitivity analysis shows the benefits of the higher margin policy fall as the elasticity of product attractiveness to price increases, as the lag in the response of customers to price changes shortens, and as the competitors' ability to cut costs improves. On the other hand, to the extent competitors follow Analog's lead in pricing rather than aggressively cutting price as their own costs fall, the benefits of higher margins would be even greater. Likewise, the higher margin policy will be more beneficial to the extent Analog can speed new products to market, increase the quality of their products, or lock customers in to its own products by offering new products not yet cloned by the competition.

7. Discussion

Analog's TQM experience appears paradoxical because significant improvements in quality were followed by deterioration in financial results. The resolution of the paradox is the recognition that the link between successful improvement and financial results is more complex than the widespread belief that financial benefits must soon follow successful process improvement. Improvement programs are tightly coupled with the other activities of the firm, along with its customers, competitors, and the financial markets.

A core result of the model is the unbalanced impact of improvement activity on different parts of the organization. The processes with low complexity and rapid improvement rates tend to be capacity augmenting, while demand-generating activities like new product development, customer needs assessment, and reorientation of product mix and distribution strategy have high complexity and slow improvement rates.

A simple calculation reveals how fast productivity can grow before creating excess capacity. The fractional rate of change of a firm's labor requirements, l^*, is given by the fractional growth in sales, s, less the fractional rate of productivity growth, p:

$$l^* = s - p. \tag{10}$$

Given the fractional attrition rate from the labor force (denoted 'a'), the maximum rate of productivity growth consistent with a no-layoff policy is:

$$p \leq s + a. \tag{11}$$

Thus the more successfully an organization improves its manufacturing operations, the more intense the tradeoff will be. From its founding through 1985, Analog's sales growth averaged 27 percent per year. Throughout much of this period the New England economy was booming, and turnover was high—a senior human resources manager estimated it to be 10 to 20 percent per year—as employees readily found new opportunities in the vigorous electronics industry. During the boom, productivity growth of 40 to 50 percent per year could have been accommodated by sales growth and normal attrition. However, as growth faltered and unemployment rose, voluntary quits shrank to less than 5 percent per year. With negligible attrition and sales growth less than 10 percent a year, even small rates of improvement necessarily led to excess employment.

The confluence TQM with a weak economy and low attrition is not coincidental. Many companies implement quality programs in reaction to the competitive pressures caused by slow demand growth. A weak economy also suppresses voluntary turnover. TQM has become popular in the US precisely when firms are least able to absorb productivity gains without layoffs.

Our analysis applies not just to TQM but to any improvement technique, such as business process reengineering, that depends for its success on the efforts or cooperation of employees. The faster productivity rises—regardless of how the gains are achieved—the greater the risk of excess capacity. The dilemma has not received sufficient attention. For example, Bluestone and Bluestone (1992) suggest firms create commitment to improvement programs by guaranteeing job security if the workers can boost productivity by, they suggest, 6 percent a year. In mature industries where sales growth is less than 6 percent a year, the productivity improvement can only be absorbed if attrition is high or if market share can be increased at the expense of competitors. Obviously, competitors will not accept such losses meekly, raising the specter of price wars that undermine profits and force the firm into layoffs.

At Analog the dilemma was acute. Analog's history of employment security meant the first layoff would have enormous symbolic impact. The other horn of the dilemma was equally sharp. Analog's customers were demanding higher performance, and competition was intensifying. Failure to improve would have threatened Analog's industry leadership and, perhaps, its very survival.

The dilemma is intensified by the belief that people will not participate in improvement programs unless they can see the benefits right away. On one hand, academics and practitioners assert that "successful change programs begin with results" (Schaffer and Thomson 1990). Early results are widely advocated to demonstrate the validity of a program, kick-start diffusion and boost the virtuous cycle of commitment and effort (Shiba et al. 1993). On the other hand, a focus on quick results biases decisions against innovations with long time delays and leads to myopic resource allocation. Focusing on early results may lead to excess capacity, financial stress, downsizing, and the collapse of commitment to the program. Improvement programs can fail not in spite, but precisely because of their early success.

