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

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Abstract

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 pressures for layoffs that undercut commitment to continuous improvement. We explore policies to promote sustained improvement in financial as well as nonfinancial measures of performance.

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, semiconductor 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% to -4% 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. The Wallace Co., a 1990 winner of the Malcolm Baldrige National Quality Award, suffered large losses soon after winning the prize. Despite laying off more than one-fourth of the workforce to cut costs, the company filed for bankruptcy protection in 1991. 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 doesn't really work, that TQM is merely another management fad. Yet there is considerable evidence that TQM often results in significant defect reduction and quality improvement. The US General Accounting Office found that quality improved substantially among twenty finalists from the first two years of the Baldrige Award competition (GAO 1991). Yet the same study showed these firms realized negligible improvements in return on assets and return on sales.

Another common explanation for the indifferent results of many TQM programs is poor implementation. The human resources and organizational development literatures stress that improvement programs like TQM must be integrated with the overall strategy of the firm including human resource policies such as employment security (Kochan, Katz, and McKersie 1986, Beer, Spector, and Eisenstadt 1990, Kaufman 1992, Lawler, Mohrman, and Ledford 1992). Weak leadership, insufficient training and support, inadequate metrics or counterproductive incentives can surely dash a program on the rocks of organizational resistance and internal politics. Field studies conducted at MIT have documented many such 'TQM implementation false starts' (Kim 1993, Kim and Burchill 1992). 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 severe recession in the semiconductor industry beginning around 1989 that caused Analog's profits and share price to fall, masking the benefits of TQM. However, these explanations are not sufficient to explain the magnitude of the decline. The recession did slow growth, but 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 TQM experience is paradoxical not because TQM failed to improve operations but because its 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 in 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 (section 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 (sections 3-4). 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 (section 5). We test alternative strategies for the management of TQM (section 6), then discuss the implications of the results for organizational change programs such as TQM.

2. TQM at Analog Devices, Inc.[1]

Analog Devices (ADI) makes integrated circuits and systems that convert between analog and digital data. Their products are used in equipment such as computer disk drives, compact disk players, and medical instruments. Analog has about 5200 employees and worldwide operations and sales. In fiscal 1992 operating profits were $26 million on sales of $567 million.

Analog has successfully pursued a strategy of technology leadership, seeking to be the first to market with new products offering superior performance. Analog's strategy enabled it to dominate the high-end niche of the market. From its founding through the early 1980s sales grew at an average rate of 27% 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." To pursue his vision, Stata helped create the Center for Quality Management, an industry-university consortium dedicated to the development and diffusion of TQM knowledge throughout American industry (Walden and Lee 1992).

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, Ishikawa 1985, Garvin 1988, Juran 1988, Shiba, Walden and Graham 1993). Stata created the office of Quality VP, on the same level as the heads of traditional 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. Finally, they created a 'balanced scorecard' (Kaplan and Norton 1992) linking these targets to incentives and performance evaluation.

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%.

The basis for the half-life dynamic is the iterative learning loop at the heart of TQM. Participants in quality improvement processes diagnose the root causes of the defects in any process and rank them in order of importance using Pareto charts and Ishikawa diagrams (Analog Devices 1991). They then design, test, evaluate, and implement solutions using the

Shewhart/ Deming Plan-Do-Check-Act or 'PDCA' cycle (Shewhart 1939, Walton 1986). The team continues to cycle around the learning loop until the defect is corrected, then moves on to the next most important defect. The fractional rate of improvement can thus be expressed as:

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

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 at time t, D, are then governed by

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

where $D_{min} \geq 0$ is the theoretical minimum defect level. Thus $D = D_{min} + (D_{t0}-D_{min})\exp(-\phi(t-t_0))$ and the half-life $t_h = \ln(2)/\phi$.

Improvement half-lives vary across processes and functions. Figure 1 summarizes the relationship Schneiderman hypothesized between the technical and organizational complexity of a process and its improvement half-life. Comparatively simple processes like the functioning of a single piece of equipment on the factory floor 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. Equation (1) explains why: Both the improvement per cycle and the number of cycles per month 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 implemented rapidly and the results observed immediately, cause and effect are easily discerned, the process is well understood, problem solving teams involve fewer people from fewer functional backgrounds, and few organizational boundaries and layers 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, problem solving involves coordination and cooperation of many people with diverse skills and interests, and multiple organizations within and outside the firm are involved.

Analog used the half-life system to set performance targets for product defects, delivery lead time, and on-time delivery performance for the five year plan beginning in 1987 (Stata 1989). They designed a balanced scorecard that displayed, for each division, the predicted and actual performance on a variety of nonfinancial measures of performance. The scorecard (table 1) summarized financial and nonfinancial metrics in a convenient format, allowing management to evaluate progress objectively.[2] The scorecard also identified divisions with exceptionally good or poor performance, generating intense internal competition to improve.

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% to 96%, average yield soared from 26% to 51%, and cycle time fell from 15 to 8 weeks (Kaplan 1990b). Several indicators, however, had not improved. 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 for management and employees. Analog sought to avoid layoffs by transferring people to other operations, but such 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%, 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. While Analog provided extensive outplacement assistance for the affected workers, the effect on morale was substantial. 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 manager of the TQM activity in one of the divisions 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%, outgoing defects and yield stalled at 50 PPM and 49%, respectively; 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 the real organizations. Models provide a means to explore the likely 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 various 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, Roberts 1978) 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, company presentations and materials, and public financial data. Secondary sources such as Kaplan (1990a, 1990b) were used as well. We drew upon established system dynamics models of the firm (e.g. Forrester 1961, Lyneis 1980, Hall 1976, Morecroft 1985, Roberts 1978) and experimental studies of managerial decision making (Sterman 1989a, 1989b, Paich and Sterman 1993, Lant 1992) to specify model structure and the decision rules for the actors.

