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Work-Team Implementation and Trajectories of Manufacturing Quality: A Longitudinal Field Study

Rajiv D. Banker, Joy M. Field, Kingshuk K. Sinha,

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Rajiv D. Banker • Joy M. Field • Kingshuk K. Sinha*
School of Management, The University of Texas at Dallas, Richardson, Texas 75083
Wallace E. Carroll School of Management, Boston College, Chestnut Hill, Massachusetts 02467
Curtis L. Carlson School of Management, University of Minnesota, Minneapolis, Minnesota 55455
rbanker@utdallas.edu • fieldjo@bc.edu • ksinha@csom.umn.edu

The study examines the sustainability of manufacturing quality improvements following the implementation of work teams on production lines. We posit that the impact on manufacturing quality, measured as the defect rate trajectory, is monotonically nonincreasing over time and may, more specifically, assume the shape of an inverted S-curve. Employing a longitudinal research design, we investigate four work teams over a 28-month period in a field setting. Each team corresponds to one of the four interconnected production lines in an electromechanical assembly plant operated by a Fortune 500 firm. Results of our empirical analysis support the sustainability of quality improvements associated with work team implementation and partially support the S-shaped trajectory as the particular form of sustainability. However, variations in the manufacturing quality trajectories reflect the characteristics of the work team and the production line on which each the team is instituted. From the standpoint of practice, this study highlights the importance of work-team design and implementation decisions, especially the need to be proactive in identifying and resolving initial implementation difficulties.
(*Work-Teams; Manufacturing Quality; Field Study*)

1. Introduction

Driven by pressures to improve quality, manufacturing firms are implementing work teams on production lines. Most evidence relating work-team formation to quality improvement is either anecdotal or based on cross-sectional studies with little insight into the process of team implementation over time. Our objective in this paper is to delineate the trajectories of manufacturing quality following the implementation of work teams at an assembly plant to determine if work teams have a *sustainable* positive impact on manufacturing quality. The paper builds on an earlier paper (Banker et al. 1996) that examined the immediate impact of work-team implementation, but did not address the issue of sustainability of impact.

Previous research on quality circles (another organizational mechanism commonly used to facilitate worker participation in workplace decisions) indicates that, despite initial performance improvements, the positive effect of quality circles on manufacturing performance is *not* sustainable (Griffin 1988, Mohrman and Novelli 1985, Lawler and Mohrman 1987, Meyer and Stott 1985). However, unlike quality circles, which exemplify ''consultative participation,'' the work teams we study are an institutionalized form of ''substantive participation'' (Levine and Tyson 1990).[1] Based on these characteristics, we expect

*Kingshuk K. Sinha is the corresponding author for this paper.
[1]In quality circles, a consultative form of participation, workers are

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that manufacturing quality improvements associated with work-team implementation will be sustainable. Measuring quality improvement as defect-rate reduction, we posit that the defect-rate trajectory is monotonically nonincreasing over time, reflecting sustainability of quality improvements. Empirical analysis of data from four production lines of an electromechanical assembly plant over a 28-month period suggest that quality improvements after the formation of work teams are, in fact, sustainable over time. The specific shape of the trajectory of manufacturing quality reflects the characteristics of the team and the production line on which it is formed.

The remainder of this paper is organized as follows. Section 2 discusses the theoretical underpinnings of this study. Section 3 describes the research setting and § 4 the estimation model and methods. Section 5 presents the results of our empirical analysis and § 6, the concluding remarks.

2. Theoretical Foundations

2.1. Sustainability of Manufacturing Quality Improvements

Griffin (1988) examines the changing impact of work teams on a perceptual measure of manufacturing quality at four points in time and finds that, while quality circles initially improve quality, the positive impact on quality is not sustainable, and quality eventually begins to erode. This supports conceptual work on quality circles predicting that quality circles self-destruct over time because of their organization as parallel structures, separate and distinct from day-to-day activities, and the lack of decision-making authority by team members (Mohrman and Novelli 1985, Lawler and Mohrman 1987, Meyer and Stott 1985, Sillince et al. 1996).

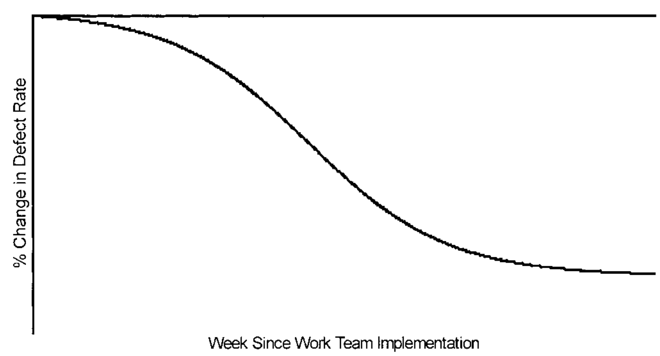
Based on a review of empirical studies in economics, industrial relations, and organizational behavior on the effect of participation on performance, Levine and Tyson (1990) conclude that participation is more likely to have a positive impact on performance when it involves *substantive* rather than *consultative* arrangements. Substantive participation involves work teams making *and* implementing decisions, while consultative participation is limited to idea generation. Both Levine and Tyson (1990), and Lawler and Mohrman (1987) consider the purely advisory role of quality circles to be detrimental to the sustainability of their impact on quality.

Another factor contributing to the frequent failure of quality circles as a sustainable form of group participation is that they are organized as a parallel structure or an auxiliary program, in the sense that they are separate and distinct from an organization's ongoing activities (Lawler and Mohrman 1987). Rather, to be viable and effective over the long term, group participation should be institutionalized and considered "a way of life" (Meyer and Stott 1985, Lawler and Mohrman 1987). Characteristics of work teams that promote institutionalization are mandated membership (Magjuka 1989), decision-making authority, and management involvement and support (Lawler and Mohrman 1987).

2.2. Trajectories of Manufacturing Quality

To examine the sustainability of quality improvements after the formation of work teams on production lines, we posit as the benchmark an inverted S-curve trajectory of manufacturing quality, measured as the percentage change in the defect rate (see Figure 1). Observe from the figure that at the *initial portion* of the trajectory quality remains relatively flat. Qual-

Figure 1 **A Typical Trajectory of Defect Rate-Reduction Following Work-Team Implementation**



allowed to give their opinions, but final decisions are still made by management. The difference between consultative and substantive forms of participation is not in the content of the decisions but in the degree of worker influence.

ity improves sharply in the *middle portion* before plateauing in the *final portion.* Although sustainable quality improvement trajectories can assume forms other than the inverted S-curve, we find support in the literature for this particular form. This shape for the manufacturing quality trajectory is derived by triangulating the mutually reinforcing findings of studies from three theoretical perspectives—group development, technology implementation, and organizational learning.

Tuckman (1965) in his widely cited model of group development, suggests a developmental sequence consisting of four phases: forming, storming, norming, and performing. Forming involves an orientation to the group in which the group members seek to define the boundaries of both interpersonal and task behavior. Storming is characterized by resistance to group influences and emotional responses to task issues. In the norming phase, group members overcome the resistance to group influences and develop a group, rather than individual, perspective. In the performing phase, interpersonal and group issues have been resolved, and the group's energy is primarily directed at addressing the task. Performance improvements are realized mainly in the performing phase (Mohrman et al. 1995).

