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The impact of total productive maintenance practices on manufacturing performance

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Abstract

In this paper we investigate the relationship between Total Productive Maintenance (TPM) and manufacturing performance (MP) through Structural Equation Modeling (SEM). We find that TPM has a positive and significant relationship with low cost (as measured by higher inventory turns), high levels of quality (as measured by higher levels of conformance to specifications), and strong delivery performance (as measured by higher percentage of on-time deliveries and by faster speeds of delivery). We also find that the relationship between TPM and MP can be explained by both direct and indirect relationships. In particular, there is a significant and positive indirect relationship between TPM and MP through Just-In-Time (JIT) practices.

Keywords: Maintenance and reliability; Empirical research; Statistical analysis

1. Introduction

The purpose of this paper is to present an empirical analysis of Total Productive Maintenance (TPM). While Just-In-Time (JIT), Total Quality Management (TQM) and Employee Involvement (EI) have been recognized as strong contributors to manufacturing performance (MP) both in the practitioner literature (Schonberger, 1986, Miller and Schenk, 1997) and the academic literature (Cleveland et al., 1989; Flynn et al., 1995; Jarrell and Easton, 1997; Sakakibara et al., 1997), there has been limited recognition (Maier et al., 1998) of the role that maintenance plays in improving MP. However, TPM can be thought of as integral to a World Class Manufacturing Strategy that also involves JIT, TQM, and EI. In particular, Schonberger (1986) argues that JIT, TQM, EI, *and* TPM are critical components of World Class Manufacturing. Therefore, it is hypothesized that companies that implement TPM will not only be able to enhance their maintenance practices but also improve their MP.

This paper focuses on the relationship between TPM and MP. We propose a conceptual framework to examine the nature of this relationship. Since TPM, JIT, and TQM are critical to a world class manufacturing strategy, we believe that it is necessary to consider JIT and TQM when assessing TPM. Therefore, our framework considers both direct and indirect relationships (through JIT and TQM) between TPM and MP. After

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proposing our framework, we then test it using survey data collected from 117 plants across three industries and four countries.

The remainder of this paper is organized as follows. In Section 2 of the paper, we define our model and our hypotheses. In Section 3, we describe our data. In Section 4, we discuss the measurement of our model variables. In Section 5, we present our analysis approach. Then, in Section 6, we present and discuss the results from our study. Finally, we present our conclusions.

2. Framework definition

In this section, we define the components of our framework (shown in Fig. 1) relating TPM and MP. After discussing the components of the framework, we present the theory that supports this framework and discuss the hypothesized relationships that will be analyzed in this paper.

2.1. TPM elements

Seiichi Nakajima, vice-chairman of the Japanese Institute of Plant Engineers (JIPE), the predecessor of the Japan Institute of Plant Maintenance (JIPM), promoted TPM throughout Japan and has become known as the father of TPM. In 1971, TPM was defined by JIPE as follows:

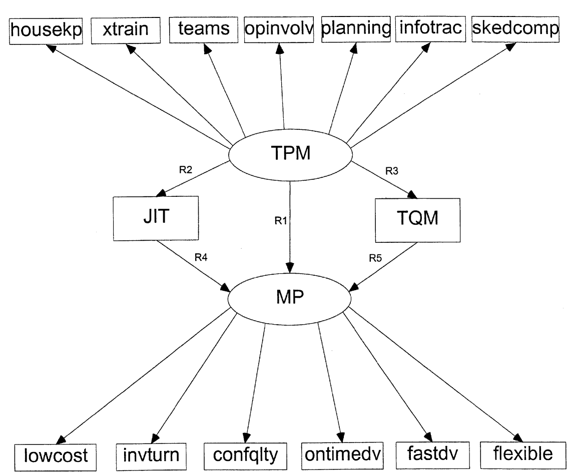

Fig. 1. Framework.

> TPM is designed to maximize equipment effectiveness (improving overall efficiency) by establishing a comprehensive productive-maintenance system covering the entire life of the equipment, spanning all equipment-related fields (planning, use, maintenance, etc.) and, with the participation of all employees from top management down to shop-floor workers, to promote productive maintenance through motivation management or voluntary small-group activities. (Tsuchiya, 1992, p. 4)

TPM provides a comprehensive company-wide approach to maintenance management, which can be divided into long-term and short-term elements. In the long-term, efforts focus on new equipment design and elimination of sources of lost equipment time and typically require the involvement of many areas of the organization. In this paper, we focus on the short-term maintenance efforts that are normally found at the plant level of the organization. In the short-term, TPM activities include an autonomous maintenance program for the production department and a planned maintenance program for the maintenance department.

Throughout this paper, we measure TPM as in McKone et al. (1999). We consider seven elements of TPM in the paper: four elements of autonomous maintenance — *housekeeping* on the production line, *cross-training* of operators to perform maintenance tasks, *teams* of production and maintenance personnel, and *operator involvement* in the maintenance delivery system; and three elements of planned maintenance — *disciplined planning* of maintenance tasks, *information tracking* of equipment and process condition and plans, and *schedule compliance* to the maintenance plan. These seven elements will be discussed in more detail in Section 4, when we discuss the measurement of our framework variables.

2.2. MP dimensions

There are many different ways of measuring MP. However, the most predominant approach in the literature is to use cost, quality, delivery, and flexibility as the four basic dimensions of MP. In some studies, these dimensions have been expanded to include several additional measures (Hayes et al., 1988; Miller and Roth, 1994). We consider the four basic dimensions because the plant is most concerned with these measures. In our study, we have two components of cost–cost as a percentage of sales and inventory turns, two components of delivery–percentage of on-time deliveries and speed of delivery, and one component each for quality and flexibility.

Use of the four basic dimensions to measure MP can be traced back to Skinner (1969) who launched the current interest in manufacturing strategy and MP measurement with his now classic article. Skinner has been followed by many others who have also advocated the four basic dimensions, including Schroeder (1993) and Ward et al. (1995). These authors have sometimes referred to the four dimensions as competitive priorities or manufacturing capabilities, but we refer to them here as MP dimensions.

2.3. JIT and TQM elements

In this paper, we consider comprehensive measures of the level of JIT and TQM implementation. We capture multiple aspects of JIT development: vendor relations, customer relations, and several aspects of JIT production — the management of materials, scheduling of resources where and when needed, and setup reduction (Sakakibara et al., 1993, 1997). We also consider several aspects of TQM development: supplier management, customer involvement, the internal system for quality, and top management leadership for quality (Flynn et al., 1994, 1996). These are indicators of the level of implementation of JIT and TQM.