The model has a broad boundary (figure 2). The endogenous variables include physical variables such as orders, shipments, production, wafer starts, finished goods and in-process inventories; financial accounts including a full income statement, balance sheet and cash flow statement; managerial accounting data such as overhead absorption and labor and materials variances; quality metrics including product defects, manufacturing cycle time, delivery time, OTD percentage, and manufacturing yield; and motivational variables such as the commitment of the workforce to TQM, the support resources provided for the TQM effort, the workforce's perceived job security, and top management commitment to TQM. The model contains only five exogenous inputs: the producer price index and labor cost index to capture inflation in input costs; a macroeconomic index of the demand for electronic components (capturing the effect of the recession on industry demand); the yield of the S&P 500 (a determinant of the discount rate investors use to value Analog's expected earnings); and an index of the diffusion of TQM throughout US industry (a determinant of how quickly ADI's competitors can improve as a result of their own TQM efforts). While the model is too large to describe fully here, we discuss two formulations important in understanding the dynamics of TQM: 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).[3]

3.1 Modeling the Product Life Cycle

The dynamics of demand were critical to the impact of TQM on Analog. Improvements in product quality and delivery reliability boost product attractiveness, potentially increasing market share in existing product lines. 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 market segments in which it competes is determined by the attractiveness of ADI's 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 excessively large, attractiveness plummets even if price remains below the competition.

The total size of the market for Analog's products depends on the number and market potential of each product in ADI's portfolio. 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

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

where g^e is the fractional growth in the Federal Reserve 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 product age variable is highly significant, while the economic growth term g^e is not.[4] Sales of typical new products grow at about 100% per year during the first several years (figure 3). The fractional growth rate slows as the products diffuse through the marketplace. Products mature after six to eight years, followed by gradual decline until they are withdrawn or replaced. While some products may enjoy steady sales for a decade, vigorous demand growth requires the continual introduction of new products.

3.2 Building Commitment to TQM

A hallmark of TQM is employee involvement: quality 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, eq. (2), we assume the fractional rate of improvement is proportional to both the potential half-life and the commitment of the workforce, C. Because changes in product mix, equipment, and 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 fractional decay rate η is likely to be low for processes where the improvements leading to higher quality are embedded in physical capital (e.g. changes in plant layout that streamline transfers between workstations) and higher in processes requiring substantial human input (e.g. scheduling delivery dates). We assume η is small for manufacturing yield, cycle time, and process defects, and higher for on time delivery.

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 $0 \leq C \leq 100\%$ 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 eq. (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. The attention devoted to TQM by management is endogenous. C^* falls below 100% when, for example, financial stress demands more of management's attention. The second term represents the 'pull' effect generated by successful results. The more people are involved in TQM efforts, the more they will communicate their enthusiasm to others through word of mouth and presentations. Thus the pull effect is proportional to the current commitment level and the word of mouth effect, w, creating a positive feedback loop by which commitment can be self-generating (provided word of mouth is favorable). The impact of word of mouth is necessarily limited as commitment approaches 100% by the term (1-C).

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 cut costs and 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. The rate at which employees will adopt TQM is limited even in the face of rapid improvement, thus $f_r' \geq 0$, and $f_r'' \leq 0$ for $r > 0$.

desire to build commitment to TQM by demonstrating early results focused attention on operational issues and slowed progress in new product development, contributing to excess capacity. Improvement was faster in operations and slower in R&D, marketing, distribution, and management. TQM created excess capacity and disrupted the historic relationship between direct and indirect costs, a relationship embedded in organizational norms for 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 in 1993

The success of TQM created imbalances and side effects that fed back to undermine commitment to continuous improvement. At Analog the side effects of successful improvement were severe, even threatening Analog's survival as an independent firm. Analog did survive, however, and by mid 1993 had recovered significantly. In 1990 Analog acquired Precision Monolithics, one of its competitors. With the acquisition, lower costs and a modest economic recovery, net income in 1992 had grown to $15 million on sales of $567 million. The stock price in May 1993 had rebounded to about $20/share, a rise of more than 300% from the trough in 1990, compared to a rise of about 45% for the S&P 500 as a whole.[8] The simulated Analog recovers as well, even without the acquisition – though without the possibility of a takeover either. A weaker firm, or a firm experiencing these difficulties when capital to fund takeovers was more readily available, might not have survived.

TQM at Analog has 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. 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. Market research firm Dataquest recently 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 5b shows simulated job security and stability recovering after 1991 as improving financial results boost morale. As morale recovers, a second wave of TQM begins in the model around 1992 (figure 5a). The second wave in the model, as in reality, stresses improvement in product development and the other drivers of indirect costs (figure 5a, 5d). Both the simulated and actual stock price rebound from the 1991 lows (figure 4). These developments arise endogenously in the simulation and emerged from the model before the evidence for the rebound of TQM activity and financial improvements were available.

6. Policy Tests

6.1. Analog does not implement TQM

The base case shows how Analog's success in boosting the quality and productivity of operations led to unanticipated side effects that contributed to financial stress, downsizing, and consequent collapse of commitment to TQM. The obvious question is then '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. Schneiderman commented 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." Further, 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 for quality, reliability, and cost, the simulated no-TQM Analog quickly loses market share. In the simulation, revenues fall over 80% from base case levels by the beginning of 1991 and the stock price plummets due to large ongoing losses. The simulated Analog is forced to begin major layoffs in 1989, earlier than the base case.

TQM initiatives require support from management in the form of training, assistance, rewards, and recognition. Resources such as time or additional staff are needed to enable people to participate in TQM and still do their normal jobs. We model the adequacy of support resources, a, as the ratio of the support available to that required. Support requirements are proportional to the level of TQM effort and thus to commitment. Support resources depend in part on management's focus: as management shifts its attention to financial firefighting and organizational restructuring, managerial attention and support for TQM falls. The assumed relationship $f_a\{\cdot\}$ is an s-curve such that $f_a\{1\} = 0$ and $f_a'\{\cdot\} > 0$.

Finally, if workers are threatened or overburdened by layoffs and reorganizations, if they are preoccupied by the turmoil caused by financial crisis and pressures to cut costs, word of mouth will be negative. We define job security and stability from 0 (financial stress, consolidation and/or layoffs cause severe turmoil) to 1 (workers have confidence in the stability of the current organization and do not fear layoffs). Thus $f_s\{1\} = 0$, and $f_r\{\cdot\} < 0$ for $0 \le s < 1$.

