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The literature on JIT production suggests a causal link between work-in-process inventory and manufacturing productivity. Such a connection has been described in numerous case studies but never tested statistically. This paper uses historical data for 52 Japanese automotive companies to evaluate the inventory-productivity relationship. We find that firms increased their productivity rank during periods of substantial inventory reduction. More detailed tests suggest that inventory reductions stimulated gains in productivity: On average, each 10% reduction in inventory led to about a 1% gain in labor productivity, with a lag of about one year. Such effects were more immediate for Toyota affiliates, but undetectable for close suppliers of Nissan. These findings imply that inventory reduction served as an important driver of process improvement for many Japanese automotive companies, although some firms emphasized other methods.
(*Inventory*; *Productivity*; *Just-In-Time Manufacturing*; *Auto Industry*; *Japan*; *Empirical Study*)

1. Introduction

In recent years manufacturing managers and academic researchers have dramatically changed their view of work-in-process (WIP) inventories. These inventories, held as a buffer between processing steps in manufacturing plants, were once considered essential for maintaining a steady production flow. But the wide acceptance of “just-in-time” (JIT) production has led to the contrary view that these inventories prevent the discovery of problems on the shop floor and can thus be detrimental to productivity. According to this new perspective, inventory reductions expose defects in the manufacturing process, forcing managers and workers to eliminate (rather than accommodate) sources of process variability.

Various authors have described causal mechanisms linking inventory reduction to productivity growth (e.g., Schonberger 1982, Hall 1983). Nevertheless, many questions remain unanswered. Does inventory reduction lead to productivity gains, or does it merely serve as an indicator that process variability has been reduced so that less buffer stock is required? And if inventory reductions do stimulate productivity gains, how quickly do the gains appear, and what is the magnitude of effect?

Details of JIT implementation have been addressed in numerous case studies, but there has been little statistical analysis of the connection between work-in-process inventory and manufacturing productivity.[1] In this paper we investigate this connection using data

[1] For case studies, see Monden (1981, 1983) and surveys by Im and Lee (1989) and Voss and Robinson (1987).

for 52 Japanese automotive assemblers and parts suppliers over the period from 1965 to 1991.

We employ three different statistical approaches to evaluate the nature and magnitude of linkage between WIP inventory and productivity. First, we apply an algorithm to the inventory data to identify periods of substantial WIP reduction. During these periods, firms are found to have (1) increased their productivity rank, and (2) exhibited significantly higher rates of productivity growth. Second, we use regression analysis to examine the correlation between inventory levels and labor productivity. Third, we perform more elaborate tests of the time structure of inventory-productivity relationships. These tests show that WIP reductions were followed on average by productivity gains, with a typical lag of about one year. Significant differences are observed, however, between "keiretsu" company groups. In general, the findings point to a statistically significant link between WIP reduction and productivity growth for most companies in our sample.

2. Theoretical Framework

The connections between work in process inventory and factory productivity can be represented in a causal link diagram, as shown in Figure 1. This diagram illustrates the links between productivity, the level of WIP, and the detection, analysis, and resolution of production problems.

Figure 1 makes a distinction between "actual" and "required" WIP inventory. In any production line, WIP is used to protect the production flow from the variability and discontinuities of production. In general, as variability rises and as discontinuities become more pronounced, more WIP will be necessary to achieve a certain level of output. The minimum amount of WIP needed to guarantee the desired level of output is what is called "required WIP inventory" in the diagram. Depending on how the production line is managed, actual WIP inventory will fall behind, equal, or exceed the required level.

The diagram shows five important links, which can be characterized as follows. If the gap between actual and required WIP inventory is made small, the production problems that create the need for buffer inventories become visible (Link 1). Types of problems that may surface include machine failures, defective production, time-consuming machine setups, long transportation distances, unbalanced lines, and lack of coordination. Link 1 is often described by the "rocks in the water" metaphor for JIT: The *rocks* on the bottom of the riverbed (the production problems) are exposed by lowering the *water* in the river (the amount of WIP inventory).