2.4. Hypotheses

2.4.1. TPM positively influences MP

We first hypothesize that TPM implementation has a positive influence on MP. This hypothesis is based on the experiences of numerous companies as well as the theory discussed in the technology and strategy literature.

The benefits from implementing TPM have been well documented at numerous plants. Constance Dyer, Director of Research and TPM Product Development, Productivity Inc., says that companies that adopt TPM are seeing 50% reductions in breakdown labor rates, 70% reductions in lost production, 50–90% reductions in setups, 25–40% increases in capacity, 50% increases in labor productivity, and 60% reductions in costs per maintenance unit (Koelsch, 1993). Many companies, such as Steelcase (Koelsch, 1993), Tennessee Eastman (Garwood, 1990), Nissan (Suzuki, 1992), Nippondenso (Teresko, 1992), and Michigan Automotive Compressor (MACI, 1995) have told similar success stories. All claim that TPM had a significant impact on their maintenance effectiveness and their MP.

The academic literature also supports the idea that TPM, which enhances the technology base of the plant, can lead to improved MP. Adler and Shenhar (1990) indicate that companies that develop their technological base are able to capitalize on technology's ability to make a positive contribution to performance. TPM can improve the technological base of a company by enhancing equipment technology and improving the skill of employees (improving two of Adler and Shenhar's dimensions of technology — the technology and organizational assets). Therefore, by improving the technology of the plant, TPM should help improve MP.

Furthermore, TPM helps to improve the organization's capabilities by enhancing the problem-solving skills of individuals and enabling learning across various functional areas. Tyer (1991) and Tyer and Hauptman (1992) found that successful change in technology depends on the deployment of organizational structures that enable individuals to work across functional boundaries to identify problems, develop solutions, and execute plans. Similarly, Hayes and Wheelwright (1984) suggest that companies need to build the skills of their workforce and develop worker participation in order to compete through World Class Manufacturing. TPM changes the structure of the organization to break down traditional barriers between maintenance and production, foster improvement by looking at multiple perspectives for equipment operation and maintenance, increase technical skills of production personnel, include maintenance in daily production tasks as well as long-term maintenance plans, and allow for information sharing among different functional areas. Therefore, TPM should develop the capability of the organization to identify and resolve production problems and subsequently improve MP.

Our first hypothesis considers the relationship R1 in Fig. 1 and is referred to as

H1. *TPM has a positive and direct relationship with MP.*

2.4.2. TPM indirectly affects MP through JIT and TQM

JIT, TQM, EI, and TPM programs have often been referred to as components of "World-Class Manufacturing" (Schonberger, 1986, 1990; Steinbacher and Steinbacher, 1993). The relationship between JIT, TQM, and MP has been supported in academic research (Flynn et al., 1995, 1996). McKone et al. (1999) showed that the implementation level of TPM was closely linked to the implementation level of JIT, TQM, and EI. Companies with higher implementation levels of JIT, TQM, and EI also had higher implementation levels of TPM. A more general study by Tunälv (1992) showed empirically that business units with a manufacturing strategy placed significantly more emphasis on product- and process-related programs (such as JIT, quality management practices, and preventive maintenance) than those without a strategy. These same business units were also more successful in their financial performance.

In this study, we have not included EI as a separate component in our framework since it pervades all the other World Class Manufacturing components — TPM, JIT, and TQM — and, therefore, is implicitly included in our framework. Moreover, we cannot comprehensively capture the implementation of EI as a separate component of World Class Manufacturing due to limitations of the database that we are using. Therefore, the following discussion considers the relationships between JIT, TQM, TPM, and MP.

Hayes and Wheelwright (1984) emphasized the need to match the facilities and technology choice with business manufacturing programs and people. A manufacturing program is successful only when it improves MP and is aligned with the business strategy. Similarly, the system frameworks of various authors (Gerwin, 1976; Galbraith, 1977; Van de Ven and Ferry, 1980) all hypothesized that consistency among organizational design characteristics leads to higher performance. These studies suggest that we should not consider the impact of TPM on MP without considering the other relevant organizational characteristics.

TPM, when part of a world class manufacturing strategy that incorporates JIT and TQM, should lead to improved MP. The importance of the relationship between JIT and TPM is clear. JIT's emphasis on waste reduction creates an environment where inventory is reduced, production processes are interdependent, and the plant operation is susceptible to breakdowns of any process. TPM provides dependable equipment, reduces the number of production disturbances, and increases plant capacity by providing effective equipment maintenance. A study by Sakakibara et al. (1997) showed that there was not a significant relationship between the use of JIT practices and MP; however, the combination of JIT management and infrastructure practices were related to MP. Similarly, we believe that TPM practices indirectly influence MP by supporting JIT practices.

The relationship between TPM and TQM is also important. TQM aims to reduce variation in the product and eliminate defects. A strong maintenance program is needed to provide reliable equipment maintenance and reduce equipment process variation. Flynn et al. (1995) found that quality practices focusing solely on quality improvement might not be a sufficient means for a plant to attain and sustain its competitive position. It is likely that the use of TPM to improve equipment performance and increase the skills of workers could be an additional factor in supporting TQM and explaining competitive advantage. Therefore, we believe that TPM indirectly improves MP by supporting TQM efforts.

In this paper, we consider the indirect effect of TPM on MP through JIT and TQM. Barley (1990) indicates that technologies change organizational and occupational structures by transforming patterns of action and interaction and that roles and social networks are held to mediate technology effects. Similarly, organizational practices, such as JIT and TQM, may support TPM (a program focused on improving the technology base) and its effect on MP.

Our second set of hypotheses considers the indirect relationships between TPM and MP through JIT (R2 and R4 in Fig. 1) and through TQM (R3 and R5 in Fig. 1). Our hypotheses for the indirect relationships between TPM and MP (given that the direct relationship between TPM and MP is considered) are:

H2a. *JIT accounts for a significant portion of the positive relationship between TPM and MP.*

H2b. *TQM accounts for a significant portion of the positive relationship between TPM and MP.*

It is important to mention that our framework, as presented in Fig. 1, is one possible set of relationships. Clearly, the framework explores both the direct and indirect links between TPM and MP. While other relationships are possible (e.g., TQM influences JIT or TPM), this paper concentrates on TPM and its relationship with MP.

3. Description of data

The data used for empirical analysis of the framework were collected as part of the World Class Manufacturing (WCM) Study (Flynn et al., 1994) being conducted by a team of researchers at several universities in the US, Europe, and Asia. The WCM database used for our research was assembled in 1997 from three different regions of the world and three different industries using a common set of questionnaires. The database addresses TPM, JIT, and TQM and includes 117 different manufacturing plants.