The interplay of leadership, results, support, and job security determines the dynamics of commitment. For example, the introduction of TQM by management creates some commitment, stimulating initial improvement efforts. Provided support resources are adequate and job stability is high, strong early results of the improvement effort will encourage others to participate in TQM, leading to still greater results. Commitment will diffuse rapidly and defects will fall. However, if rising commitment takes too much time away from people's primary jobs, or if the productivity gains created by improvement lead to reorganization and job losses, the negative 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 and managers. The broad model boundary helps ensure important feedback effects and possible reactions to policies are captured. The robustness of the model was assessed through extreme conditions tests. We conducted a variety of sensitivity tests, both of parametric sensitivity and sensitivity to the level of aggregation. We used partial model testing (Homer 1983) to test the structure and parameters of 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 endogenous system to replicate the data. We consider various goodness-of-fit measures including the mean absolute percent error (MAPE) between simulated and actual data and the Theil inequality statistics (Theil 1966). The Theil statistics partition the mean square error between model and data among three components: bias (unequal means of simulated and actual data); unequal variation (unequal variances); and unequal covariation (imperfect correlation between the two series). Sterman (1984) shows how these components of error can be used to diagnose flaws in simulation models.

The simulation begins in 1985; most of the historical data run through 1991.[5] We assess the historical fit of the model against twelve variables for which time series data were available (table 2, figure 4). The MAPE ranges from 3% to 22% and R^2 ranges from .70 to .99. The fits for unit sales, revenue, cost of goods sold, R&D budget, and cumulative new products introduced are excellent, with $R^2 \ge .91$, mean absolute percent errors $\le 7\%$, low bias and low unequal variation. The operational measures of performance – yield, defects, on time delivery and cycle time – have more variation than the aggregate measures, so the MAPE tends to be larger. Still, yield, cycle time, and OTD have MAPE $\le 13\%$ and $R^2 > 74\%$, and the majority of the error is unsystematic noise. The MAPE for defects is 22%, but the $R^2 = .91$ 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 quite good, with MAPE = .13 and .19, respectively, $R^2 = .81$ and .82, respectively, and low bias and unequal variation error. The largest error is in operating income, with MAPE = 18% and $R^2 = .70$. Operating income is the small difference of two large numbers (revenue less cost), so small errors in either create much larger percentage errors in income. While unbiased, simulated operating income has a slightly lower variance than the actual data, which are quite noisy. 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 on 1 January 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.[6] These activities raise commitment (figure 5a), leading to initial improvement efforts in various divisions. At first, job security and stability is high and resources are ample to support them (figure 5b, 5c). 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 and more employees jump on the TQM bandwagon defects begin to fall throughout the manufacturing organization (figure 4).

As the number of improvement teams grows, management support becomes inadequate. At the beginning Art Schneiderman and his small staff could provide guidance, support, and cheerleading to the small number of initial projects. As TQM spread, however, line managers 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 5c).

Management attention is limited and must be allocated among competing demands. In the model managerial attention is allocated differentially as a function of perceived improvement in different sectors. The quality VP said "some people saw the value of TQM right away, but the majority needed to see results before committing themselves, and a few resisted and could never be persuaded. 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 a larger share of support resources from 1987 through 1990 as it demonstrates the quickest results (figure 5d).

In addition to improving operations, Analog had to restructure its strategy and capabilities to align better with changes in technology, competition, and customer needs. These efforts included shifting R&D effort towards SPLICs and DSPs, attempts to speed product development, 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, since 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 reported product development times do not exhibit appreciable improvement, despite the assumed potential to fall with a half-life of 24 months (figure 5e).

Thus efforts to speed new product development and reorient Analog's capabilities to meet changing customer needs could not stimulate demand fast enough to match the improvement in capacity caused by faster cycle time, higher yield, and fewer defects. However, if higher quality allowed Analog to capture additional market share, sales might rise enough to match the increase in capacity. This was not the case. Analog's simulated market share rises slightly until early 1988 but then falls back despite the large increase in product quality. Analog's competitors were not standing still. TQM knowledge is not privately appropriable. 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 unit production costs dropped. Our interviews indicated that, as in many firms (see e.g. Cyert and March 1963), Analog set prices by marking up unit production costs by a standard percentage. The traditional markup ratio, a little over 200%, was sufficient to cover indirect costs per unit and provide a reasonable return. The traditional markup changed only slowly. Between 1985 and 1989, unit production costs fell by about 16%, and average selling prices fell by just over 17% (table 3). However, indirect costs per unit fell only slightly. R&D, sales, marketing, distribution, and management, the activities driving indirect costs, all have high technical and organizational complexity. They have intrinsically longer improvement half lives than the manufacturing activities driving unit production costs. Further, as discussed above, commitment to TQM in these areas was low, slowing improvement below the already low potential rate. By 1989 unit indirect costs had fallen only 9%. Though falling in absolute terms, indirect costs became a larger fraction of total costs. Analog's traditional gross margins were no longer sufficient to yield a reasonable profit. Operating income per unit fell by 45% (table 3).[7]

Analog's stock price fell as earnings dropped and as investment analysts responded to the rising indirect cost fraction by criticizing what they took to be ADI's apparent 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 the simulated stock price falls (figure 4) as revenue growth slows, earnings decline, and the simulated capital markets grow concerned about ADI's high costs. As share prices fell, the ratio of Analog's market value to cash flow dropped below 6 years (figure 4), making Analog vulnerable to takeover attempts (an acquirer could pay off the cost of gaining 51% control with just three years of cash flow). The pressure to boost the share price by cutting costs and trimming excess capacity led Analog to consolidate operations and lay off about nine percent of its workforce. The simulated layoffs occur in mid-1990, roughly the same timing as in reality. Managing the consolidation takes time away from TQM, and the anxiety and confusion caused by the layoffs hurt morale. Job security and stability plummet (figure 5b) and commitment to TQM in manufacturing falls (figure 5a). Improvement stalls, and on time delivery falls back from its peak (figure 4). With quality stagnant but the competitors' still improving, Analog's competitive position deteriorated. 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. But TQM also created unanticipated side effects. Management's

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 Analog's competitors and customers would have pursued TQM even if Analog did not. Though TQM caused unanticipated difficulties and stresses for Analog, 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 workforce may still decline through attrition). 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 yields a tradeoff between short and long term effects. In the short run performance is worse (table 4, figure 6). Maintaining the no-layoff policy does keep commitment to TQM from collapsing. Nevertheless, the critical defect measures improve 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, illustrating the 'worse-before-better' tradeoff.

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 financial pressures from arising; rather it intensifies them. Note that despite the no-layoff policy, commitment to TQM in operations falls from nearly 100% in 1988 to 50% by 1991. 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 fire-fighting, further eroding commitment to TQM.