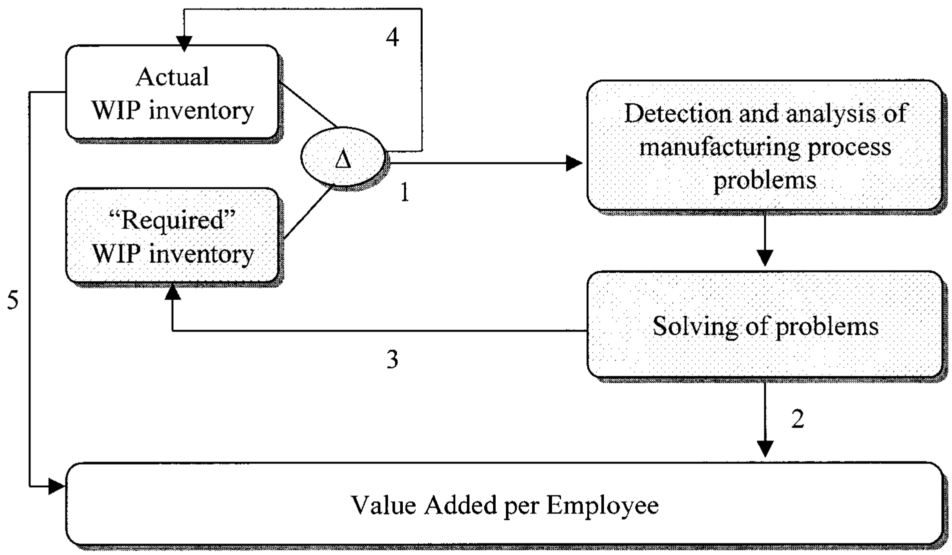
Once visible, these problems can be solved, which will have a positive effect on productivity (Link 2). How, if, and when this will happen depends on the problem solving capabilities present in the factory. Sakakibara et al. (1997) call these capabilities *JIT infrastructure*. Once a problem surfaces, workers or teams of workers need to determine the root cause of the problem and design, test, and implement a solution. The problems that cause the need for WIP inventory typically involve some type of production waste. When this waste is removed, whether it is waste of materials, worker time, or machine time, productivity rises. In addition, the quality of the final product may improve, which may enable the firm to obtain higher prices or lower warranty costs.

The removal of production problems feeds back to reduce the need for WIP inventory (Link 3), allowing actual WIP to be adjusted downward (Link 4). To achieve this reduction in a production line that is controlled by kanban cards, some cards must be removed from the system. In MRP-type systems, inventories remain unchanged until the lead time estimates and lot-sizes that are used as parameters are reset to lower values. The lag between the reduction in "required" WIP and the reduction in actual WIP will depend on how tightly this link is managed.

The reduction of actual WIP lowers the costs of inventory holding and related activities, thereby making a further contribution to productivity (Link 5). In addition to savings of WIP inventories, buffer stocks of finished goods can often be cut in response to improvements in process reliability and shortened cycle time.

The causal link diagram in Figure 1 provides a framework for understanding the statistical models and for interpreting the results in this paper. Unfortunately, the model implied by Figure 1 cannot be estimated directly, as we lack data on the problem solving processes within firms. Rather, it is necessary to infer the linkages from time series observations of

Figure 1 **Causal Link Diagram**



(1) Exposing the "rocks" by lowering the "water:"
- If actual WIP inventory is cut to near or below "required" WIP, problems in the manufacturing process (leading to variability, discontinuity or waste) will be detected.
- When WIP is low, the delays between the occurrence of a problem and the detection of a problem become shorter.

(2) Solution of problems leads to productivity gains:
- Reduced rework & scrap (less material & labor cost).
- Reduced setup times (higher machine utilization and less labor cost).
- Reduced machine failures (less worker and equipment idleness and hence higher utilization).

(3) Solution of problems leads to reduction of required WIP inventory:
- Reduced setup times and costs allow smaller lot sizes.
- Improved machine maintenance decreases the need for buffer inventories.
- Reduced rework and scrap decreases the need for buffer inventories.

(4) Reduction of required WIP may lead to reduction of actual WIP:
- When actual work in process inventory is higher than what is required to achieve the desired throughput, some action must be taken to cause a reduction in actual work in process, e.g. remove kanban or adjust MRP lead times & lot sizes.

(5) Inventory reduction may raise productivity directly:
- Reduced inventory carrying costs.
- Reduced costs for materials management, warehouse management, inventory obsolescence.
- Improved customer response time and responsiveness to demand changes --> higher prices.

(actual) inventory and labor productivity across the sample of automotive companies.

The strength of the links and the speed of response may vary greatly across plants and firms. Management methods differ, and effective problem solving can occur in the factory without an initial stimulus from inventory reduction (Link 1). Indeed, we hypothesize that some firms rely on inventory reduction as a driver for process improvement, while others utilize different approaches. Cusumano (1985) contrasts the inventory-driven system developed by Toyota with the more conventional MRP system used by Nissan.[2]

In the present study we test whether the inventory-productivity linkages represented in Figure 1 have been significantly different, on average, between affiliates of Toyota and Nissan.