The WCM database contains data from plants in the US, Italy, Germany, and Japan. These four countries partially represent the three major regions of the industrialized world: North America, Europe, and Asia. In each country, plants were selected from three industries: electronics, machinery, and automobile industries. A stratified design was used to randomly select an approximately equal number of plants in each country and each industry. For this study, we did not investigate cross-country or cross-industry differences. We utilized the worldwide dataset in order to test our hypotheses with a wide variety of plants.

The selected plants were contacted by a member of the WCM research team to participate in the study. Two-thirds of the plants contacted decided to join the study. This relatively high response rate was assured by contacting the plants personally and by promising that they would receive a plant profile for comparison with other plants.

The data were collected in each plant using questionnaires that were completed by 11 managers and 12 production workers. This battery of questionnaires allowed for multiple respondents for each question, thereby providing greater reliability of the data. In addition, it allowed respondents to address their particular area of expertise. For example, certain people responded to the TPM questions and others responded to the MP questions. Also, we used two types of questions: objective and perceptual. The objective questions were answered by one respondent in each plant and addressed topics which can be measured on an objective basis such as: "what percentage of the maintenance in the plant is performed by the workers rather than by a separate maintenance crew?". The perceptual questions were arranged in multi-item scales to ensure accurate representation of the constructs of interest. Each scale consisted of several questions pertaining to the same construct; the answers to the questions were averaged to arrive at a scale score. By using different types of measures and various respondents, we eliminated potential problems with common method or common respondent bias.

In the next section, the constructs of interest concerning TPM, JIT, TQM, and MP are described. These constructs are measured by a combination of perceptual scales and objective measures from the WCM database.

4. Measurement of variables

As shown in Fig. 1, we selected seven TPM measures, one measure each for JIT and TQM, and six MP measures from the WCM database which are briefly discussed in this section. In our database 41 cases had a single missing value, 7 cases had two missing values, and 3 cases had three missing values out of 15 measures. Table 1 provides summary statistics of the 15 raw observed measures.

For our analysis, we transformed the 15 measures using optimal Box–Cox transformations to satisfy normality. Then we standardized the measures by industry since we are not interested in cross-industry differences. Cross-country standardization was not performed since plants compete globally. Where necessary we replaced missing values with the mean measurement value for the industry. All measures were adjusted so that a high value reflects a high

Table 1
Summary statistics of observed measures[a]

Measure	N	Mean	Standard deviation
1. HOUSEKP	117	3.7659	0.4943
2. XTRAIN	117	3.6559	0.4499
3. TEAMS	117	3.6771	0.4933
4. OPINVOLV	110	37.7000	33.0264
5. INFOTRAC	117	3.3493	0.5546
6. PLANNING	117	2.9541	0.4905
7. SKEDCOMP	95	72.2211	30.6147
8. JIT	117	3.2712	0.3083
9. TQM	117	3.4859	0.3472
10. LOWCOST[b]	115	0.7144	0.1822
11. INVTURN	111	8.8998	10.5478
12. CONFQLTY[b]	102	5.3240	6.7818
13. ONTIMEDV	116	88.2586	12.7730
14. FASTDV[b]	110	53.2384	66.0944
15. FLEXIBLE[b]	113	2.2566	1.0158

[a]The summary statistics were calculated using the responses to the items in the survey that have not been statistically adjusted.
[b]Indicates that a low value of the measure reflects good performance.

level of program implementation or good performance. A correlation matrix and the variances of the 15 statistically adjusted measures are shown in Table 2.

We also performed Box's *M* test to determine if the combination of data from three industries and four countries is suitable for structural equation modeling (SEM). The tests performed on the statistically adjusted data provide no evidence to conclude that there is significant difference among the covariance matrices of the measures across the three industries and the four countries. Based on this analysis, we concluded that the use of our statistically adjusted dataset was sufficient for our analysis approach.

4.1. Measurement of TPM

For this study, we have selected questions from the WCM database that fit well with our literature review on TPM and concentrate on the daily maintenance efforts that could be normally found at the plant-level of the organization. These short-term TPM efforts include both autonomous and planned maintenance activities. We have chosen to concentrate on short-term daily efforts for three reasons: (1) typically TPM efforts begin with these in-plant maintenance efforts; (2) this is a plant-level study and cannot assess the organization-wide maintenance efforts; and (3) this is not a longitudinal study and cannot evaluate the long-term efforts well. See Appendix A for details of the questions used for our analysis. Rather than simply measuring the existence of a TPM program, our questions assess the level of TPM implementation.

The autonomous maintenance variables include three perceptual measures for *housekeeping*, *cross-training*, and *teams*, and an objective measure for *operator involvement*. For *housekeeping*, we utilized a five-question scale from the WCM database. These questions relate closely to the 5-S approach, a system for industrial housekeeping practices that is discussed in books by Nakajima (1988), Suzuki (1992), Shirose (1992), and Tajiri and Gotoh (1992). To assess the level of *cross-training*, we used five questions that relate to the amount of cross-training that is provided and utilized within the plant. Our measure evaluates the skills of operators and specifies whether or not an organization has established an environment where cross-training is possible. Similarly, for the autonomous maintenance *team* measure, we measured the general level of team involvement within the plant. We utilized a five-question team scale that assesses the environment that is established for pro-

Table 2
Correlation matrix and variance of observed measures[a]

Measure	TPM							JIT	TQM	MP						Variance
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1. HOUSEKP	1.000															0.983
2. XTRAIN	0.364*	1.000														0.983
3. TEAMS	0.403*	0.615*	1.000													0.983
4. OPINVOLV	0.015	0.045	0.086	1.000												0.922
5. PLANNING	0.305*	0.485*	0.531*	0.090	1.000											0.983
6. INFOTRAC	0.424*	0.378*	0.570*	−0.031	0.654*	1.000										0.983
7. SKEDCOMP	0.121	0.003	0.175	0.305*	0.272*	0.255*	1.000									0.793
8. JIT	0.207*	0.343*	0.471*	0.064	0.525*	0.558*	0.249*	1.000								0.983
9. TQM	0.374*	0.614*	0.638*	0.100	0.679*	0.722*	0.227*	0.554*	1.000							0.983
10. LOWCOST	−0.005	−0.062	−0.081	−0.073	−0.081	−0.022	−0.012	0.049	−0.146	1.000						0.966
11. INVTURN	0.061	0.265*	0.220*	−0.073	0.312*	0.280*	−0.050	0.301*	0.285*	−0.219*	1.000					0.931
12. CONFQLTY	0.308*	0.188*	0.311*	−0.006	0.290*	0.379*	0.001	0.347*	0.315*	−0.060	0.140	1.000				0.853
13. ONTIMEDV	0.098	0.232*	0.318*	0.084	0.450*	0.412*	0.207*	0.429*	0.405*	−0.057	0.293*	0.225*	1.00			0.974
14. FASTDV	−0.062	0.111	0.239*	0.092	0.232*	0.184*	0.044	0.394*	0.169	0.116	0.268*	0.165	0.269*	1.000		0.922
15. FLEXIBLE	0.151	0.109	0.126	−0.081	0.022	0.108	0.160	0.192*	0.009	0.098	0.088	0.013	−0.035	0.187*	1.000	0.948

[a]The correlation matrix and variances were computed from the statistically adjusted measures. Statistical adjustments performed include Box–Cox transformation, standardization by industry, replacement of missing values with industry mean, and adjustment so that a high value in a measure reflects a high level of program implementation or good performance.