Job security is no guarantee of TQM success, and may be self-defeating. By preserving jobs in the short run, financial results worsen, increasing pressure for layoffs and the likelihood of top management turnover or outright takeover – the company may not have remained independent long enough to enjoy the benefits of the no-layoff policy. In the event of a takeover, the new management, faced with the need to cut costs, restore profitability, and pay down debt acquired to finance the acquisition, would almost certainly abandon the no-layoff policy.

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. Achieving this goal is difficult in a weak economy. Nevertheless, a number of policies might be effective in reducing the negative effect of downsizing on workforce commitment: (i) employees who are most successful in improving quality can be rewarded by keeping their jobs or transferring to areas where quality did not improve as rapidly, creating an incentive to improve more rapidly rather then less; (ii) TQM tools can be used to identify where cuts should be made, so that workers participate in the decision to cut jobs, increasing the perception of fairness; (iii) management can argue that without quality improvement more (or all) jobs will be lost to competitors.

We test a perfect and costless policy in which layoffs have no effect on employee commitment to TQM (the function $f_S\{s\}$ is set identically to zero). The policy not only means employee morale is completely unaffected by layoffs and financial stress, but that the time consuming and disruptive changes that accompany downsizing, including deciding where and how much to cut, reorganizing and providing outplacement services for redundant employees, have no impact on TQM effort or managerial attention and resources for TQM. Such a perfect policy can never be accomplished in reality. The policy provides a benchmark to assess the potential for policies that can reduce the turmoil and low morale associated with downsizing.

The 'wise layoff' policy mitigates the tradeoff (table 5, figure 6). 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 operating profits and share price. By 1993 the policy outperforms the no-layoff case because it leads to even higher levels of commitment to TQM in both manufacturing and product development, and thus higher quality, revenues, profit, and share price. Note that because TQM has led to even greater improvement, simulated 1993 employment is 8% less than the base case despite a 10% increase in sales.

Even in the wise layoff case the company experiences severe financial stress. Despite the policy, operating profit, share price, and market value relative to cash flow all fall substantially between 1989 and 1991, forcing Analog to lay off a significant number of employees. While human resource 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, administration and other overhead functions). Price-setting, however, continued to reflect the traditional cost structure, leading to a significant erosion of 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%, about 5% higher than the actual 1989 value (table 3). We test this policy by assuming Analog increases the markup ratio 5% 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 6, figure 7). The higher price policy has little effect on revenues in 1991 compared to the base case, but operating profits and share price rise by more than 50%. By 1993 the higher margin policy yields a substantial increase in revenue and boosts operating profit and the stock price by over one hundred and fifty percent compared to the base case.

Significantly, 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, the drop in units shipped is smaller than a static analysis would suggest. First, revenues don't drop in the short run because customers are locked in to existing contracts, and require time to redesign their own products to use competitor chips. The lock-in effect is modest, however, as we assume an average delay of only six months in the adjustment of market share to changes in price. Second, competitors respond to Analog's pricing. As Analog's prices fall in the base case, competitors are forced to lower their prices to limit the loss of market share. Under the higher margin policy, Analog's prices fall more slowly. The competitors lower their own prices more slowly as well while still maintaining their market share. However, the effect of competitor accommodation is short-lived. By the middle of 1989 the competitors' own improvement efforts have reduced their costs enough for them to undercut Analog's prices. After this point, competitors price as low as their costs permit regardless of Analog's price.

Because higher margins improve operating profit, the share price does not fall as much as in the base case, easing the pressure from the capital markets to cut costs and reducing the threat of takeover. The improvement in financial results allows 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 manufacturing 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 (about 5%). More new products increase total demand, offsetting the reduction in market share caused by higher prices.

The benefits of the higher margin policy illustrate the complexity of the feedback processes governing the dynamics of quality programs. Since we assume demand is more than unit elastic, higher margins would reduce revenues and hurt the firm if all else remained constant. By 1993, 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. The effects of higher margins on volume and quality feed back through financial results and morale to sustain Analog's commitment to improvement, boosting Analog's competitiveness.

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 much more complex. 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. Processes with low technical and organizational complexity will improve most rapidly. 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. The throughput of a machine on the factory floor can be improved quickly: the laws of physics governing the process are well understood; the improvement team consists of the operators and others from the plant; experiments can be designed and carried out rapidly; confounding variables can be kept to a minimum. In contrast, demand-generating activities such as developing new products faster and more effectively, allocating resources among divisions, and forging customer alliances require the participation of top management along with people from multiple divisions, functions, disciplinary backgrounds, and other firms. The 'laws' governing these processes are much less obvious than the laws of physics, and the tools available to improve them less highly developed. It takes longer to design and carry out experiments, and during this time changes in the environment confound the interpretation of results. Improvement programs are likely to increase capacity faster than demand, and will lower unit production costs faster than unit indirect costs.

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

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

Denoting the magnitude of the fractional attrition rate from the labor force as '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% 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 - 20% per year – as employees readily found new opportunities in the vigorous electronics industry. During the boom, productivity growth of 40 to 50% 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% per year. With negligible attrition and sales growth less than 10%/year, even small rates of improvement necessarily led to excess employment.

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

This analysis applies not just to TQM but to any improvement technique, such as business process re-engineering, 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 in the quality or human resources literature. 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%/year. In mature industries where sales growth is less than 6%/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. Yet in a stagnant economy there would be strong pressure for layoffs if TQM improved manufacturing before faster and better product development could build new markets. The other horn of the dilemma was equally sharp. Analog could not afford to delay implementing TQM. Analog's customers were demanding higher performance from their suppliers, and competition was intensifying. Failure to improve would have threatened Analog's industry leadership and, perhaps, its very survival.

The interaction of TQM with pricing compounded Analog's difficulties. Given the traditional markup, the faster manufacturing improved, the greater the gap between direct and indirect costs, and the larger the resulting reduction in profits. Lower profits then feed back to intensify the need for layoffs and divert managerial attention from TQM to financial fire-fighting – with resulting backsliding of quality, loss of market share, and pressure to cut prices further.

The core of the dilemma is the belief that people will not participate in new programs like TQM unless they can see the benefits right away. On the 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.

8. Implications and further research

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.[9] 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 in the environment. 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 interactions, 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. Since ADI's initial efforts, 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 such as cognitive mapping (Checkland 1981, Eden, Jones, and Sims 1983, Wolstenholme 1990), and simulation and gaming (de Geus 1988, 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 (recall figure 1, see 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."

Notes

[1] A more detailed description of Analog and its TQM experience is found in Kaplan (1990a, b).