3. Data

The data sample includes a total of 52 Japanese automotive companies, covering nearly all of the Japanese assemblers and most of the largest parts

[2] While Nissan adopted some features of JIT manufacturing, "even in the early 1980s, Nissan differed from Toyota in several areas. It did not employ a "pull" system . . . it produced in relatively large lots . . . (and it) chose to rely more on automation and computers to raise productivity than production-management techniques such as a complete kanban system or the job-cycle rationalization measures and rapid line speeds that Toyota employed." (Cusumano 1985, p. 307.)

Table 1 Historical Data on Labor Productivity*

	Value Added per Employee (Millions of 1980 yen)			Average Annual Percent Change	
	1970	1980	1990	1970–80	1980–90
Core Assemblers					
All core Assemblers (8)	3.7	7.9	12.0	7.9%	4.3%
Toyota	5.5	11.0	20.0	7.3%	6.1%
Nissan	4.5	9.3	12.7	7.6%	3.1%
Contract Assemblers (3)	3.5	7.0	11.8	7.2%	5.4%
Suppliers					
Toyota Suppliers (11)	2.9	6.6	10.8	8.6%	5.1%
Nissan Suppliers (11)	2.7	6.0	9.7	8.6%	4.9%
Other Suppliers (19)	2.8	6.7	10.3	9.2%	4.4%

* Data are simple averages across sample companies within each of the groups shown. (Number of firms in group listed in parentheses.)

producers. The historical time series is sufficient to allow observation of the adoption of JIT methods, which were introduced in Japan mostly from the late 1960s to the early 1980s.[3]

Firms in the sample can be subdivided as follows. Eight are "core" assemblers that design, build, and sell finished automobiles under their own name. Three are "contract assemblers" that assemble automobiles as subcontractors for the core assemblers. The remaining 41 companies are "first-tier" parts suppliers, i.e., firms that supply parts directly to the assemblers. About half of these suppliers maintain strong ties with either Toyota or Nissan. We assigned suppliers to three groups ("Toyota," "Nissan," and "others") based the breakdown of their sales to the assemblers and their membership in "supplier associations" (Sako 1996).[4] These assignments are similar to other group definitions in the literature (e.g., Saxonhouse 1980, Dodwell 1990, Toyo Keizai 1991).

The data are from Japanese annual financial reports covering the period from 1965 to 1991. The specific data items used in this study are: total company sales, value-added, total employment, fixed investment, and work-in-process inventories. These data are reported on a consistent basis by all publicly-traded manufacturing firms in Japan.[5] The data on sales and value added correspond to flows over the fiscal year, while employment, investment, and inventories are measured as stocks at the end of the year.

Productivity Measure

Labor productivity, defined as real-value-added per employee, is the productivity measure used in this study. (Value-added equals the firm's sales during the fiscal year, minus the costs of purchased materials and services.) For each firm and year, the productivity measure was computed by first converting the firm's reported value-added into constant yen (based on the Japanese wholesale price index for transport equipment), and then dividing by the average of beginning- and end-of-year employment. This yields real-value-added per employee, a standard measure of labor productivity.

Since the 1960s, Japanese automotive firms have scored impressive gains in labor productivity. Nevertheless, the rate of productivity growth has been diminishing over time.[6] Table 1 gives summary

[3] Details of the sample are described in Lieberman and Demeester (1995) and Lieberman et al. (1995).

[4] These associations, which are organized by the assemblers, serve as mechanisms for information exchange and technology diffusion.

[5] The specific data used in this study are from the *Analysts' Guide* published annually by the Daiwa Securities Corporation, with supplementary detail for the 1965–1976 period obtained directly from Daiwa Securities Corporation.

[6] Fujimoto and Takeishi (1994) discuss some of the reasons for declining productivity growth in the Japanese automotive sector.