TQM represents a significant advance in tools for organizational learning. Yet TQM is also limited. TQM relies on tools and processes that assume the separability of causes in the system under study. TQM as currently practiced assumes a quality improvement team can rank the causes of defects for a given process and address them sequentially. Tools such as Pareto charts and Ishikawa diagrams produce lists of causes of different defects. Efforts to improve different processes often progress independently of one another—a plant might have dozens of different improvement teams operating simultaneously. TQM implicitly assumes that the world can be decomposed into independent causes generating independent effects.

Decomposition is a time-honored problem solving strategy (Simon 1969). It often works effectively, provided the process under consideration is not strongly coupled to other systems. When couplings are strong, however, decomposition may lead to ineffective policies. Worse, piecemeal policies may intensify the problem (Forrester 1971, Ackoff 1978) or even lead to catastrophe (Perrow 1984). Decomposition methods ignore feedback processes and discount time delays and side effects. Decomposition in complex, tightly coupled dynamic systems optimizes the parts at the expense of the whole and the present at the expense of the future.

While many couplings on the factory floor, where TQM evolved, are weak, couplings at the upper management level are strong. Customer needs assessment, product development, strategic planning, organization design, and resource allocation involve high technical and organizational complexity. For example, a product development team is tightly coupled with other functions within the firm (process engineering, marketing, finance, etc.) and with many organizations outside the firm (customers, vendors, competitors, etc.). Experiments to evaluate different ways to translate customer requirements into product specifications take months to carry out, and face many confounding variables (see Burchill 1993 for a compelling example). Available TQM tools can not lead to rapid improvement when couplings are tight, time delays are long, and feedback is ambiguous. Tools and processes to help redesign complex activities like product development are less mature than the TQM methods that proved so effective on the factory floor. Stata commented "The thing that hung us up for the longest time in the product development [PD] area is that we didn't have anybody in the company who had a clue as to how to improve PD. It wasn't that we didn't think it was important, but how do you do it?"

The next generation of TQM tools should help managers understand the long-term, organization-wide consequences of their actions. Several techniques have been proposed to address these problems. These include concept engineering (Burchill 1993), quality function deployment (Hauser and Clausing 1988), Hoshin planning (Shiba et al. 1993), soft systems methods (Checkland 1981), and simulation and gaming (Morecroft and Sterman 1994). Further research and field tests are needed to assess the effectiveness of these tools.

Analog had all the information needed to anticipate the dynamics of TQM described here. Their own data suggested improvement half-lives of less than a year in capacity-augmenting activities like yield, defects and cycle time and longer than three years in demand-generating activities like product development (Stata 1989). While uncertainties would obviously be greater ex ante, the results depend on fundamental structural features that are not in doubt: manufacturing improves faster than product development; direct costs fall faster than indirect costs; success generates enthusiasm and leads to further effort; competitors do not stand still. What Analog lacked was a framework enabling them to understand the implications of their knowledge. Stata reflected, "We didn't have a deep enough appreciation for the complexity we faced in our systems. Typical managers today are just not skilled at that, even high up."[3]

[3] We are grateful to the people of Analog Devices, particularly Ray Stata and Art Schneiderman, for their outstanding help in this research. They generously provided their data and considerable amounts of their most precious resource—their time. Most important, they approached the important questions here in a genuine spirit of inquiry. We also thank Gary Burchill, John Carroll, Charlie Fine, Steve Graves, Paul Healy, Bob Kaplan, Daniel Kim, Tom Kochan, William Pounds, Jim Rebitzer, Elizabeth Saltonstall, Peter Schmidt, Marcie Tyre, the referees, participants in the 1993 Operations Management Summer Camp and seminar participants at MIT, Harvard, the University of Chicago, and the University of Illinois for constructive criticism and helpful suggestions. Comments are welcomed. Please direct correspondence to John Sterman at MIT, E53-351, Cambridge, MA, 02142 or ⟨jsterman@mit.edu⟩. This work was supported by the Organizational Learning Center, MIT Sloan School of Management, and by the National Science Foundation, Transformations to Quality Organizations program, Grant SBR-9422228.

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