[2] The scorecard evolved over time as better metrics were identified.

[3] The model is a large system of coupled nonlinear differential equations. Complete documentation is available from the authors upon request.

[4] The economic growth index was not significant, apparently because the variance in annual demand growth is not great enough to estimate the relationship. Nevertheless, since the macro-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.

[5] In 1991 ADI acquired one of its competitors, PMI. The acquisition is not incorporated in the model, so comparisons after 1991 are not meaningful.

[6] Actually these activities took time and were distributed over a several month period. The assumed starting time represents a good midpoint for the startup process.

[7] 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 has intensified. In the mid 1980s competitors began to produce 'pin compatible' substitutes offering identical functionality. ADI's business also began to shift from defense-related applications towards consumer markets where competition is more intense and margins are lower. If ADI used markup pricing exclusively and ignored competitive pressures, the 15.8% decline in unit production costs from 1985 to 1989 would yield the same fractional reduction in average selling prices. Average prices actually fell 17.2%, implying intensifying competition and shifting product mix caused prices to fall 9% beyond the decline in unit costs. If prices had fallen only as much as unit costs, operating income per unit would still have fallen 35% because of the smaller drop in indirect costs per unit.

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

[9] More sophisticated tools for improvement such as Taguchi and other experimental design techniques can accommodate nonlinearities and interactions. However, we are not aware of any applications of these design methods to managerial processes.

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Table 1. The balanced scorecard (adapted from version in Kaplan 1990a). The goals for the nonfinancial metrics were determined by applying the improvement half-life estimated for each process (see eq. 2).

Division _____

	Q 1 Plan	Q 1 Actual	Q 2 Plan	Q 2 Actual	...
Financial					
Revenue					
Revenue Growth					
Profit					
ROA					
QIP					
On Time Delivery					
% CRDs not Matched					
Excess Leadtime					
Labor Turnover					
Manufacturing Metrics					
Outgoing Defects (PPM)					
Process Defects (PPM)					
Cycle Time					
Yield					
New Products					
Bookings					
New Product Introductions					
Product Development Time					

Note: QIP = Quality Improvement Processes; CRD = Customer Requested Delivery Dates.

Table 2 Historical fit of model, 1985 - 1991.

Variable	MAPE	Theil Inequality Statistics: Bias	Unequal Variation	Unequal Covariation	R^2	N
Unit Sales	.04	.11	.12	.77	.94	6
Sales Revenue	.03	.01	.08	.91	.94	24
Cost of Goods Sold	.05	.08	.11	.80	.92	24
Operating Income	.18	.11	.25	.64	.70	24
R & D Budget	.07	.19	.01	.81	.91	24
Cum. Products Introduced	.04	.00	.50	.50	.99	24
Manufacturing Yield	.10	.16	.00	.84	.82	72
Outgoing Defects	.22	.06	.01	.92	.91	24
Mfg. Cycle Time	.13	.11	.02	.87	.82	24
On Time Delivery	.05	.31	.05	.64	.74	24
Market Value/Cash Flow	.19	.16	.02	.82	.82	6
Share Price.	.13	.21	.00	.79	.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.

Table 3. Changes in cost structure caused by TQM interacted with pricing policy to yield lower profit.

Historical Data

	$/unit	**1985**	**1989**	% Δ
	Ave. 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

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.

Table 4. Policy Analysis: No-Layoff policy vs. Base Case.

	1991			1993		
Variable	Base Case	No-Layoff	%Δ	Base Case	No-Layoff	%Δ
Revenue ($ Million/qtr)	113	114	1	124	132	6
Operating Income ($ Million/qtr)	6.9	5.9	-14	7.0	8.5	21
R & D Expenditure ($ Million/qtr)	17.6	17.7	1	18.7	19.6	5
Work Force in Mfg (people)	1465	2225	52	1357	1879	38
Comm to TQM in Mfg (dimensionless)	0.01	0.50	0.49 *	0.13	0.35	0.22 *
Comm to TQM in PD (dimensionless)	0.09	0.08	-0.01 *	0.35	0.40	0.05 *
Breatkthrough Products on the Market	279	278	0	315	319	1
Manufacturing Yield (%)	0.40	0.42	5	0.37	0.41	11
Outgoing Defects (PPM)	250	193	-23	432	277	-36
Mfg Cycle Time (months)	2.11	1.94	-8	2.64	2.22	-16
OTD (dimensionless)	0.94	0.96	2	0.89	0.93	4
Product Dev. Time (months)	27.0	26.9	0	26.1	26.0	0
Stock Price ($/share)	7.96	7.32	-8	9.93	10.26	3

*The values in the '%Δ' column for Commitment to TQM in Manufacturing and Product development are absolute differences.

Table 5 Policy Analysis: Wise Layoffs vs. Base Case.

	1991			1993		
Variable	Base Case	Wise Layoffs	%Δ	Base Case	Wise Layoffs	%Δ
Revenue ($ Million/qtr)	113	114	1	124	137	10
Operating Income ($ Million/qtr)	6.9	8.2	19	7.0	12.2	74
R & D Expenditure ($ Million/qtr)	17.6	17.7	1	18.7	20.1	7
Work Force in Mfg (people)	1465	1467	0	1357	1248	-8
Comm to TQM in Mfg (dimensionless)	0.01	0.52	0.51 *	0.13	0.46	0.33 *
Comm to TQM in PD (dimensionless)	0.09	0.09	0.00 *	0.35	0.50	0.15 *
Breatkthrough Products on the Market	279	279	0	315	323	3
Manufacturing Yield (%)	0.40	0.42	5	0.37	0.43	16
Outgoing Defects (PPM)	250	192	-23	432	235	-46
Mfg Cycle Time (months)	2.11	1.93	-9	2.64	2.10	-20
OTD (dimensionless)	0.94	0.96	2	0.89	0.94	6
Product Dev. Time (months)	27.0	26.9	0	26.1	25.0	-4
Stock Price ($/share)	7.96	8.91	12	9.93	19.80	99

*The values in the '%Δ' column for Commitment to TQM in Manufacturing and Product development are absolute differences.

For the Wise Layoff policy the function $f_S\{s\}$ is set identically to zero (see eq. 9), so that layoffs have no impact on commitment to TQM.

Table 6. Policy Analysis: 5% Increase in target margin phased in from 1988-1989.