Following the conceptualization of a work team as a technology (Ichniowski and Shaw 1995), we can also draw on the findings of studies on technology implementation to inform the shape of the manufacturing quality trajectory in Figure 1. Note that from a definitional standpoint, technology has 2 characteristics: (i) technology is manifested in artifacts (e.g., tools, machines, work procedures), and (ii) technology manipulates or transforms inputs to outputs (Burgelman and Rosenbloom 1989, Van Wyk 1988, Christensen 1992). As an institutionalized form of substantive participation (i.e., artifact) that generates ideas and implements changes (i.e., transforms inputs to outputs), a work team shares these characteristics. Further, according to Leonard-Barton's (1988) model of technology implementation, introduction of a new technology causes misalignment between the technology and the user. The misalignment must be corrected by either altering the technology, changing the environment, or both. Until the misalignment is corrected, performance improves slowly. Similarly, an organizational innovation, such as a work team, encounters an initial period of misalignment that must be addressed to realize its potential benefits. In essence, the first three phases of Tuckman's (1965) model—forming, storming, and norming—are analogous to Leonard-Barton's (1988) model of technology implementation.

Garvin (1993) in his conceptualization of organizational learning, suggests that improvements in manufacturing performance (e.g., quality) occur through a three-stage process. The first step is cognitive as members of the organization are exposed to new ideas, expand their knowledge, and begin to think differently. The second step is behavioral as employees internalize new insights and change their behavior. It is only in the third step that performance improvements (i.e., superior quality) result from the changes in behavior. In essence, this conceptualization suggests a delay between the beginning of the organizational learning process and the realization of the performance improvements in the period immediately following the formation of work teams. More specifically, the introduction of work teams is intended to overcome the cognitive inertia that is a barrier to performance improvement (Reger et al. 1994). The activities of the work team, including participation of workers in problem solving and decision making, involves processes that deviate from the status quo and confront the associated cognitive inertia. However, as Garvin (1993) suggests, these new processes take time to develop, which helps explain the initial lag in performance improvements.

Triangulating the mutually reinforcing findings of studies from the three theoretical perspectives, we posit a positive but slow impact on quality during the *initial period,* as shown in Figure 1. A departure from the posited slow improvement of quality during the initial period occurs when preexisting relationships among members promote a team orientation. Under such conditions, quality improves immediately and sharply as the forming, storming, and norming stages of Tuckman's (1965) model of group development do not occur.

Rapid quality improvement in the *middle portion* of the inverted S-curve is consistent with the performing phase of group development in Tuckman's (1965) model. The technology implementation model also suggests that performance improves continually over time as improvements in the underlying technology accrue cumulatively to the product. Following the analogy of a work team as a "technology," "improvements" are the generation and implementation of ideas for operational enhancements. Work teams generate ideas, and it is the implementation of these ideas and the degree to which they relate to quality that contribute to cumulative improvements in product quality (Mohrman and Novelli 1985). The rate of quality improvement, however, is likely to be different in different contexts. For example, ceteris paribus, the rate of defect reduction for labor-intensive production lines is likely to be faster than for capital-intensive production lines (Hirsch 1956, Yelle 1979).

This process of generating and implementing improvement ideas is an example of "induced" learning, as opposed to "autonomous" learning that is typically represented by variables such as cumulative volume. Induced learning involves an explicit process intended to achieve performance improvements. Other examples of induced learning are captured in variables such as engineering changes and workforce training (Adler and Clark 1991). Quality-based learning, in particular, results from the quality improvement process associated with uncovering and eliminating the source of quality problems and requires investments in prevention and appraisal activities (Fine 1986, 1988). After resolving initial implementation difficulties, it is in the *middle portion* of the inverted S-curve that the most of the benefits of this learning process are realized.

The plateau in the *final portion* of the inverted S-curve trajectory can be explained by the fact that the work teams reach a natural or physical limit in their ability to generate and implement high-impact improvement ideas (Mohrman and Novelli 1985). This explanation is consistent with Christensen's (1992) contention that the rate of technological improvement slows because greater effort is required to realize additional improvements as the technology approaches its natural or physical limit. Finally, Muth's (1986) modeling of the manufacturing progress function as a random search within a fixed population of technological possibilities is consistent with the idea of a natural or physical limit. It is conceivable, however, that the plateau in the *final portion* of the trajectory is not likely to be observed if the number of possible improvement ideas and the ease with which the ideas can be identified and implemented continue to be high at the culmination of a particular study.

The S-curve trajectory of manufacturing quality is sufficient (but not necessary) to demonstrate sustainability of quality improvements; sustainability can assume forms other than an S-curve. However, because the literature provides justification to consider the S-curve form as a benchmark for the trajectory of quality improvements following work-team implementation, the adherence of a team's manufacturing quality trajectory to an S-curve has to be empirically examined. Adherence to an S-curve will not only demonstrate sustainability, but also the particular form of sustainability.

3. Research Setting

The research setting for this study is a unionized plant, which is operated by a division of a Fortune 500 firm. The plant has dedicated direct and indirect personnel, separate accountability, and separate record keeping. In September 1992, a work team was formed on each of the four production lines of the plant. The empirical analysis for this study is based on data collected over a 28-month period from September 1992–December 1994. A subset of this data was analyzed for an earlier study (Banker et al. 1995) that examined the immediate impact of work team implementation.

3.1. Production System

The family of products manufactured in this electromechanical plant consists of a series of small motors used in industrial and residential applications. The family of motors has been designed using a modular strategy for increased manufacturing flexibility. All motors are built with component parts that have the same size and shape, but alternative combinations of the component parts result in numerous models. Consistent with this strategy, the manufacturing process employs a high degree of flexible automation. While there are variations in the extent of automation across the four production lines, the type of automation is the same: pick-and-place robots are interconnected by automated conveyor systems. A simultaneous engineering approach was implemented to coordinate product and process designs. The plant operates in a just-in-time (JIT) production environment with minimal inventory in excess of what is required for current production. Commercial production of the family of motors began in September 1990. By the last quarter of 1991, production on all four lines of the plant was fully ramped up with a full first shift and a partial second shift. Throughout the study period, the production of the family of motors continued at the fully ramped-up levels.

In terms of facility layout, the plant is organized into three subassembly lines and one final assembly line. The three subassembly lines correspond to the three basic components of the motors: submotor, gear train, and printed circuit board. Each completed submotor, after undergoing functional tests, feeds into the gear train line where it is incorporated into the gear train subassembly. The completed gear train subassembly and the printed circuit board feed into the final assembly line where they are incorporated into the end product.

3.2. Characteristics of Production Lines

There are significant variations in the characteristics of each line, especially in terms of products, capital and labor intensity, and labor skills:

Submotor line assemblies are of two types—with or without a mechanical spring-return device. The more complex process steps are performed at the highly automated upstream end of the submotor line that operates with very little human intervention. However, several workers are needed to manually complete the submotor. The number of workers on the submotor line varied from 7–11 over the study period.

Gear train line consists of two areas—machining and assembly. Some of the parts used in the gear train are machined on the line. Unlike elsewhere in the plant, workers in the machining area of the gear train line are trained machinists. The assembly area is highly automated, and there are very few production workers in this area. As a group, they have more seniority than workers on the other production lines. They tend to be a very cohesive group, and there is little turnover. The number of workers on the gear train line ranged from 4–6 over the study period.