Table 2 Historical Data on WIP/Sales*

	WIP as % of Sales			Percent Change	
	1970	1980	1990	1970–80	1980–90
Core Assemblers					
All Core Assemblers (8)	3.5%	1.5%	1.4%	−55.3%	−11.8%
Toyota	0.9%	0.4%	0.5%	−58.9%	39.9%
Nissan	1.9%	1.1%	1.4%	−43.0%	25.4%
Contract Assemblers (3)	1.2%	0.9%	1.1%	−27.2%	23.7%
Suppliers					
Toyota Suppliers (11)	3.5%	1.7%	2.0%	−51.7%	17.4%
Nissan Suppliers (11)	3.3%	1.6%	1.3%	−52.9%	−19.5%
Other Suppliers (19)	6.4%	3.4%	2.6%	−47.2%	−21.3%

* Data are simple averages across sample companies within each of the groups shown. (Number of firms in group listed in parentheses.)

measures of labor productivity for assemblers and suppliers over the period from 1970 to 1990. Toyota's productivity level has been consistently high; suppliers to Toyota have also performed better than average, although by a much smaller margin. Within the ranks of both assemblers and suppliers, productivity variation has been substantial.

WIP Inventory

Our analysis of JIT focuses on reductions in each firm's work-in-process inventory. Table 2 documents the substantial inventory reductions that have occurred in the Japanese automotive sector since the 1960s.[7] Most companies in the sample cut their WIP/sales ratio by more than 50% during a period of intense activity from the late 1960s to the early 1980s. Table 2 shows that Toyota has operated with very lean inventories, and key suppliers to Toyota have held much less WIP than the "other" suppliers. However, the Nissan suppliers in the sample have maintained even lower average levels of WIP and a superior rate of inventory reduction.

Fixed Capital Investment

Labor productivity normally increases with the amount of fixed investment per worker. Differences in capital intensity reflect basic differences in production processes and managerial choices about the degree of process automation. Much of the productivity growth in Japanese manufacturing since World War II can be attributed to rising investment per worker (Norsworthy and Malmquist 1981, Jorgenson and Kuroda 1992, van Ark and Pilat 1993).

To control for the effect of capital investment on labor productivity, we include a measure of tangible fixed assets per employee in our regression tests. Tangible fixed assets equals the depreciated value of the firm's property, plant, and equipment at the end of each fiscal year. This accounting measure was adjusted for inflation and divided by the firm's total number of employees to give an estimate of total investment per employee.

4. Periods of Substantial Inventory Reduction

Our first approach to characterizing the connection between WIP reduction and productivity growth is based on the observation that, for most companies in the sample, there was a well-defined period when major inventory reductions occurred. To identify these periods objectively, we applied a simple algorithm to the inventory data. We then tested whether the periods of inventory reduction coincided with changes in firms' relative productivity growth and productivity rank. This analysis was limited to parts suppliers to avoid confounding the effects of inventory reduction

[7] See Lieberman and Asaba (1997) for a comprehensive assessment of these reductions and a comparison with inventory levels in the United States.

with other productivity differentials related to firm type.

The algorithm for identifying periods of substantial WIP reduction was implemented as follows. For each firm we prepared the time series on the ratio of WIP inventory to sales. We then found the earliest year, if any, where the WIP / sales ratio for each of the next six years fell below a trajectory involving 4% annual reduction, or more stringently, 8% annual reduction. To establish the end of the period, we identified the earliest year for which the WIP / sales ratio fell within 20% of the average ratio of the remaining years of data. While these standards are arbitrary, the results proved robust to alternative identification procedures.[8]

Figure 2 shows the periods of substantial inventory reduction that were identified by the algorithm. The supplier companies are grouped to reflect their links with the major assemblers. Within each group, the earlier adopters are listed first. Among the core assemblers, Toyota, Honda, and Nissan began cutting in-process inventories during the 1960s or earlier; the smaller assemblers followed in the 1970s. Among the supplier companies, those allied with Toyota tended to start cutting inventories several years earlier than most others. For six of the 52 companies, the algorithm was not able to find a meaningful period and it was clear on inspection that those companies did not display a period of substantial WIP reduction.

For the parts suppliers, we used two methods to test for differential productivity growth during the inventory reduction periods. The first method utilizes annual productivity rankings of the companies. The second method involves analysis of relative productivity growth.

In the first method, we ranked all of the parts suppliers in decreasing order of their labor productivity within each observation year. For the suppliers that satisfied the criterion for significant inventory reduction, we recorded their productivity rank in the year prior to the start of substantial WIP reduction and one year after the end of this period.

Table 3 reports the results. Of the 41 suppliers in the sample, 35 met the "4% criterion" for substantial inventory reduction. Of these, 25 increased in productivity rank during their WIP reduction period, and 10 decreased in rank (significant at the .01 level). Results are stronger using the more stringent criterion of 8% WIP reduction per annum. This criterion was met by 33 suppliers, of which 26 increased in rank and seven decreased (significant at the 0.001 level).