	1991			1993		
Variable	Base Case	+5% Margin	%Δ	Base Case	+5% Margin	%Δ
Revenue ($ Million/qtr)	113	114	1	124	134	8
Operating Income ($ Million/qtr)	6.9	10.9	58	7.0	17.8	154
R & D Expenditure ($ Million/qtr)	17.6	17.8	1	18.7	19.7	5
Work Force in Mfg (people)	1465	2074	42	1357	1697	25
Comm to TQM in Mfg (dimensionless)	0.01	0.92	0.91 *	0.13	0.72	0.59 *
Comm to TQM in PD (dimensionless)	0.09	0.22	0.13 *	0.35	0.41	0.06 *
Breatkthrough Products on the Market	279	295	6	315	328	4
Manufacturing Yield (%)	0.40	0.44	10	0.37	0.46	24
Outgoing Defects (PPM)	250	170	-32	432	180	-58
Mfg Cycle Time (months)	2.11	1.85	-12	2.64	1.88	-29
OTD (dimensionless)	0.94	0.97	3	0.89	0.96	8
Product Dev. Time (months)	27.0	26.2	-3	26.1	24.3	-7
Stock Price ($/share)	7.96	15.06	89	9.93	28.40	186

* The values in the '%Δ' column for Commitment to TQM in Manufacturing and Product development are absolute differences.

Figure 1. Dependence of improvement half lives on technical and organizational complexity. Adapted from Schneiderman (1991).