Printed circuit-board line is the most capital-intensive line in the plant. Ideally, once the assembly process begins, printed circuit boards are not touched by workers until they are completed. Workers on this line are primarily involved in inspecting the completed boards. The number of workers on the printed circuit-board line ranged from 4–6 over the study period.

Final assembly line is the most labor intensive line in the plant. Product diversity on this line is high because the end product is assembled from various combinations of the more standard inputs from the three subassembly lines. Assembly of the printed circuit board to the gear train is handled by experienced workers because it is a delicate job. Several production workers are involved in final functional testing, which is a job that requires trouble-shooting skills. During the time we spent in the plant, we observed that the production engineer and production workers on this line, in particular, had an especially good working relationship. The workers often stopped by the engineer's office to discuss issues, and the engineer did the same with the workers on the production line. The number of workers on the final assembly line varied from 14–18 over the study period.

The specific types of manual jobs performed on the four lines include wiring, subassembly, circuit testing, insertion, drop-in, operational checks, component preparation, and functional testing. Even though these jobs require different skills, they can be learned quickly without any special training. Job rotation was not practiced either within or across the teams on the four production lines during the study period.

3.3. Workforce Characteristics and Policies

All production workers in the plant are members of the union. They are paid on an hourly wage basis. Company policies guiding wage rates, and medical and retirement benefits did not change during the study period. The contractual agreement between the union and the division did not contain any clause on employment security for production workers. Most production workers are long-time employees with average tenure of 18 years and average age of 42 years. Variations observed in the number of production workers on each production line are due to individuals being laid off, retiring, leaving for higher wage jobs elsewhere in the division, and the vacancies not being filled immediately. Our inquiries did not reveal any production worker leaving the plant because of the introduction of work teams. During the study period, vacancies on the production lines were filled with either workers from other plants in the division or from the pool of previously laid-off workers.

3.4. Evolution of Work Teams

Our research site was the first plant in the division to be selected for work-team implementation. The primary reason for this choice was the enthusiastic response of the plant manager. Other plant managers in the division had initially expressed concerns about the feasibility and effectiveness of work teams in a unionized environment. However, the union supported the introduction of work teams as an effort to make the plant more competitive to remain viable in the long term, which is an issue of increasing importance.

The initial months following the introduction of work teams focused on establishing trust between production workers and ''management,'' which included all nonunion personnel. The facilitator for work team implementation believed that developing trust was important in overcoming the production workers' resistance to work team formation. Given the numerous instances in the past of programs being introduced and then abandoned, production workers were skeptical of management's commitment to team implementation. Further, being unionized, the plant did not have a history of cooperation between workers and management. The facilitator played an important role in establishing trust between production workers and management by demonstrating that management was willing to implement their ideas.

Another notable issue following the formation of work teams was the development of conflict within the teams. The amount of conflict varied by team. The facilitator cited the submotor team, in particular, as one that had a high level of initial internal conflict, some of which persisted throughout the study period. On the other hand, continuing from the period before the team formation, relations among the gear trainline team members were especially harmonious. The conflict levels on the printed circuit board and final assembly teams were between these two extremes, and the facilitator did not identify any major issues related to conflict resolution among these team members.

After the initial months of trust building and conflict resolution, the facilitator made a concerted effort to get the work teams focused on solving problems. For six months, January–June 1993, all members of the four work teams went through a ''10-module toolkit training''[2] that was specifically aimed at facilitating their ability to work as a team.

3.5. Functioning of Work Teams

Typically, work-team meetings are held once a week. The meetings begin with a discussion, usually lead by either the plant manager or facilitator, that always covers quality, the past week's accomplishments, customer delivery, and variances from budgets. The meetings also serve as a forum to occasionally share information on topics such as the division's budget and performance, including the plant's standing, competitors' products, changes in the customer base, and problems with the products in the field. The bulk of the meeting is conducted by the team leader, chosen from among the production workers, and centers around the action log. The action log is a meeting log containing action items generated by the team listing the date that the item was submitted, the problem and/or plan of action, the person(s) submitting the item, the person(s) responsible for addressing the

[2]The topics of the 10-modules are: (i) vision of a competitive factory with a future, and values related to people, customer, quality, safety, and competitiveness, (ii) mutual goals, interdependent working relationships, and commitment to the group effort, (iii) organizing effective meetings, (iv) defining team goals and purpose, (v) understanding one's self and others, (vi) reviewing team processes, (vii) listening effectively, (viii) providing constructive feedback, (ix) benefits of having conflicts and techniques for conflict resolution, and (x) the process of problem solving.

item, the target date for resolution, the current status, and the date completed. The team members first discuss the current status of outstanding items and then any new items to add to the action log. At the time the item is submitted, the team leader assigns someone to be responsible for action on the item and establishes a target date for completion. If the item is a problem, the action may involve gathering information on possible solutions. If the item is a plan of action, the action is implementing the item.

Examination of the action logs of the work teams on the production lines suggested that around mid-1993, the orientation of the issues entered in the log book began to shift from individual to group-level issues. Examples of group-level issues include: (i) revising the parts ordering system and (ii) increasing training on a specialized machine to reduce defects. While some of the issues were still assigned to the production engineer, others were increasingly being assigned to individual workers or the team as a whole. This was in contrast to the orientation of the actionable entries in the log book in the months immediately following the introduction of work teams when they were mostly individual-oriented issues, such as the need for new chairs and tools for a particular work station. Further, the responsibility for resolving these issues was usually given to a production engineer or the plant manager. Also, around mid-1993, the plant manager demonstrated his support for, and confidence in, their accomplishments by authorizing the work teams to implement suggestions for improvements costing less than $200—an amount that covered a significant number of ideas for operational improvements. Expenditures above $200 continue to be handled by the plant's usual operating procedures, such as the capital budgeting process, that can be initiated by the team. The evolution of the work teams, as evidenced by the action logs and increased managerial support, indicates that institutionalization of substantive participation was, in fact, achieved.

4. Empirical Model and Methods

To examine the trajectories of defect-rate reductions associated with work-team implementation, we employ a longitudinal-research design. This design also enables us to assess whether defect-rate reductions following the implementation of work teams are sustainable. Our inquiries and review of plant documents did not reveal any intervention, besides the introduction of work teams in September 1992, that could potentially confound the impact of work teams on manufacturing quality. For example, no new product families or operational practices were introduced, nor were there any changes in process technologies or facility layout. Human resource management-policies, such as those related to compensation, recruitment and selection, employment security, job assignment, skills training, and communication (Ichniowski et al. 1997, MacDuffie 1995), were the same across the four production lines and did not change during the study period. In addition, we control for other factors known to affect manufacturing quality to isolate the effect of work teams on manufacturing quality. We rely on the convergence of results of econometric analysis and the insights gained from qualitative data to support our conclusions (Mohrman and Novelli 1985, Wagner et al. 1988).