Table 3 also reports the analysis of relative productivity growth during periods of substantial inventory reduction. In each observation year, we computed a relative productivity growth rate for each firm by subtracting the average productivity growth rate of suppliers from the value shown for the company. During periods of substantial inventory reduction, firms exceeded the sample average by about 1.5% to 2.0% depending on the criterion used. These productivity growth differentials are highly significant statistically.

5. Correlation Between Productivity and Inventory Levels

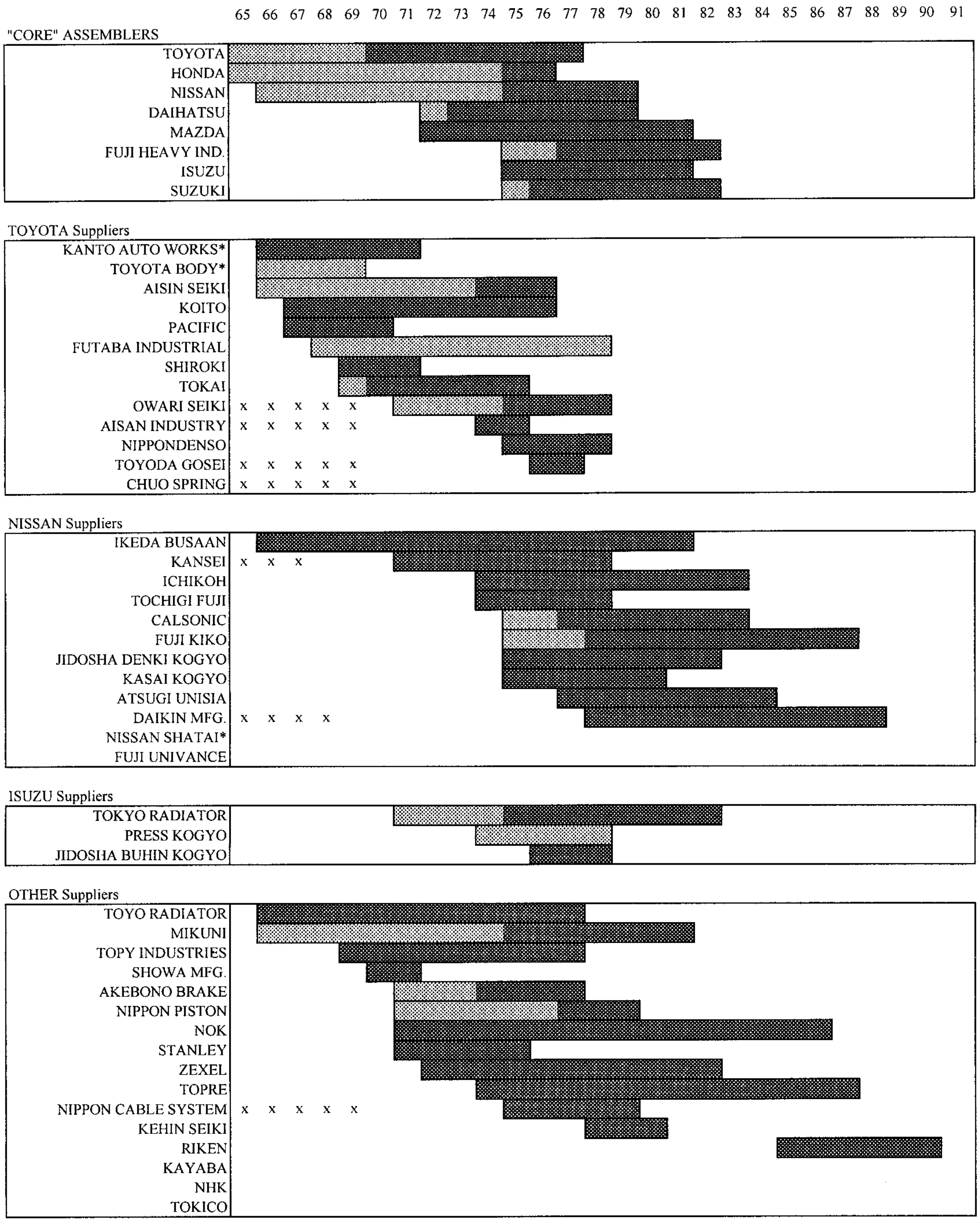
Our second approach to assessing the inventory-productivity link was to use regression analysis to examine the correlation between labor productivity and the level of WIP inventory. Given that we have annual data for a cross section of companies (i.e., panel data), there are several ways that such a correlation might be observed.