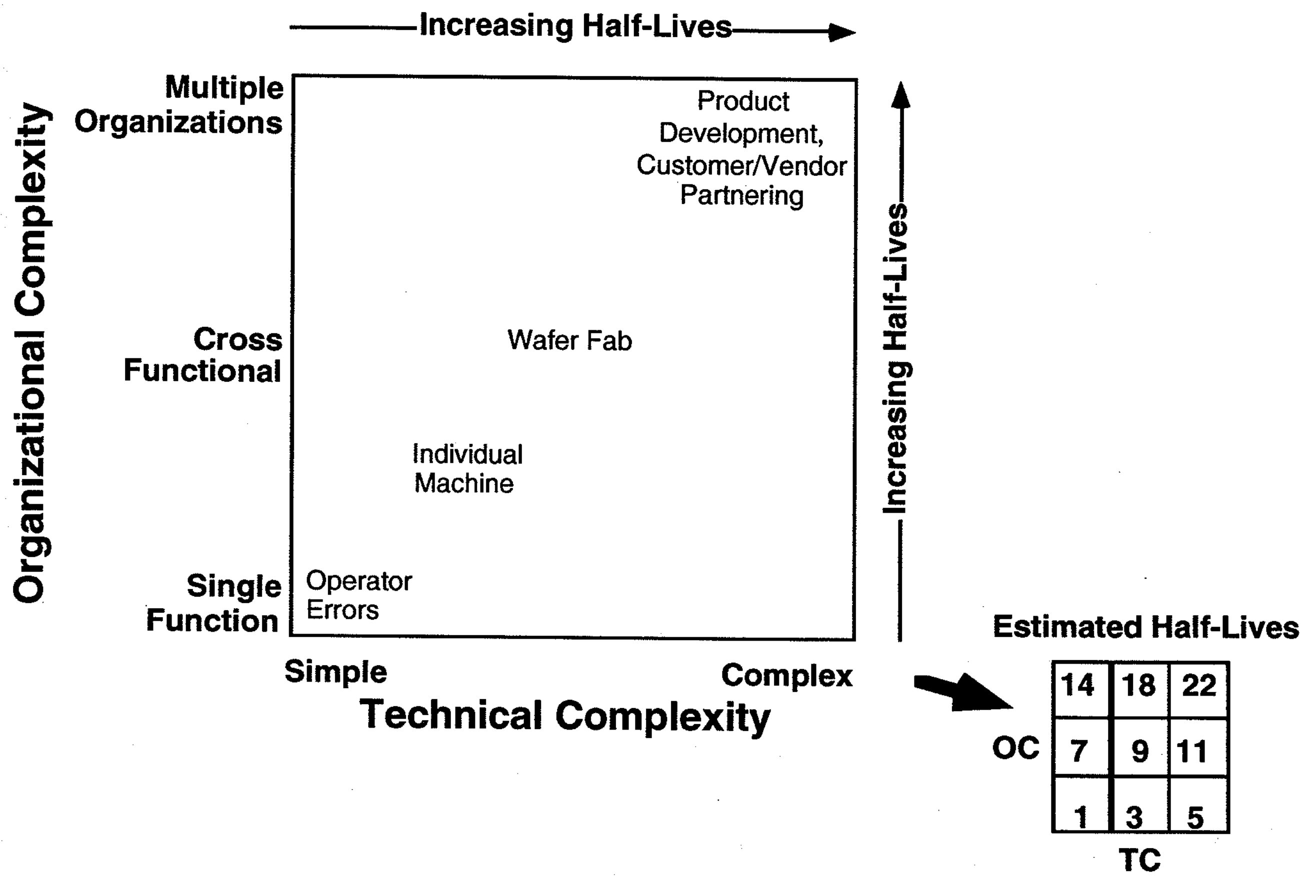


Figure 2. Overview of Model Structure

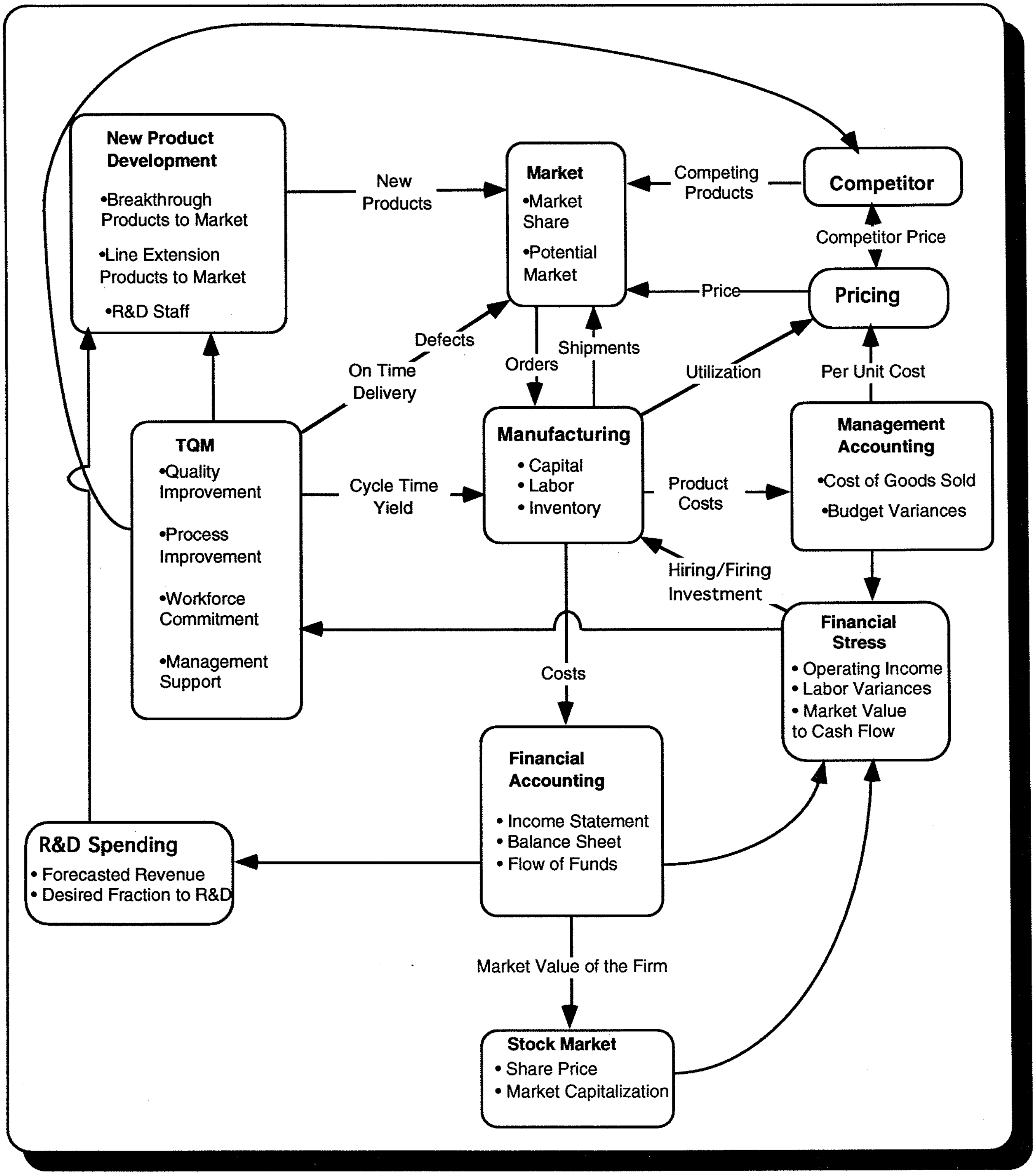
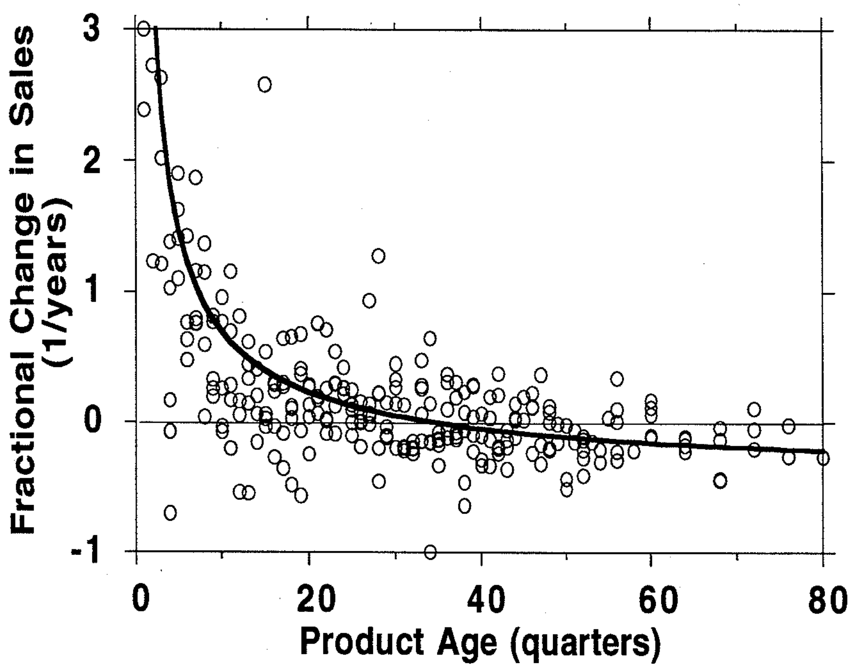


Figure 3. Dependence of Sales Growth on Product Age.