*Indicates that the correlation is significant at the 0.05 level (two-tailed).

duction and maintenance teams. Finally, for *operator involvement*, we used an objective measure of the percentage of operators who are directly involved in the maintenance delivery process. This measure provides another indicator of the implementation level of autonomous maintenance.

While both the operators and maintenance personnel are involved in the planning and execution of maintenance within a TPM program, the maintenance personnel are ultimately held accountable for long term maintenance planning and the state of readiness of the equipment. With the data that was available, we considered three measures of planned maintenance: two perceptual measures for *disciplined planning* and *information tracking*, and an objective measure for *schedule compliance*. A *disciplined planning* approach typically dedicates time for scheduled maintenance activities, assigns tasks to specific people and inspects for good quality workmanship. We considered four questions that address the planning of the maintenance department. An information system that tracks past and current equipment performance is also important to a successful maintenance department. We assessed the *information tracking* systems that are relevant to equipment performance through five questions. Finally, compliance to a planned maintenance schedule is a measure of the successful application of the maintenance tools and execution of the plans. We used a self-reported *schedule compliance* measure as another indicator of planned maintenance implementation.

4.2. Measurement of MP

In this study, we are measuring MP at the plant level. Since the plant does not control sales or costs outside the plant, overall financial measures of plant performance are not appropriate. Rather, the basic dimensions of plant performance which are controlled by the plant are used: cost, quality, delivery, and flexibility (Skinner, 1969; Schroeder, 1993; Ward et al., 1995). We discuss our measurement of each of the four dimensions of plant performance in this section. Appendix B has the details of our survey questions on MP.

Cost is interpreted to mean not only the traditional accounting cost of manufacturing, but also the economic costs associated with inventories. For manufacturing cost, we measured the manufacturing cost of goods sold as a percentage of sales. We measured inventory costs as the inventory turnover ratio. A high turnover ratio indicates a low cost position. Both of these ratios are dimensionless and are not subject to currency differences between countries.

Quality from a manufacturing point of view is measured as the percentage of good products that are produced (conformance to specifications) or if the quality is good enough defects can be measured in ppm (parts per million). Of course, quality can also be measured by customer satisfaction, which is influenced not only by the lack of defects but also by product designs and after-sales service. Since product design and service are cross-functional responsibilities, we do not include customer satisfaction here as a MP measurement and only consider conformance quality.

Delivery performance includes two different measures: the percentage of orders delivered on time (or filled from stock) and the manufacturing lead-time from when an order is placed until it is delivered. These measures are indicative of a plant's ability to deliver quickly and as promised.

Finally, flexibility can be measured in a number of different ways. We have chosen to use one measure: the length of time that it takes to change the master production schedule. Most plants have a frozen production horizon inside of which they do not take additional orders or make changes to existing orders. This production horizon measures a plant's capability to make changes and, of course, a shorter horizon offers more flexibility.

4.3. Measurement of JIT and TQM

Our goal for measuring JIT and TQM was to measure the general level of program implementation rather than to simply consider the existence of the specific program. Since the focus of this study is the relationship between TPM and MP, we measured JIT and TQM at an aggregate level, using one manifest variable for each, combining several aspects of program implementation. We did not include the years of implementation efforts since we were more concerned with the level of JIT or TQM implementation than the time since initial adoption. See Appendix

C for details of the survey questions used for our measures.

To measure the implementation of JIT, we considered various JIT practices and developed a linear combination of five scales used in Sakakibara et al. (1993, 1997). Our measurement captures JIT delivery by suppliers, JIT link with customers, pull system support, repetitive nature of the master production schedule, and setup reduction efforts within the plant. This is a comprehensive measurement of JIT involving five different scales that measure different aspects of JIT.

To measure the implementation level of TQM, we considered customer involvement, rewards for quality, supplier quality management, and top management leadership for quality. Previous studies have found that these aspects of TQM adequately represent a broad-based view of the construct (Flynn et al., 1994, 1996).

4.4. Validity and reliability of scale measures

Our research used data from the WCM Study and many of the constructs have been used and tested in previous studies (Sakakibara et al., 1993, 1997; Flynn et al., 1994, 1996; McKone et al., 1999). In addition, the items used for each construct fit well with the concepts of TPM, JIT, and TQM discussed in the framework and existing literature and therefore have a high degree of content validity. Although it may be difficult to completely separate the concepts of TPM, JIT, and TQM, the measures used for these constructs are not identical. The discriminant validity of the factors for TPM, JIT, and TQM were tested using confirmatory factor analysis approach (Bagozzi, 1980; Burnkrant and Page, 1982). In the tests, models of separate but correlated factors were compared to models in which the pair of factors was hypothesized to have a unity correlation or to be unidimensional. The difference between the two models was evaluated using a change in χ^2 test with one degree of freedom. In the comparisons of the TPM–JIT models and the TPM–TQM models, the χ^2 difference values were significant, indicating that TPM is indeed a separate scale and is only correlated with JIT and TQM.

We used Cronbach's coefficient α to evaluate the reliability of the scales at the plant-level. The α scores for each scale ranged from 0.77 to 0.90. Since all α scores were considerably higher than the 0.70 acceptable level advocated by Nunnally (1978), all scales exhibit a high degree of reliability.

5. Method of analysis

Our analysis focused on understanding the nature of the relationship between TPM and MP. Through SEM using AMOS 3.61 (Arbuckle, 1997), we tested our specified framework (refer to Fig. 1 for a diagram of the model and the testable paths). We evaluated our measurement model and considered the relationship between observed TPM measures and a latent TPM construct, and between plant performance measures and a latent MP construct. We also tested our specified hypotheses between the latent TPM and MP constructs and the observed JIT and TQM measures. The results of the SEM analysis allowed us to describe the correlation between variables, to understand which TPM variables best explain the TPM construct, to understand the nature (direct and indirect) of the relationship between TPM and MP, and to understand which MP measures best explain the MP construct (the variables that are highly influenced by TPM).