4.1. Measurement of Variables and Model Specification

The dependent variable is the *defect rate,* which is measured as the number of defective units produced as a proportion of total units, produced on the production line in a given period. The independent variable of interest is *time following work-team implementation.* Because we posit an inverted S-curve trajectory for defect rate, we employ a sufficiently general estimation model to allow for this as well as other forms. Following Badiru (1992), we employ a polynomial form with linear, quadratic, and cubic transforms of the number of weeks following work-team implementation.[3]

Following Hayes and Clark (1985) and Banker et al. (1996), we identified a number of control variables representative of factors other than work team implementation that have the potential to affect manufac-

[3]We did not restrict our analysis to models that assume an S-curve form a priori; see for example, Mahajan et al. (1990). Also, to check for more complex forms, we included a t^4 term in the first iteration of our analysis, but it was not significant.

turing quality. Included among such factors are four groups of managerial policies related to equipment, work-in-process (WIP) inventory, workforce, and confusion in the plant. We do not include equipment policies because most of the plant's stock of equipment, related maintenance, and other policies were in place at least five months before the beginning of the study period and did not change appreciably during the period. In addition, we did not include work-in-process inventory in the analysis because the plant has had a just-in-time (JIT) production environment since its inception and operates with minimal inventory. Our examination of the WIP data, available only at the plant level, indicated that the WIP level had been fairly constant throughout the study period. Defective units on all four lines were reworked and repaired on the same day that they were detected.[4]

The variables related to workforce policies are operationally defined as follows. *Overtime* is measured as average overtime hours per worker for each production line in a given period. *Absenteeism* is the number of workers absent as percentage of total workers in the plant in a given period. *Turnover* is operationalized as two variables: (i) *headcount addition* is the number of workers who joined as percentage of total workers on a production line in a given period, and (ii) *headcount deletion* is the number of workers who left as percentage of total workers on a production line in a given period.

The variables related to policies affecting plant confusion are operationally defined as follows. *Product diversity* is measured as a Herfindahl index (Gollop and Monahan 1991) to reflect product heterogeneity on a production line in a given period. The Herfindahl index is of the form $1 - \Sigma\, s_j^2$, where s_j is the share of the *j*th distinct product in the total production. *Product complexity* is measured as the volume-weighted average of device complexity based on manufacturing difficulty (e.g., Cooper et al. 1992, Ittner 1992) on each production line for a given period.[5] The complexity index is of the form $c_j x_j / \Sigma\, x_j$, where c_j is the complexity value for Product *j*, and x_j is the volume of the Product *j*. For each production line, the product diversity and complexity measures are normalized by their average values. *Fluctuations from planned production volume* are operationalized using two variables: (i) *upward fluctuations* are the percent deviation from the planned production rate for the plant in a given period, if positive, and otherwise zero, and (ii) *downward fluctuations* are the percent deviation from the planned production rate for the plant in a given period, if negative, and otherwise zero. *Engineering change orders* is the number of such orders issued on a production line in a given period.

Two more control variables are included in our analysis. *Volume,* measured as the number of units produced on each production line in a given period, is included to control for possible capacity utilization effects. Finally, our discussion with the plant manager indicated that engineers experimented with alternative adhesives on the gear train line during the months April–September 1993. Such experimentation is considered to be outside the normal production process and is known to cause unusually high defect rates on the line. We use a dummy variable, *experimentation,* to indicate this period. The variable assumes the value of 1 for the adhesive experiment period, and 0 for the remaining periods.

To determine the nature of the effect of work teams on manufacturing-quality over time, we develop a model consisting of a system of four equations based on the product flows in the plant. The complete estimation model is presented in Table 1. In particular, note that Equation (4) for defect rate on the final as-

[4]The effect of WIP on quality is related to the coupling between WIP and cycle time (i.e., ceteris paribus, the lower the WIP, the faster the cycle time, and vice versa). During the study period, the average cycle time was 45 minutes, a figure considered to be satisfactory by plant management. As a result, further reductions in WIP and cycle time were not considered by the management.

[5]From the engineering department, we obtained ratings on the critical features of the products on the four production lines—namely, (i) control mechanism, (ii) mechanical characteristics, and (iii) electrical characteristics—in terms of their manufacturing difficulty. Each of these features was assigned a numerical value (the higher the number, the more complex it was). These features are coded in the model number assigned to the products. With information on the product model numbers and production volume for a given period, we calculated volume-weighted average complexity for the period.

Table 1 Formulation of Estimation Model as a System of Four Equations Based on Product Flows in the Plant

$$SDEF_t = \alpha_0 + \alpha_1 SOT_t + \alpha_2 ABSENT_t + \alpha_3 SADDS_t + \alpha_4 SDELS_t + \alpha_5 SDIV_t + \alpha_6 SCOMP_t + \alpha_7 VOLUP_t + \alpha_8 VOLDN_t + \alpha_9 SECO_t + \alpha_{10} SVOL_t + \alpha_{11} TLIN_t + \alpha_{12} TSQR_t + \alpha_{13} TCUB_t + \epsilon_t \quad (1)$$

$$GDEF_t = \beta_0 + \beta_1 GOT_t + \beta_2 ABSENT_t + \beta_3 GADDS_t + \beta_4 GDELS_t + \beta_5 GDIV_t + \beta_6 GCOMP_t + \beta_7 VOLUP_t + \beta_8 VOLDN_t + \beta_9 GECO_t + \beta_{10} GVOL_t + \beta_{11} GTEXP_t + \beta_{12} TLIN_t + \beta_{13} TSQR_t + \beta_{14} TCUB_t + \phi_t \quad (2)$$

$$BDEF_t = \delta_0 + \delta_1 BOT_t + \delta_2 ABSENT_t + \delta_3 BADDS_t + \delta_4 BDELS_t + \delta_5 BDIV_t + \delta_6 BCOMP_t + \delta_7 VOLUP_t + \delta_8 VOLDN_t + \delta_9 BECO_t + \delta_{10} BVOL_t + \delta_{11} TLIN_t + \delta_{12} TSQR_t + \delta_{13} TCUB_t + \varphi_t \quad (3)$$

$$FDEF_t = \gamma_0 + \gamma_1 FOT_t + \gamma_2 ABSENT_t + \gamma_3 FADDS_t + \gamma_4 FDELS_t + \gamma_5 FDIV_t + \gamma_6 FCOMP_t + \gamma_7 VOLUP_t + \gamma_8 VOLDN_t + \gamma_9 FECO_t + \gamma_{10} FVOL_t + \gamma_{11} TLIN_t + \gamma_{12} TSQR_t + \gamma_{13} TCUB_t + \gamma_{14} SDEF_t + \gamma_{15} GDEF_t + \gamma_{16} BDEF_t + \eta_t \quad (4)$$

where the variables in Period t are defined as:

$SDEF_t$, $GDEF_t$, $BDEF_t$, $FDEF_t$	manufacturing defect rate for the submotor, gear train, printed circuit board, and final assembly lines, respectively
SOT_t, GOT_t, BOT_t, FOT_t	overtime for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$ABSENT_t$	absenteeism rate
$SADDS_t$, $GADDS_t$, $BADDS_t$, $FADDS_t$	addition of production workers for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$SDELS_t$, $GDELS_t$, $BDELS_t$, $FDELS_t$	deletion of production workers for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$SDIV_t$, $GDIV_t$, $BDIV_t$, $FDIV_t$	product diversity for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$SCOMP_t$, $GCOMP_t$, $BCOMP_t$, $FCOMP_t$	product complexity for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$VOLUP_t$	upward fluctuations from planned production volume
$VOLDN_t$	downward fluctuations from planned production volume
$SECO_t$, $GECO_t$, $BECO_t$, $FECO_t$	engineering change orders for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$SVOL_t$, $GVOL_t$, $BVOL_t$, $FVOL_t$	production volume for the submotor, gear train, printed circuit board, and final assembly lines, respectively
$GTEXP_t$	adhesive experiment period on the gear train line
$TLIN_t$	work-team implementation linear term
$TSQR_t$	work-team implementation quadratic term
$TCUB_t$	work-team implementation cubic term
ϵ_t, ϕ, φ_t, η_t	random-residual terms

sembly line includes defect rates for submotor, gear train, and printed circuit-board lines that feed into it.