We first investigated whether a negative relation between labor productivity and the WIP / sales ratio could be identified when companies are compared annually in cross-section, as demonstrated for the major assemblers in Lieberman (1990). We found strong correlations of this type for the core assemblers in many observation years. For the parts suppliers, however, the correlation was significant only in the mid-1970s, when inventory levels varied dramatically across the companies.

One explanation for these results is that the suppliers are heterogeneous in their manufacturing processes, so their "required" levels of WIP inventory differ. This masks the inventory-productivity relationship when viewed in simple cross-section across firms. To control for heterogeneous WIP requirements, we estimated a "fixed effects" regression model where the

[8] There are no standard procedures for identifying the periods, so we experimented with several algorithms, which gave similar results. The procedure described here is the simplest of those tested.

Figure 2 Periods of Substantial Reduction in Work-in-Process Inventory[1]



Years during which the inventory reduction satisfied the criteria of the algorithm for 4% annual reduction, but not those of the more stringent algorithm.

Years during which the inventory reduction satisfied the criteria of both algorithms (annual reduction > 8%).

[1] As identified by algorithms described in text.

[*] Contract assembler.

[x] Data not available for this year.

Table 3 **Tests for Productivity Changes During Periods of Substantial Inventory Reduction**

Total number of suppliers in sample	41	41
Minimum requirement for "substantial inventory reduction" (per annum reduction over 6 year period)	4%	8%
Number of suppliers exhibiting "substantial inventory reduction"	35	33
Number whose productivity rank increased	25	26
Number whose productivity rank decreased	10	7
P-value (*binomial test*)	.01	.001
Differential productivity growth rate (average, per annum, during inventory reduction period)	1.51%	1.98%
P-value (*t-test*)	.01	.001

dependent variable is labor productivity, and each firm has a separate constant term that captures the differences in firm-specific factors. We also included time dummies in the regression to allow for annual changes in average industry productivity. The remaining explanatory variables are the WIP / sales ratio and the level of capital investment per worker, where the latter serves primarily as a control measure.[9]

The estimates are shown in Table 4. The error terms in this regression model are serially correlated; to correct, we used a first-order autoregressive adjustment. The WIP / sales coefficient appears highly significant and its magnitude (approximately -0.07) implies that a 10% reduction in WIP was associated with nearly a 1% increase in productivity, other things equal. Tests showed that the coefficient was consistent across time periods and did not differ significantly between assemblers and suppliers or among the keiretsu company groups.[10]

The estimates in Table 4 show that higher capital investment per worker had a significant effect on labor productivity, as expected. The coefficients suggest that each 10% increase in per capita investment led to about a 1% to 2% gain in labor productivity.

One concern in this regression model is the potential for spurious correlation or simultaneity bias in the WIP / sales coefficients. For example, an unanticipated decline in sales could lead to a rise in the WIP / sales ratio as well as a decline in productivity. To check the possibility of bias, we estimated the equation using instrumental variables. This led to no change in the resulting coefficient estimates, although the standard errors increased slightly due to the reduced efficiency of the estimator.

6. "Causality" Tests

While the findings of the previous sections reveal an association between WIP and productivity, they give little information on the causal relations outlined in Figure 1. A deeper assessment requires the application of methods that can shed light on the time structure of the inventory-productivity interaction. In this section we report tests of "Granger causality," an approach commonly used in the econometrics literature to explore the nature of causation between two time-series variables (Granger 1969, Pierce and Haugh 1977, Bishop 1979, Geweke et al. 1983, Berndt 1991). Such tests determine whether lagged information on a variable X has any role in explaining Y_t, after controlling for lagged Y and other factors. While these tests can establish precedence relations among variables that interact over time, they cannot demonstrate that these effects are causal in the conventional sense.

The theoretical model represented by Figure 1 implies that reductions in WIP may stimulate productivity gains (links 1, 2, and 5); and conversely, problem solving activities, which lead to productivity improvement, may feed back to reduce the level of WIP inventory (links 2, 3, and 4). Given that the anticipated relations between WIP and productivity go in both directions, we estimate two related regression models.

Effects of WIP Reduction on Labor Productivity

We first examined whether lagged and contemporaneous changes in WIP inventory have any ability to

[9] We used the inventory ratio for the end of the observation year. The level of fixed investment is for the beginning of the year, reflecting plant and equipment that was in place for the full year. All variables were taken in logarithms, which allow the regression coefficients to be interpreted as elasticities.