We took a hierarchical (staged) approach to testing hypothetical models that describe the relationship between both observed and unobserved measures for TPM, JIT, TQM, and MP. This staged approach, similar to hierarchical regression, allows us to determine if the addition of new set of relationships adds significantly to our explanation of the variation in the data. Therefore, we can test H2a and H2b by evaluating the difference in model fit when the indirect relationships are added to the model.

At each stage of the model testing process, we verified that the assumptions required for SEM were met. The critical ratio of Mardia's (1970, 1974, 1985) coefficients of separate and joint multivariate kurtosis and skewness did not indicate significant differences from zero (Bollen, 1989). Tests using Mahalanobis distance showed no evidence of the existence of outliers. χ^2 plots of the squared Mahalanobis distances did not exhibit any systematic curvature. Thus, there is no evidence to conclude that the data does not satisfy multivariate normality.

For each of our models, maximum likelihood estimation was used, the procedure converged for estimation, the model was identified, and all residual variances were positive. At each step of the model testing process, we compared the fit of the models. For model evaluation, we used several standard model evaluation criteria. (1) The Degrees of Freedom (*DF*) represents the difference between the number of independent statistics and the model parameters fitted. (2) The Likelihood Ratio Test (LRT) statistic is minimized and is usually interpreted as a χ^2 variate. (3) The Likelihood Ratio Test to Degrees of Freedom (LRT/*DF*) Ratio is a relative χ^2 measure for model fit. A value of less than 5 for this ratio indicates acceptable fit (Wheaton et al., 1977; Marsh and Hocevar, 1985). (4) The Goodness of Fit Index (GFI) rescales the fit of the observations and the expectations between 0 and 1, where 1 represents a perfect fit. (5) Bollen's (1989) Incremental Fit Index (IFI) basically represents the point at which the model being evaluated falls on a scale running from the null model (where all correlations are zero) to a perfect fit, where a perfect fit would equal 1. This index is adjusted for the *DF* of the model. (6) The Root Mean Square Residual (RMR) index represents the average size of the residual correlations. (7) The Root Mean Square Error of Approximation (RMSEA) is a measure of the population discrepancy that is adjusted for the *DF* for testing the model. A value of 0.08 or less for RMSEA would indicate a reasonable error of approximation (Browne and Cudeck, 1993).

There is one common problem encountered in testing all model hypotheses in SEM. The LRT can be interpreted as a χ^2 variate for testing the null hypotheses of zero residual correlations; however, the χ^2 variate is sensitive to sample size (Cochran, 1952; Bentler and Bonnet, 1980). For example, an insignificant χ^2 value does not always indicate a poor model fit and does not suggest that a model is not meaningful (Hayduk, 1996). Instead, we need to look at other model fit statistics and also compare the difference in fit between models. By comparing the difference in LRT statistics (dLRT) with the associated difference in degrees of freedom (d*DF*), we can test whether a model improves the fit over another nested model (Anderson and Gerbing, 1988; Mulaik et al., 1989; McArdle and Prescott, 1992). In this way, we are able to separate a good-fitting model from a poor-fitting model and can determine if one model provides a significantly better fit than another model. To test our hypotheses, we need to determine if the addition of a new relationship to our model helps to improve the explanation of the variation in the data. Therefore, comparing the difference in LRT statistics (dLRT) with the associated d*DF* is important to testing our hypotheses.

6. Results and discussion

Through SEM, we tested our hypothesized relationships between TPM and MP. Each stage of our analysis resulted in a new model, the results of which are shown in Table 3. Models 2, 3, and 4 are a nested sequence of models that allow us to provide information about distinct aspects of the structural equation model embedded within the sequence. By using the dLRT statistics, we are able to isolate where fit and lack of fit arise in the model in the nested sequence and can test hypotheses H2a and H2b. In this section, we will review our analysis results and discuss the meaning of the results. First, we discuss our test for hypothesis H1 and then proceed to discuss tests for both hypotheses H2a and H2b.

The first step in our analysis was to test hypothesis H1, the direct relationship between TPM and MP. We considered a model without JIT and TQM measures (Model 1 in Table 3) and found that TPM has a positive and significant relationship with MP. The model showed that a 0.80 coefficient explained the relationship between the latent TPM and MP constructs. The fit of the model without JIT and TQM was good, with LRT/*DF*=1.73, GFI=0.88, IFI=0.85, RMR=0.07, and RMSEA=0.08.[1] As a result, we cannot reject hypothesis H1 that TPM has a positive relationship with MP.

Our results show that the TPM construct primarily consists of six measures: three autonomous maintenance measures–housekeeping (item loading=0.48), cross-training (0.62), and teams (0.75); and three

[1] We have considered values of the model fit criteria that are slightly below the cutoff values recommended by some authors. Since we are primarily interested in the differences in fit between models, we considered this model as an acceptable starting point.

Table 3
Results of SEM
The parameter estimates are standardized maximum likelihood estimates

Parameter estimates	Models			
	Model 1: TPM related to MP without JIT and TQM in the model	Model 2: TPM related to MP and unrelated to JIT and TQM	Model 3: TPM related to MP and related to JIT and TQM	Model 4:[a] TPM related to MP with indirect effect through JIT and TQM
Factor loadings				
TPM→housekp	0.48	0.48	0.45	0.45
TPM→xtrain	0.62	0.62	0.63	0.64
TPM→teams	0.75	0.75	0.74	0.74
TPM→opinvolv	0.07*	0.07*	0.09*	0.09*
TPM→planning	0.79	0.79	0.78	0.78
TPM→infotrac planning	0.79	0.79	0.81	0.81
TPM→skedcomp	0.27	0.27	0.27	0.27
MP→lowcost	−0.11*	−0.11*	−0.12*	−0.03*
MP→invturn	0.46	0.46	0.46	0.43
MP→confqlty	0.45	0.45	0.44	0.44
MP→ontimedv	0.60	0.60	0.61	0.57
MP→fastdv	0.38	0.38	0.38	0.44
MP→flexible	0.12*	0.12*	0.10*	0.18*
Path coefficients				
TPM→MP (R1)	0.80	0.80	0.80	0.81
TPM→JIT (R2)		0.00[b]	0.66	0.64
TPM→TQM (R3)		0.00[b]	0.87	0.89
JIT→MP (R4)		0.00[b]	0.00[b]	0.46
TQM→MP (R5)		0.00[b]	0.00[b]	−0.35*
Evaluation criteria				
DF	64	91	89	87
LRT	110.44	336.09	150.30	137.19
LRT/DF	1.73	3.59	1.69	1.58
GFI	0.88	0.76	0.86	0.87
IFI	0.85	0.52	0.88	0.90
RMR	0.07	0.19	0.07	0.07
RMSEA	0.08	0.15	0.08	0.07