4.2. Data Collection

We collected quantitative data for this study from the plant's production, quality, personnel, and accounting records. Data on all variables except overtime were available on a weekly basis. Overtime hours were determined from accounting reports that were available only on a monthly basis. Data on all the variables except absenteeism and fluctuations from planned production rates were available by production line. While the impact of deviations from planned production rate is measured at the plant level, the effect at the individual production line is similar because production volume is coordinated among the lines.

We supplemented the collection of quantitative data with the collection of qualitative information. We conducted taped interviews with the plant manager, production engineer, team facilitator, production workers and supervisors, labor relations manager, divisional management team, and the division manager most closely associated with the plant. We took notes over a period of three years from informal discussions with several individuals associated with this plant. We collected copies of weekly action logs for each team over the study period, a description of the facility layout, process flow and functions, repair manuals and an explanation of the defect codes, interoffice correspondence, business plan, and budget information.

4.3. Conditions for an Inverted S-Curve Trajectory

We consider the properties of the defect-rate trajectory $x(t)$, where x = defect rate, and t = number of weeks since work team implementation. With reference to Figure 1, the percentage change in the defect rate is then $(x(t)/x(0)) - 1$, where $x(0)$ is the defect rate immediately preceding work team implementation. The y-axis in Figure 1 is designated as the percentage change in the defect rate, rather than simply the defect rate to facilitate comparisons among different defect-rate trajectories; the conditions for an inverted S-curve trajectory are identical because the 2 measures differ only by a constant.

A monotonically nonincreasing defect rate over time implies dx/dt is nonpositive over the entire implementation period; see Equation (5). This condition alone is sufficient to demonstrate sustainability. However, the S-curve form of sustainability further requires that dx/dt slowly becomes more negative during the initial implementation period and continues more steeply as the work teams move beyond the initial implementation period. After dx/dt reaches a minimum at the inflection point, t_{inf}, it continues to become less negative. Such a curve requires d^2x/dt^2 nonpositive for $t < t_{\text{inf}}$, 0 for $t = t_{\text{inf}}$, and nonnegative for $t > t_{\text{inf}}$; see Equation (6). Consequently, d^3x/dt^3 is nonnegative for all t, as in Equation (7). In summary, the defect-rate trajectory, $x(t)$, is characterized as follows:

$$dx/dt \le 0 \quad \forall\ t = 1, 2, \ldots, T. \tag{5}$$

$$d^2x/dt^2 \begin{cases} \le 0 & \text{for } t < t_{\text{inf}}, \\ = 0 & \text{for } t = t_{\text{inf}}, \\ \ge 0 & \text{for } t > t_{\text{inf}}. \end{cases} \tag{6}$$

$$d^3x/dt^3 \ge 0 \quad \forall\ t = 1, 2, \ldots, T. \tag{7}$$

The estimation of polynomial models, such as (1)–(4) in Table 1, often results in collinearity problems

Table 2 **Conditions for the Inverted S-Shaped Trajectory of Defect-Rate Reduction**

	Necessary Condition	Required for Equation:
1.	$\omega \ge 0$	(7)
2.	$2\gamma + 6\omega(t - \bar{t})\|_{t_{\min}} \le 0$	(6)
3.	$2\gamma + 6\omega(t - \bar{t})\|_{t_{\max}} \ge 0$	(6)
4.	$\beta + 2\gamma(t - \bar{t}) + 3\omega(t - \bar{t})^2\|_{t_{\min}} \le 0$	(5)
5.	$\beta + 2\gamma(t - \bar{t}) + 3\omega(t - \bar{t})^2\|_{t_{\max}} \le 0$	(5)

among the variables. To alleviate this concern we center the variables involving t by subtracting off the mean value of t, $\bar{t}$. Thus, we model the longitudinal effect of work-team implementation on defect rates and derivatives of this trajectory as:

$$x(t) = \alpha + \beta(t - \bar{t}) + \gamma(t - \bar{t})^2 + \omega(t - \bar{t})^3, \tag{8}$$

$$dx/dt = \beta + 2\gamma(t - \bar{t}) + 3\omega(t - \bar{t})^2, \tag{9}$$

$$d^2x/dt^2 = 2\gamma + 6\omega(t - \bar{t}), \tag{10}$$

$$d^3x/dt^3 = 6\omega. \tag{11}$$

The necessary Conditions 1–5, summarized in Table 2, are jointly sufficient for sustainability as evidenced by the inverted S-curve trajectory depicted in Figure 1.

4.4. Model Estimation and Diagnostics

Equations (1)–(4) form a system of four equations with endogenous variables from the first three equations as independent variables in the fourth equation. In general, this structure requires estimation using three-stage least squares (3SLS) with autocorrelation, if necessary (Fair 1970). However, the estimation procedure can be simplified if we determine that the equations lack contemporaneous correlation (Lahiri and Schmidt 1978).

We first checked the time-series data for autocorrelation and found evidence of first-order autocorrelation in all four equations. Further, using the Lagrange multiplier statistic (Breusch and Pagan 1980), we determined that contemporaneous correlation is not significant. Thus, the model need not be estimated using 3SLS. Because first-order autocorrelation is present, and the autocorrelation coefficient (ρ) is unknown, we estimate the model using full feasible generalized least squares (FGLS) with the Prais-Winston estimator.

The presence of heteroscedasticity can result in inefficient estimates of the parameters and biased, inconsistent estimates of their standard errors. For all the models, we plotted the residuals from FGLS regressions and found visual evidence of heteroscedasticity. White's general test (1980) confirmed the presence of heteroscedasticity. Therefore, we estimated the FGLS regression equations using White's heteroscedasticity-consistent estimator (1980).

We addressed a potential problem with collinearity among the linear, squared, and cubic terms involving weeks since work team implementation by centering these time-dependent variables. After estimating the model, we examined the variance-inflation factors (VIFs) (Neter et al. 1990) and Belsley, Kuh, and Welsch (BKW) collinearity diagnostics (1980) to check for any remaining collinearity problems. Even after centering the time-dependent variables, the diagnostics suggested potential collinearity problems between the linear and cubic terms for the printed circuit board and final assembly lines. Removing the cubic terms and reestimating these two models resulted in changes in the magnitude of the estimated coefficient for the linear terms in both the printed circuit line and final assembly regressions and a change in sign of the linear term for the printed circuit-board line regression. Thus, we must exercise caution in interpreting the individual coefficients.

Standard tests for significance of estimates and the resulting inferences are based on the assumption of normality of residuals. Using the Shapiro-Wilk test (1965), we reject the null hypothesis of normality at the 5% significance level for the submotor, gear train, and printed circuit-board regressions. However, using White's heteroscedasticity-consistent estimator to test linear hypotheses (e.g., the significance of estimated coefficients) in the usual way gives correct results asymptotically, regardless of the distribution of the residuals (White 1980).