[10] The coefficient for the Nissan companies was about half the magnitude shown for the full sample, but the difference was not statistically significant. When the sample was limited to the period after 1970, as in the regressions reported in the next section, the coefficient for the contract assemblers fell significantly below that of other firms. One explanation is that the contract assemblers made most of their inventory reductions prior to 1970.

Table 4 **Regression Analysis of Labor Productivity**

Dependent Variable: Value-added per Employee					
	4.1	4.2	4.3	4.4	4.5
Estimation method*	OLS	AR1	AR1	AR1	IV
Time dummies	yes	yes	yes	yes	yes
Firm dummies	yes	yes	yes	no	yes
Investment per Employee	0.290	0.139	0.148	0.132	0.250
	(16.4)	(5.9)	(6.3)	(5.8)	(13.4)
WIP/Sales ratio	−0.068	−0.068		−0.061	−0.071
	(−6.3)	(−5.8)		(−5.6)	(−3.7)
R-squared	0.968	—	—	—	0.960
SSR	16.11	9.00	9.26	9.76	11.74
D.W.	0.65	1.9	1.88	2.05	0.72
Rho	—	0.721	0.719	0.887	—
Number of observations	1265	1265	1265	1265	1265

* Estimation methods are: Ordinary Least Squares (OLS), Maximum Likelihood First-Order Autoregressive (AR1), and Instrumental Variables (IV). For IV, the instruments include all the explanatory variable except for WIP/Sales, plus lagged values of investment per employee, number of employees, and WIP/Sales. (Latter measure lagged two years or more.)

Numbers in parentheses are *t*-statistics.

explain changes in labor productivity, after controlling for lagged productivity and changes in sales. The regression equation is:

$$\Delta V_t = \alpha + \sum_{i=1}^{4} \beta_i \Delta V_{t-i} + \sum_{i=0}^{4} \gamma_i \Delta S_{t-i} + \sum_{i=0}^{4} \eta_i \Delta W_{t-i} + \sum_{i=0}^{4} \lambda_i \Delta K_{t-i} + \varepsilon_t, \qquad (1)$$

where

ΔV_t is value-added per employee in year t, divided by value-added per employee in year $t - 1$;

ΔS_t is sales in year t, divided by sales in year $t - 1$;

ΔW_t is WIP inventory at the end of year t, divided by WIP at the end of year $t - 1$;

ΔK_t is fixed investment per employee at the end of year t, divided by investment per employee at the end of year $t - 1$; and ε_t is a random error term.

All variables were measured in logarithms, which allows the coefficients to be interpreted in terms of growth rates. We include lags through year $t - 4$, given that all coefficients became insignificant by the fourth year. To accommodate this lag structure, the dependent variable starts in 1970 for most firms.

Equation 1 can be viewed as a forecasting equation. Changes in labor productivity for a given firm can be predicted given information on the firm's historical productivity trend and the current and lagged growth of sales. The question posed by the "causality" test is whether this forecast can be significantly improved using additional information on changes in WIP inventory.

More formally, one would expect a firm's current productivity growth, ΔV_t, to be largely determined by its lagged productivity (ΔV_{t-i}) and by short-term fluctuations in sales (ΔS_{t-i}), the latter being typically beyond the control of the firm. The main hypothesis to be tested is whether, after inclusion of these two series in the regression equation, changes in WIP inventory (ΔW_{t-i}) have a detectable impact on productivity (i.e., the η_i terms in Equation 1 are jointly significant). Moreover, one would expect the coefficients for η_i to be negative, assuming that reductions in inventory contribute to an increase in labor productivity.

Equation 1 also incorporates a test for the productivity effects of increasing capital investment per worker (ΔK_{t-i}). The λ_i coefficients should be positive, assuming that investment leads to higher labor productivity. These coefficients may also reveal a gestation lag for new investment to become effective, as documented previously by Chew et al. (1990, 1991).

Determinants of Changes in WIP Inventory

Our second regression equation tests for the potential feedback of successful problem solving on the level of inventory holdings (i.e., links 2, 3, and 4 in Figure 1):

$$\Delta W_t = \alpha + \sum_{i=1}^{4} \beta_i \Delta W_{t-i} + \sum_{i=0}^{4} \gamma_i \Delta S_{t-i} + \sum_{i=0}^{4} \eta_i \Delta V_{t-i} + \sum_{i=0}^{4} \lambda_i \Delta K_{t-i} + \varepsilon_t, \qquad (2)$$

where the variables are defined as above. In this equation, changes in WIP inventory (ΔW_t) are assumed to be determined by lagged inventory changes (ΔW_{t-i}) and changes in sales (ΔS_{t-i}). The primary test of interest is whether reductions in WIP are preceded by productivity gains (i.e., the η_i terms in Equation 2 are negative and significant). Moreover, it is possible that new investment may disrupt the manufacturing process in the short term, leading to some increase in the need for WIP (i.e., positive coefficients for λ_i).