[a] Indicates that the model is the best fitting model.
[b] Indicates a fixed parameter.
* Indicates a free parameter that is not significantly different from zero ($t<2.0$).

planned maintenance measures–information tracking (0.79), disciplined planning (0.79), and schedule compliance (0.27). One of the autonomous maintenance measures — operator involvement — does not have a significant relationship with our TPM construct. In addition, schedule compliance, while significant, is poorly explained by our TPM construct (squared multiple correlation of 0.07). Both of these measures are objective measures, measured on different scales than the other TPM measures. These objective measures also have more missing values. It is possible that these measures have measurement error or do not accurately represent the nature or level of TPM implementation at the plant.

Even though two of the TPM measures have low item loading, they were not excluded from subsequent analyses because item loading of all measures remain stable whether or not they were excluded from the model. Furthermore, the exclusion of the low loading measures from the models led to poorer overall model fit. Our MP construct consists of four statistically significant measures of performance. High MP is consistent with low cost (as measured by higher inventory turns [item loading=0.46]), high quality levels (as measured by higher levels of conformance to specifications [0.45]), and strong delivery performance (as measured by a higher percentage of on-time deliveries [0.60] and by faster speeds of delivery [0.38]). Therefore, our TPM construct influences our MP construct and is associated with low cost inventory positions, high internal quality, and responsive delivery.

However, our MP construct, and therefore our TPM construct, has no significant relationship with low cost (as measured by manufacturing cost as a percentage of sales) or flexibility (as measured by the time horizon of the fixed production schedule). The non-significant relationship with low cost may be explained by the following: (1) maintenance is a small portion of total costs, and therefore, a change in maintenance costs has a non-significant impact on our cost measure; (2) manufacturing costs are calculated in different ways depending upon the company; therefore, it is difficult to compare the results between companies; or (3) TPM allows for effective use of the budgeted maintenance expenses and is able to improve inventory turns, quality, and delivery while maintaining stable production costs. The non-significant relationship with flexibility could be a result of our measure of flexibility. It is difficult to change the planning horizon without process, equipment, and planning system modifications. Another possible explanation is that the transformation of our flexibility measure, while helpful in satisfying condition for normality, may not represent the non-linear relationship between TPM and flexibility.

Nevertheless, it is interesting to notice the multi-dimensionality of our MP construct. TPM does not impact only one dimension of MP but impacts several dimensions of performance. The idea of compatibility of manufacturing dimensions had been discussed in recent literature. Ferdows and De Meyer (1990) proposed a “sandcone” model which represents a sequential approach to achieving compatibility among the four dimensions. Also, Hayes and Pisano (1996) and Menda and Dilts (1997) advocate compatibility of manufacturing dimensions and the absence of trade-offs. While maintenance has traditionally been seen as a means of controlling cost, our results show that TPM simultaneously impacts components of cost, quality, and delivery.

Next, we tested hypotheses H2a and H2b. To test these hypotheses, we explored a series of nested models that included our TPM and MP constructs as well as our JIT and TQM measures. The results of these models are shown in Table 3. First, we tested the direct relationship between TPM and MP, when JIT and TQM are unrelated to TPM and MP (Model 2). For this model, all relationships in Fig. 1, except R1, are set equal to zero. The fit of Model 2 is significantly better than a model where the relationship between TPM and MP is also set to zero (dLRT=39.13 on d*DF*=1). However, overall this model has a relatively poor fit (LRT/*DF*=3.59, GFI=0.76, IFI=0.52, RMR=0.19, and RMSEA=0.15). The poor fit is due to the fact that we consider there to be no relationship between JIT and TQM and any other latent or manifest variable in the model. It is likely that JIT, TQM, TPM, and MP are related in some manner.

Next, we considered several models where the relationships between TPM and JIT and TPM and TQM are tested. Model 3 permits TPM to influence MP as well as the level of JIT and TQM implementation, allowing R1, R2, and R3 from Fig. 1 to be non-zero while R4 and R5 are set equal to zero. When the fit of Model 3 is compared to the fit of Model 2, there is a significant improvement in fit (dLRT=185.79 on d*DF*=2). This suggests that when a plant has multiple manufacturing practices, they cannot be considered to be independent; rather, they can be considered to be mutually supportive of each other. In this case, TPM has a significant and positive influence on both JIT and TQM implementation, indicating a reliable association of TPM with JIT and TQM and supporting our hypothesized relationships. This result is also consistent with McKone et al. (1999) where higher levels of TPM implementation were associated with higher levels of JIT and TQM implementation.

Model 4 enables us to test the set of hypotheses H2a and H2b, the indirect relationship of TPM with MP (R1, R2, R3, R4, and R5 are all allowed to be non-zero). This model has a good fit (LRT/*DF*=1.58, GFI=0.87, IFI=0.90, RMR=0.07, and RMSEA=0.07) and also improves the fit over previous models. When compared to Model 2, where only direct relationships between TPM and MP are considered, Model 4 significantly improves the fit of the model (dLRT=198.90 on d*DF*=4). This suggests that TPM has both direct and indirect relationships with MP. By comparing Model 3 to Model 4 (dLRT=13.11 on d*DF*=2), we see that while Model 3 provides a good fit, Model 4 provides a better fit to our data. Model 4, not only considers the direct relationships between TPM and JIT, TQM and MP but also the indirect relationships between TPM and MP (through JIT and TQM).