Finally, we use influence diagnostics (Belsley et al. 1980) to identify outliers for further consideration. Observations corresponding to suspected outliers in the residuals were identified in several of the equations, ranging up to 3% of total observations. These outliers were deleted, and the regression equations were reestimated. In the submotor, gear train, and final assembly-line equations, the conclusions were essentially the same as the results using the full data set. For these equations, we report the results based on the full data set. However, in the printed circuit-board line equation, the observation corresponding to the first week after team implementation is a suspected outlier; deleting this observation changes the results somewhat. Also, because FGLS omitting the first observation is an alternative to full FGLS using the Prais-Winston estimator (Greene 1993), we estimate this equation without the first observation.

5. Discussion of Results[6]

Table 3 summarizes the equation-by-equation FGLS regression results for the system of Equations (1) to (4) corresponding to the four production lines. For the submotor, gear train, and final assembly-line equations, the F-test for the linear, quadratic, and cubic terms as a group (corresponding to work team implementation) is statistically significant at the 1% level. Further, for each of these 3 lines, none of the conditions for the inverted S-curve in Table 2 were rejected. This provides evidence in support of sustainable quality improvements following work team implementation and, in addition, for the particular form of sustainability we suggest as a benchmark. For the printed circuit-board line equation, however, the F-test for the linear, quadratic, and cubic terms for

[6]We conducted two sets of analyses to confirm that the quality improvements are associated with work team implementation. In the *first analysis*, we included data from the pre-team period, in addition to the post-team period for the four production lines in the plant. In the *second analysis*, we compared the time trajectory of quality associated with the work team implementation at the research site (experimental plant) to a similar plant at the same location without work teams (the control plant). The results of the analyses are presented in the Appendix. We gratefully acknowledge the suggestions of two anonymous reviewers to conduct these additional analyses.

work team implementation is not significant. Also, Conditions 1 and 2 for the inverted S-curve are rejected—suggesting the quality initially improves, then worsens, and then improves again—as shown in Figure 2. However, in the absence of a significant work-team effect, any further analysis of the trajectory is not warranted.

Figure 2 depicts the defect-rate trajectories following the formation of work teams on the submotor, gear train, printed circuit board and final assembly lines.[7] In the ensuing paragraphs, we discuss the results specific to the teams on each of the four production lines.

Submotor Line. Following the implementation of work teams in September 1992 through the end of our study period in December 1994, the reduction in the defect rate on the submotor line is 57% after controlling for the other variables in the model. The overall effect is significant at the 1% level. The work-team implementation trajectory, shown in Figure 2, is consistent with the posited-benchmark trajectory in which defect-rate reductions were achieved and sustained.

Gear Train Line. The reduction in the defect rate on the gear train line over our study period is 58% after controlling for the other variables in the model. The overall effect is significant at the 1% level. Two characteristics of the gear train work team are notable with respect to their impact on sustainable quality improvements. First, according to the team facilitator, relations among the team members on the gear train line were consistently congenial and collaborative. Jehn (1997) cites relationship conflict, in particular, as distracting from the performance improvement task and the resolution or lack of relationship conflict enabling the team to shift attention to the performance-improvement task and realize performance gains. Thus, immediately after work-team formation, the team members were able to focus on quality improvements, rather than initial implementation difficulties such as conflict resolution. Their ability to generate and implement improvement ideas was further reinforced by their history of working collaboratively.

Second, although the gear train line is capital intensive, the percent defect-rate reduction is the second largest among all the lines (comparable to the submotor line). This is explained by the fact that workers on the gear train line are trained machinists. Workers such as these machinists, who are extensively familiar with the equipment, have the skills to make important contributions to improving quality on the production (Baloff 1966). Both the lack of relationship conflict and alignment of the technical skills with the quality-improvement task allow the team to successfully apply its efforts to implementing quality improvements that accrue to the manufacturing process and product, and which are sustainable.

In Table 3, the coefficient estimate for overtime and upward fluctuations from planned-production volume on the gear train line is significant, indicating that higher levels of these two variables are associated with higher defect rates. Also, the coefficient estimate for dummy variable for the period (during which experiments were conducted with alternative adhesives on the gear train line) is positive and significant, indicating higher defect rates during this period.

Printed Circuit Board Line. As noted earlier, the overall model for the printed circuit board line is not significant at the 5% level. The work-team implementation variables as a group are not significant either, and the estimated effect of work team implementation on defect rates is relatively small. The insignificant result can be explained by the fact that printed circuit board line is the most capital intensive of the four production lines, but the workers on the printed circuit-board line are not highly skilled with respect to the equipment. Thus, while the printed circuit-board team is characterized by institutionalization of substantive participation, its members lack the technical skills for implementing high-impact quality improvements. An examination of the printed circuit-board team action log supports this explanation. From the beginning, the focus of the items in the action log tends to be on immediate problem resolution

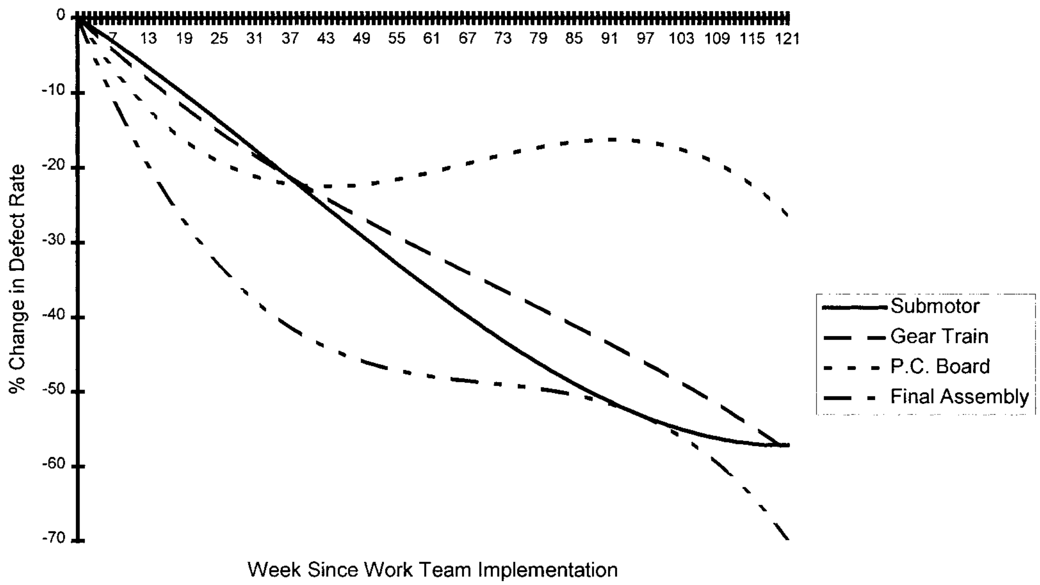
[7]Because the plots of the trajectories in Figure 2 are intended to show both the incremental performance of each team over the study period and the relative performance among the teams, we adjusted their intercepts to set all defect rates at the same initial value.