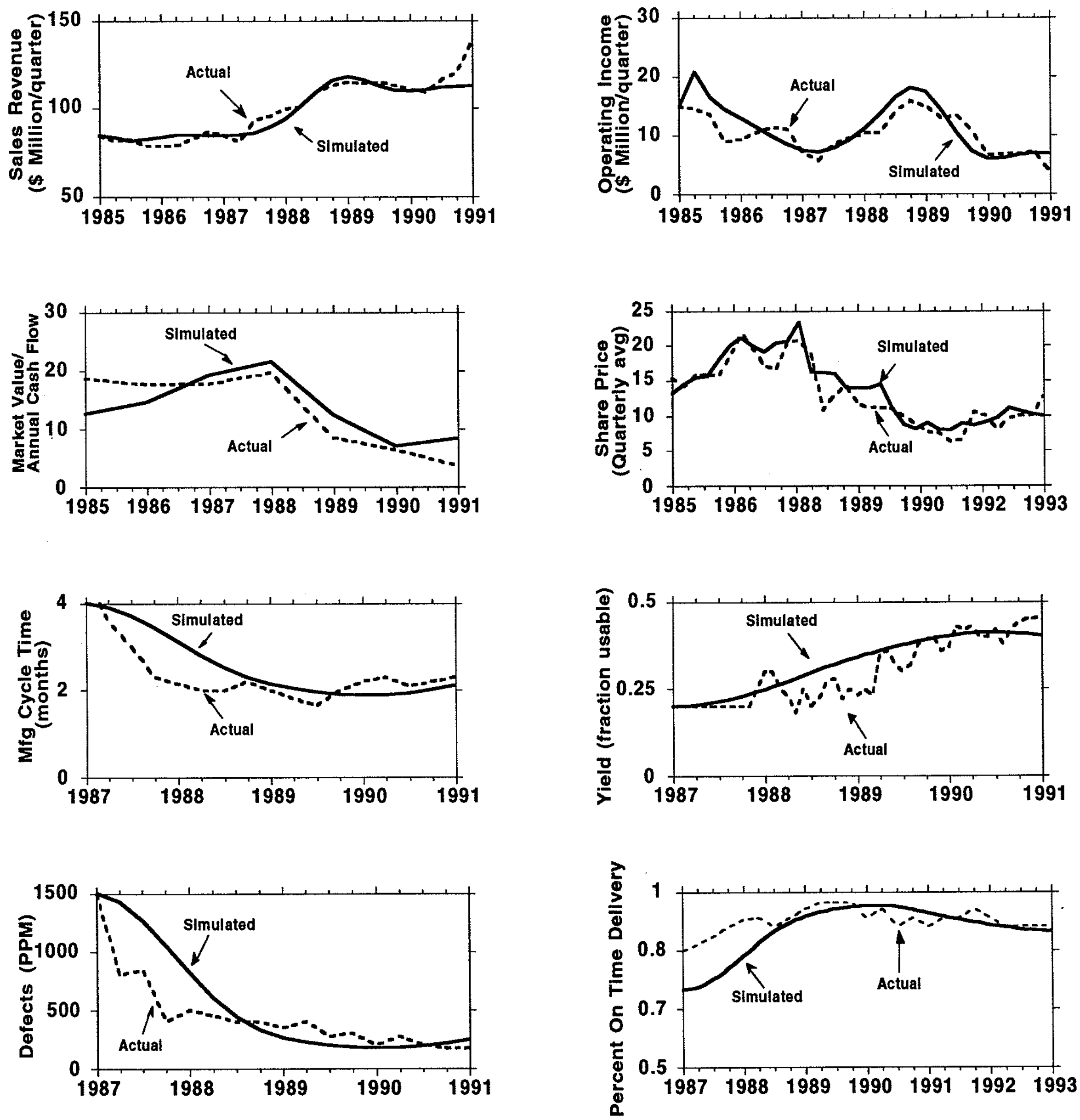


Model: $g_{i,A,t} = \alpha + \beta(A_{i,t})^{\gamma} + \delta g^{e}_{t} + \varepsilon_t$ for product i of age A in year t

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

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

Figure 4. 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.

Figure 5a. Base Case: Fraction of workforce committed to TQM.

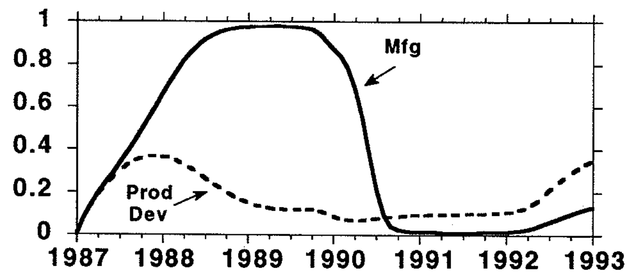


Figure 5b. Base Case: Perceived Job Security (0 = no security; 1 = no layoffs believed possible)

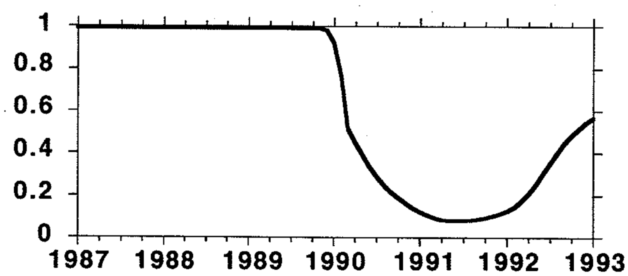


Figure 5c. Base Case: Adequacy of resources to support the TQM program.

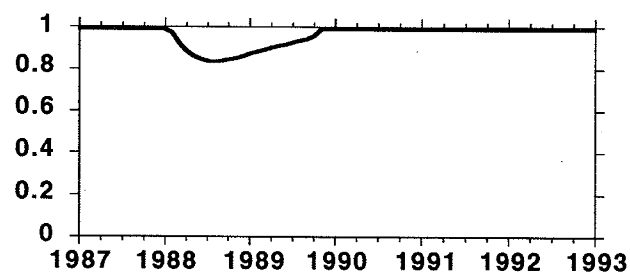


Figure 5d. Base Case: Fraction of TQM support resources allocated to manufacturing.

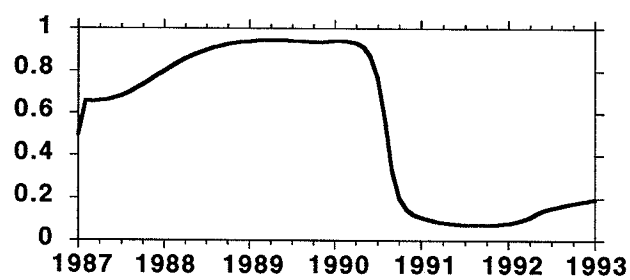


Figure 5e. Base Case: Reported and Target Product Development Time

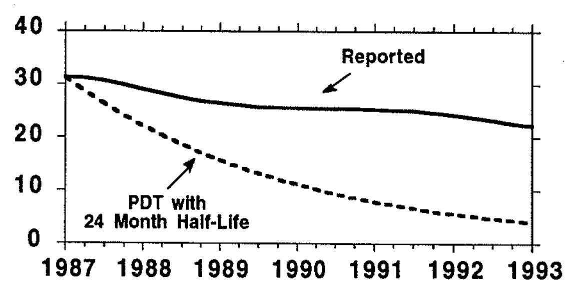


Figure 6. A no-layoff policy causes a Long-term/Short-term tradeoff in financial results.

The 'Wise Layoff' policy, where job cuts have no impact on morale or TQM effort, moderates the tradeoff.

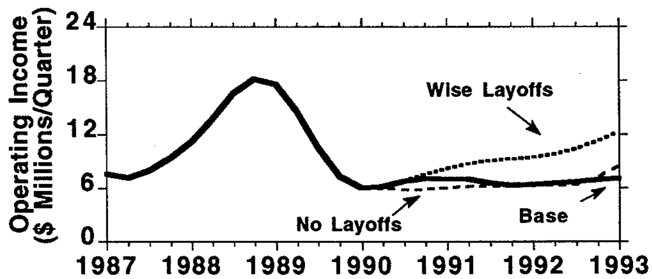


Figure 7. Raising markups to compensate for the slower reduction in indirect costs improves financial performance.