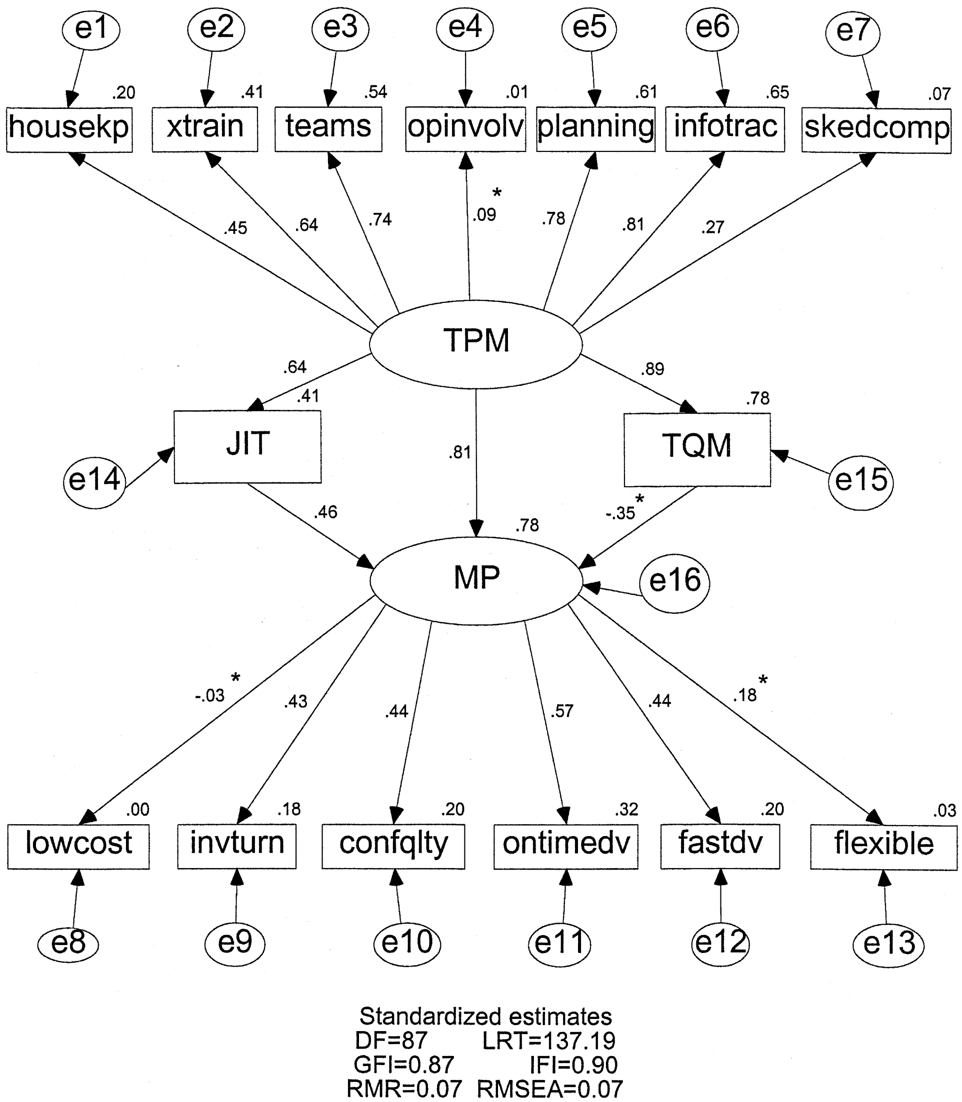

Fig. 2. Best fitting model — Model 4. A value along an arrow is a standardized factor loading or path coefficient. A value above an endogenous variable indicates the squared multiple correlation (SMC) between that variable and the variables (other than residual variables) directly affecting it. The "*" indicates a free parameter that is not significantly different from zero (t<2.0).

Our final model, Model 4, is the best fitting model and is pictured in Fig. 2. It is important to notice that the relationship between TQM and MP, R5 in Fig. 1, is non-significant. This leads us to reject hypothesis H2b. There are three possible explanations for this result. (1) Our definition of TPM included some measures that could be included in TQM. In fact, the variance of our TQM measure is mostly explained (0.78 is the squared multiple correlation, shown in Fig. 2) by our TPM construct. This suggests that TPM and TQM are interrelated. (2) TQM represents an integrated theory of management philosophy (Powell, 1995) rather than a clearly defined technology or set of techniques. It is feasible that TQM could invoke a goal of improving quality without dictating a well-defined routine for accomplishing it (Westphal et al., 1997). Campbell (1994, p. 7) mentions that when TQM acquires institutional status, quality practices may be evaluated by a "logic of social appropriateness" rather than a "logic of instrumentality". (3) Loose coupling may occur between TQM practices designed for customer demands and the activities on the plant floor designed for plant performance. TQM is found to have a stronger impact on customer satisfaction than plant performance (Choi and Eboch, 1998). Perhaps TQM, as measured in this study, considers the socially accepted aspects of the program rather than the instrumental aspects of the program that would directly improve MP. This helps explain why TQM, as measured in this paper, does not contribute to MP and why TPM does provide such a large explanation of MP. Our TPM construct has a clearly defined set of methods for improving performance while our TQM measure considers only general management approaches.

While TQM does not provide a significant explanation of the positive relationship between TPM and MP, the relationship between TPM and MP through JIT is significant and positive (R2 and R4 in Fig. 1). Therefore, we cannot reject hypothesis H2a. Our results support our theory that TPM helps improve the equipment performance which in turn supports JIT's efforts to reduce inventory, shorten lead-times, and eliminate other wastes. The impact of TPM should not be considered in isolation but must be considered with respect to the other manufacturing practices. These results augment those of Sakakibara et al. (1997), who showed that a combination of JIT management and infrastructure practices were related to MP. Our results suggest that JIT practices need to be supported by TPM efforts and that together JIT and TPM can improve MP.

7. Conclusions

The results of the analyses indicate that TPM, as measured for this paper, has a strong positive impact on multiple dimensions of MP. While TPM directly impacts MP, there is also a strong indirect relationship between TPM and MP through JIT. Our results are important for two reasons. (1) Maintenance programs have long been used as a means to control manufacturing costs. Our results show that TPM does more than control costs, it can improve dimensions of cost, quality, and delivery. TPM can be a strong contributor to the strength of the organization and has the ability to improve MP. (2) World Class Manufacturing programs, such as JIT, TQM, and TPM, should not be evaluated in isolation. They are closely related and in combination can help foster better MP. Future research should further consider the relationships between these practices and their combined impact on performance.

We plan to continue our research in this area to further explain the relationship between manufacturing practices and MP. In particular, we plan to identify the common infrastructural and unique practices of TQM, JIT, and TPM, and test their interrelationships and impact on MP. Also, we would like to investigate the nature of the relationships in different contextual situations (for example, cross-country and cross-industry differences), combining the work from McKone et al. (1999) and this paper. In addition, we would like to consider the life cycle of the practices and evaluate the impact of the development time on MP. Hopefully, this type of research will support and encourage successful implementation of TQM, JIT, and TPM.

Based on this research, the authors recommend that practitioners pay closer attention to their maintenance management practices and their impact not only on costs but also on quality and delivery performance. Our future research will provide additional details about specific practices that lead to improved performance in various environmental and organizational situations.