Table 3 **Equation-by-Equation FGLS Regression Results for Post-Team Period Using Heteroscedasticity-Consistent Covariance Matrix Estimator (Dependent Variable: Manufacturing Defect Rate; Standard Errors are in Parentheses)**

Variables	Submotor Line	Gear Train Line	Printed Circuit-Board Line	Final Assembly Line
Intercept	−0.00431	−0.00545	0.0409*	−0.0429
	(0.0104)	(0.0615)	(0.0195)	(0.0538)
Overtime	−0.00130	0.00391**	−0.000127	0.00152
	(0.00114)	(0.00121)	(0.00265)	(0.000879)
Absenteeism	0.0456	−0.0409	0.0261	−0.0365
	(0.0238)	(0.0487)	(0.0577)	(0.0297)
Headcount addition	0.00609	−0.00282	−0.0927	0.0274
	(0.0182)	(0.0391)	(0.0703)	(0.0438)
Headcount deletion	0.0915	−0.0558	−0.0270	0.0264
	(0.0484)	(0.0527)	(0.158)	(0.0574)
Product diversity	0.0239	0.111	0.0136	0.00193
	(0.0210)	(0.139)	(0.0124)	(0.00671)
Product complexity	0.000162	−0.0575	−0.0575	0.0693
	(0.0223)	(0.176)	(0.0540)	(0.0511)
Upward fluctuations from planned production volume	−0.0110	0.0991*	−0.0201	−0.0225
	(0.0183)	(0.0475)	(0.0634)	(0.0272)
Downward fluctuations from planned production volume	0.00269	0.0141	−0.0299	−0.00353
	(0.00817)	(0.0152)	(0.0270)	(0.0115)
Engineering change orders	0.00798	−0.0170	−0.0148	−0.000737
	(0.00903)	(0.00958)	(0.0135)	(0.00178)
Volume	0.000000422	−0.00000131	−0.00000213	−0.00000204
	(0.00000151)	(0.00000224)	(0.00000180)	(0.00000201)
Experimentation		0.0476**		
		(0.00630)		
Work-team implementation linear term	−0.000299**	−0.000231*	0.000852[a]	−0.0000581[a]
	(0.0000855)	(0.000116)	(0.000597)	(0.0000877)
Work-team implementation quadratic term	0.00000104	0.00000828	0.00000168*	0.00000193
	(0.00000163)	(0.00000165)	(0.00000711)	(0.00000114)
Work-team implementation cubic term	0.0000000159	−0.0000000191	−0.000000588*[a]	−0.0000000628[a]
	(0.0000000468)	(0.0000000489)	(0.000000232)	(0.0000000355)
Defect rate—submotor line				−0.150
				(0.0879)
Defect rate—gear train line				−0.0264
				(0.0435)
Defect rate—board line				0.0670
				(0.0356)
R^2	0.4811	0.7494	0.1585	0.3775
Adjusted R^2	0.4123	0.7129	0.0469	0.2758
F for R^2	6.990**	20.509**	1.420	3.714**
N	112	111	112	115

*$p < 0.05$.
**$p < 0.01$.
[a]Collinearity between the linear and cubic terms in these equations results in unstable estimates and difficulty in interpreting the magnitude, direction, and significance of the individual coefficients.

Figure 2 **Defect-Rate Trajectory After Work-Team Implementation**



with a few equipment requests and long-term improvement ideas.

Final Assembly Line. The reduction in the defect rate on the final assembly line over our study period is 70% after controlling for the other variables in the model. The overall effect is significant at the 1% level. This significance, despite none of the work-team implementation variables in Table 3 being significant, is explained by the masking effect of collinearity between the linear and cubic terms. According to the team facilitator, the production engineer and workers on the final assembly line had a very good working relationship and had worked together to resolve immediate problems prior to the team formation. This suggests that trust building may not have been a hindrance in the initial implementation period, allowing the team to focus on quality improvements, with early and sustainable results similar to the gear train line. On examining the action log of this line we found support for this explanation. The action log item count was high in the initial implementation period relative to the other lines. Lastly, the temporary plateau in defect-rate reduction, followed by further reductions, is consistent with sustainability and is, in fact, an insignificant departure from an S-curve, i.e., Conditions 1, 2, and 3 in Table 2 were not rejected.

6. Conclusion

The purpose of this longitudinal field study was to estimate the trajectory of manufacturing quality following work-team implementation to determine whether these quality improvements are sustainable. In conducting the study, we supplemented econometric analysis of quantitative data with qualitative data from four production lines of an electromechanical assembly plant for a period of 28 months. The qualitative data provided a rich context for developing the regression models and interpreting the results.

The primary contribution of this study is in providing a theoretical explanation and finding empirical support for the argument that manufacturing quality improvements associated with work team implementation are *sustainable.* This is an important extension to an earlier study (Banker et al. 1996) (conducted over a shorter time-period) that found empirical support only for the immediate positive impact of work team implementation. The finding of this study (i.e., quality improvements associated with work team implementation are sustainable) is especially significant when contrasted with the findings of studies examining the impact of quality circles, which is another organizational mechanism commonly used to facilitate worker participation. These studies found that performance improvements associated with quality circles are *not* sustainable.

Contrasting the manufacturing quality trajectory of the four lines has implications for managing the work team implementation process. Quality improved relatively quickly on the final assembly and gear train lines during the initial implementation period. Preexisting relations on both lines, which carried over to the work teams, were characterized by relatively low relationship conflict and a culture of collaboration. This seems to suggest the importance of being proactive in identifying initial implementation difficulties and resolving them through the early use of techniques such as group problem solving and conflict resolution training, so that the quality impact of work teams can be realized faster.

A potential limitation of this study is its 28-month length. We chose to end the study at 28 months because a number of confounding practices, such as job rotation and training in total-quality management, were being introduced at that time. Thus, 28 months was the longest period we could reasonably attribute defect-rate reductions solely to work-team implementation. However, in support of our results, follow-up interviews with management and workers more than a year and a half after the end of the study indicated that the teams continued to contribute to improvements in manufacturing quality.

Another limitation of this study, and of most longitudinal field studies, is the ‘‘generalizability’’ of findings based on a small sample size. Despite this caveat, we believe longitudinal field studies are fundamental to obtaining actionable insights into effectively managing work teams in organizations. The differential impact of different work teams on manufacturing quality, at the same plant that we document in this study, provides a start toward the development of a theory of work teams that relates the effectiveness of a team (over time) with the characteristics of the team and the production line on which it is instituted.

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Appendix

We analyzed additional data for five months before the formation of work teams on the four production lines (i.e., five months before the beginning of the study period, September 1992–December 1994) to detect the existence of a pre-team quality improvement trend. Such a trend would confound any post-team improvement trend and make it difficult to attribute quality improvements to work teams. The model we estimated was similar to the study model (Equations 1–4) but included a *pre-team time trend* measured as the number of weeks since the beginning of the five-month period before work-team implementation and 0 after work-team implementation.

The results, shown in Table A1, indicate that quality was *worsening* before work-team implementation (i.e., positive estimated coefficients for the pre-team period), with the coefficient estimates statistically significant for the submotor and printed circuit-board lines. To the extent that the analysis shows quality improving after work-team implementation, the results for the pre-team period suggest that the estimate for post-team effect is actually conservative. This ensures that the analysis of the post-time period separately is not merely reflecting a preexisting improvement trend. We prefer to analyze the post-team data separately because the estimates for the coefficients of the other variables may be affected by whether the data corresponds to pre- or post-team implementation.