Appendix A. Measurement of TPM implementation

Concept	Factor	Measure
Autonomous maintenance	House-keeping, α=0.8563[2]	Our plant emphasizes putting all tools and fixtures in their place.
		We take pride in keeping our plant neat and clean.
		Our plant is kept clean at all times.
		I often have trouble finding the tools I need.[3]
		Our plant is disorganized and dirty.[3]
	Cross-training, α=0.8005[2]	Employees receive training to perform multiple tasks.
		Employees at this plant learn how to perform a variety of tasks/jobs.
		The longer an employee has been at this plant, the more tasks or jobs they learn to perform.
		Employees are cross-trained at this plant so that they can fill in for others if necessary.
		At this plant, employees only learn how to do one job/task.[3]
	Teams, α=0.8812[2]	During problem solving sessions, we make an effort to get all team members' opinions and ideas before making a decision.
		Our plant forms teams to solve problems.
		In the past 3 years, many problems have been solved through small group sessions.
		Problem solving teams have helped improve manufacturing processes at this plant.
		Employee teams are encouraged to try to solve their problems as much as possible.
	Operator involvement	What percent of the maintenance on the machines involved in the production of this product is performed by the workers, rather than by a separate maintenance crew?[4]
Planned Maintenance	Disciplined planning, α=0.7666[2]	We dedicate a portion of every day solely to maintenance.
		We emphasize good maintenance as a strategy for achieving quality and schedule compliance.
		We have a separate shift, or part of a shift, reserved each day for maintenance activities.
		Our maintenance department focuses on assisting machine operators perform their own preventive maintenance.
	Information tracking, α=0.8132[2]	Charts plotting the frequency of machine breakdowns are posted on the shop floor.
		Information on productivity is readily available to employees.
		A large percent of the equipment or processes on the shop floor are currently under statistical quality control.
		We use charts to determine whether our manufacturing processes are in control.
		We monitor our processes using statistical process control.

[2] α refers to Cronbach's alpha, used to measure the reliability of the scale.

[3] Indicates that the variable is reversed scored.

[4] Response is in terms of percentage. All other responses are in the scale score format with 1 being strongly disagree and 5 being strongly agree.

Schedule compliance	What percent of the time is the maintenance schedule (for equipment used to produce this product) followed?[4]

Appendix B. Measurement of MP

Concept	Meaning	Measure
Low cost (LOWCOST)[5]	Manufacturing cost of goods sold as a percentage of sales.	Manufacturing costs / Sales value of production
Inventory turnover (INVTURN)	Manufacturing cost of goods sold as a percentage of average inventory.	Manufacturing costs / (Value of average annual finished goods inventory; Value of average annual work-in-process inventory; Value of average annual raw materials inventory)
Quality (CONFQLTY)[5]	Conformance to specifications.	What is the percentage of internal scrap and rework?
On-time delivery (ONTIMEDV)	Ability to deliver as promised.	What percentage of the orders are shipped on time?
Fast delivery (FASTDV)[5]	Ability to deliver quickly.	What is the average lead-time from the receipt of an order until it is shipped (in days)?
Flexibility (FLEXIBLE)[5]	Flexibility to change master production schedule.	What is the time horizon for the fixed production schedule? (1) 1 day, (2) 1 week, (3) 1 month, (4) 3 months or more

Appendix C. Measurement of JIT and TQM Implementation

Concept	Factor	Measure
JIT, α=0.9045[6]	JIT delivery by suppliers	Our suppliers deliver to us on a JIT basis.
		We receive daily shipments from most suppliers.
		Our suppliers are certified, or qualified, for quality.
		We have long-term arrangements with our suppliers.
		Our suppliers deliver to us on short notice.
		We can depend upon on-time delivery from our suppliers.
		Our suppliers are linked with us by a pull system.
	JIT link with customers	Our customers receive JIT deliveries from us.

[5] Indicates that the variable is adjusted so that a high value reflects good performance.

[6] α refers to Cronbach's alpha, used to measure the reliability of the scale.

		Most of our customers receive frequent shipments from us.
		We are expected to supply on short notice to our customers.
		We always deliver on time to our customers.
		We can adapt our production schedule to sudden production stoppages by our customers.
		Our customers have a pull type link with us.
	Pull system support	We use a back-flushing system, where components are subtracted from inventory every time a product is made.
		We have laid out the shop floor so that process and machines are in close proximity to each other.
		Direct Labor is authorized to stop production for quality problems.
		We use a pull system for production control.
		The control of production is in the hands of the workers.
		Generally, workers on the production floor have the authority to decide how to handle production problems.
		We have low work-in-process inventory on the shop floor.
		When we have a problem on the production floor, we can identify its location easily.
	Repetitive nature of master schedule	Our master schedule repeats the same mix of products from hour to hour and day to day.
		The master schedule is level-loaded in our plant from day to day.
		We make every model every day.
		A fixed sequence of items is repeated throughout our master schedule.
		We are able to use a mixed model schedule because our lot sizes are small.
		Within our schedule, the mix of items is designed to be similar to the forecasted demand mix.
	Setup reduction	We are aggressively working to lower setup times in our plant.
		We have converted most of the setup time to external time while the machine is running.
		We have low setup times of equipment in our plant.
		Our crews practice setups to reduce the time required.
		Our workers are trained to reduce set-up time.
		Management emphasizes importance of set-up time reduction.
TQM α=0.8934[6]	Customer involvement	We frequently are in close contact with our customers.
		Our customers seldom visit our plant.[7]

[7] Indicates that the variable is reversed scored.

	Our customers give us feedback on quality and delivery performance.
	Our customers are actively involved in the product design process.
	We strive to be highly responsive to our customers' needs.
	We regularly survey our customers' requirements.
Rewards for quality	Workers are rewarded for quality improvement.
	Supervisors are rewarded for quality improvement.
	If I improve quality, management will reward me.
	We pay a group incentive for quality improvement ideas.
	Our plant has an annual bonus system based on plant productivity.
	Non-financial incentives, such as jackets, coffee cups, etc., are used to reward quality improvement.
Supplier quality management	We strive to establish long-term relationships with suppliers.
	Our suppliers are actively involved in our new product development process.
	Quality is our number one criterion in selecting suppliers.
	We rely on a small number of high quality suppliers.
	We use mostly suppliers which we have certified.
	We maintain close communication with suppliers about quality considerations and design changes.
Top management leadership for quality	All major department heads within our plant accept their responsibility for quality.
	Plant management provides personal leadership for quality products and quality improvement.
	The top priority in evaluating plant management is quality performance.
	All major department heads within our plant work towards encouraging JIT production.
	Our top management strongly encourages employee involvement in the production process.
	Plant management creates and communicates a vision focused on quality improvements.
	Plant management is personally involved in quality improvement projects.

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