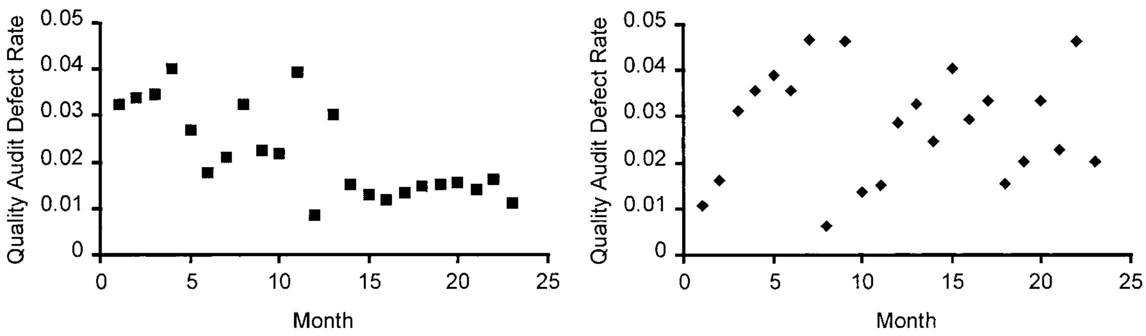
Another approach to ascertain whether quality improvements are actually related to work-team implementation is to compare quality levels at the plant with work teams (the experimental plant) to a similar plant without work teams (the control plant) over time. We chose another automated assembly plant that is at the same location and under the same general management as the control plant. Although we could not collect the same amount of detailed production and quality data for the control plant as for the experimental plant, we obtained quality audit data by month for each plant over a two-year period, 1992 and 1993, that spans the pre-team period and a portion of the post-team period. Based on the evolution of the work teams, the beginning of 1993 is when we would expect to start observing significant quality improvements (i.e., after the initial implementation period). The quality audit data measures the defect

Table A1 Equation-by-Equation FGLS Regression Results for Pre- and Post-Team Periods Using Heteroscedasticity-Consistent Covariance Matrix Estimator (Dependent Variable: Manufacturing Defect Rate; Standard Errors are in Parentheses)

Variables	Submotor Line	Gear Train Line	Printed Circuit-Board Line	Final Assembly Line
Intercept	−0.0178	−0.0764	0.0288	−0.0448
	(0.0129)	(0.0836)	(0.0630)	(0.0329)
Preteam period	0.00165**	0.00114	0.00387*	0.000161
	(0.000431)	(0.000602)	(0.00163)	(0.000429)
Overtime	−0.000666	0.00405	−0.000384	0.00276
	(0.00118)	(0.00221)	(0.00359)	(0.00147)
Absenteeism	0.00263	−0.0208	0.0218	−0.119
	(0.0300)	(0.0511)	(0.0724)	(0.0563)
Headcount addition	0.0281	−0.0264	−0.185	−0.0136
	(0.0294)	(0.0470)	(0.166)	(0.0402)
Headcount deletion	0.0900	−0.0447	−0.114	−0.0581
	(0.0461)	(0.0481)	(0.166)	(0.0603)
Product diversity	0.0197	0.0756	0.0179	−0.0110
	(0.0251)	(0.188)	(0.0197)	(0.00945)
Product complexity	0.0230	0.0383	0.0629	0.110**
	(0.0247)	(0.271)	(0.0814)	(0.0297)
Upward fluctuations from planned production volume	0.0253	0.0623	−0.177*	−0.0457
	(0.0371)	(0.0484)	(0.0884)	(0.0340)
Downward fluctuations from planned production volume	0.00728	0.0147	−0.0800*	−0.00268
	(0.00852)	(0.0195)	(0.0383)	(0.0139)
Engineering change orders	0.00283	−0.0221	0.00977	0.000890
	(0.00819)	(0.0135)	(0.0121)	(0.00318)
Volume	0.000000344	−0.00000265	−0.00000505*	−0.00000685
	(0.00000214)	(0.00000226)	(0.00000231)	(0.00000434)
Experimentation		0.0384**		
		(0.00976)		
Work-team implementation linear term	−0.000246*	−0.000371*	0.000915**[a]	0.000161[a]
	(0.0000996)	(0.000155)	(0.000328)	(0.000124)
Work-team implementation quadratic term	0.000000847	−0.00000262	0.00000464	−0.000000754
	(0.00000175)	(0.00000240)	(0.00000400)	(0.00000205)
Work-team implementation cubic term	−0.0000000128	0.0000000293	−0.000000454**[a]	−0.0000000939[a]
	(0.0000000552)	(0.0000000663)	(0.000000131)	(0.0000000476)
Defect rate—submotor line				0.183
				(0.166)
Defect rate—gear train line				−0.0109
				(0.0685)
Defect rate—board line				0.103**
				(0.0277)
R^2	0.4476	0.4620	0.2506	0.4001
Adjusted R^2	0.3815	0.3919	0.1617	0.3091
F for R^2	6.770**	6.584**	2.818**	4.394**
N	132	131	133	130

*$p < 0.05$.
**$p < 0.01$.
[a]Collinearity between the linear and cubic terms in these equations results in unstable estimates and difficulty interpreting the magnitude, direction, and significance of the individual coefficients.

Figure A1 Comparison of Experimental and Control Plants Using Quality-Audit Data



a. Experimental plant **b. Control plant**

Table A2 Regression Results for Experimental Plant with Control Plant Included (Dependent Variable: Quality-Audit Defect Rate)

Variables	Coefficient Estimate	Standard Error
Intercept	0.0206**	0.00549
Control plant defect rate	−0.130	0.120
Year = 1992 (preteam)	0.0160*	0.00595
1992 trend	−0.000638	0.000634
1993 (post-team) trend	−0.000307	0.000557
R^2	0.6203	
Adjusted R^2	0.5359	
F for R^2	7.351**	
N	23	

$*p < 0.05$.
$**p < 0.01$.

rate *after* manufacturing has addressed known defects and is a surrogate for first-pass quality. Thus, the data may provide evidence of defect-rate changes, but we would not expect to accurately observe the shape of the quality-improvement trajectory.

A comparison of the quality-audit defect rates in Figure A1 indicates that the quality-audit defect rate at the experimental plant was lower in 1993 than in 1992 (Figure A1.a), while the quality-audit defect rate in the control plant varied around the same average in both 1992 and 1993 (Figure A1.b). We regressed the experimental plant quality-audit defect rate on the control plant defect rate, a dummy variable for 1992, a trend for 1992, and a trend for 1993. More specifically, we estimated the following model:

$$DEF_t = \lambda_0 + \lambda_1 CONTRL_t + \lambda_2 PTYR_t + \lambda_3 PRETRND_t + \lambda_4 PSTTRND_t + \zeta_t,$$

where the variables in Period t are defined as:

DEF_t = Quality-audit defect rate for the experimental plant,
$CONTRL_t$ = Quality-audit defect rate for the control plant,
$PTYR_t$ = Pre-team period (1 if 1992, 0 otherwise),
$PRETRND_t$ = Pre-work-team implementation linear time trend,
$PSTTRND_t$ = Post-work-team implementation linear time trend, and
ζ_t = Random-residual term.

As shown in Table A2, there is no significant relationship between the quality-audit defect rate for the experimental and control plants, a significantly higher defect rate in 1992, and insignificant trends in 1992 or 1993. In addition, a regression of the control plant quality-audit defect rate on the latter three variables (not shown) indicated no significant effect for 1992, 1992 trend, or 1993 trend. Thus, we observe significant quality improvements for the experimental plant after the implementation of work teams and no improvement in quality for the control plant during the same period. Taken together, the results of the two sets of additional analyses provide strong evidence that the quality improvements in the experimental plant during the study period are related to work team implementation.

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