Given the system of simultaneous relationships represented by Equations 1 and 2, estimation by ordinary least squares may lead to biased estimates of the coefficients. In particular, ΔW_t and ΔV_t are endogenous. To avoid erroneous estimates, the potential simultaneity bias must be tested and, if necessary, corrected.

Regression Analysis of Annual Changes in Labor Productivity

Estimates of Equation 1 are reported in Tables 5a and 5b. The first three regressions cover the full sample of 52 companies; all remaining regressions are for groups of firms as indicated. The OLS estimates were found to be free of simultaneity bias, based on a Hausman test.[11] However, the error terms were found to be heteroskedastic; as a correction, we report *t*-statistics based on heteroskedastic-consistent (robust) standard errors.

The regressions in Table 5a show that, as expected, productivity was strongly influenced by contemporaneous changes in sales, ΔS_t. Moreover, they show that after controlling for sales and productivity trends, changes in WIP inventory preceded changes in productivity.[12] In the regressions for the full sample (5.2 and 5.3), the ΔW_{t-1} coefficients are negative and highly significant, implying that inventory reductions were followed by productivity gains, with a lag of about one year. The ΔW_t and ΔW_{t-2} coefficients are negative but smaller in magnitude, denoting some productivity gains in the year of inventory reduction and two years after. The ΔW_{t-3} and ΔW_{t-4} coefficients are insignificant, indicating the absence of further impact after two years. The total effect is given by the sum of the ΔW_t coefficients, which is about -0.10. This implies that a 10% reduction in WIP inventory contributed to about a 1% increase in productivity on average across the sample.

Regression 5.3 includes the ΔK terms, which capture the productivity effects of changes in investment per worker. The ΔK coefficients, which are jointly significant, suggest a gestation lag of one or two years for new investment to become effective. The coefficients sum to about 0.20, which implies that a 10% increase in capital per worker led ultimately to about a 2% increase in labor productivity. The addition of these controls for capital investment has no appreciable effect on the WIP coefficients.

We performed tests to determine whether the effects of WIP reduction were consistent across the company groupings. In Table 5a the sample is broken down into assemblers and suppliers; in Table 5b the sample is divided into three groups: (1) Toyota affiliates, (2) Nissan affiliates, and (3) "Others."

Some minor differences between assemblers and suppliers are shown in Table 5a. There is evidence that the assemblers had a slightly longer gestation lag between inventory reduction and productivity gains. Their ΔW coefficients remain significant into the

[11] We applied the following Hausman test for simultaneity bias (Berndt 1991, pp. 379–380): Fitted values of ΔW_t were obtained from reduced form regressions on the exogenous and predetermined variables, and these values were added as explanatory variables in equations 5.2 and 5.3. The fitted values were not significant in these regressions, indicating that the hypothesis of simultaneity bias in the ΔW_t coefficients can be rejected.

[12] The ΔW coefficients are jointly significant at the 0.001 level based on an F test or Wald test.

Table 5a Regression Analysis of Annual Productivity Changes

	Dependent variable: $\Delta V(t)$ = growth in labor productivity						
	All Firms			All Assemblers		All Suppliers	
	5.1	5.2	5.3	5.4	5.5	5.6	5.7
α	0.02**	0.02**	0.01	0.02	0.01	0.02**	0.01
	(3.88)	(3.70)	(1.29)	(0.98)	(0.54)	(3.98)	(1.45)
$\Delta V(-1)$	0.02	0.01	−0.02	−0.10	−0.11	0.04	0.00
	(0.39)	(0.17)	(−0.37)	(−0.73)	(−0.79)	(0.67)	(0.01)
$\Delta V(-2)$	−0.18**	−0.17**	−0.19**	−0.24*	−0.23*	−0.15**	−0.17**
	(−4.21)	(−4.12)	(−4.38)	(−2.24)	(−2.05)	(−3.25)	(−3.75)
$\Delta V(-3)$	0.04	0.04	0.01	−0.02	−0.05	0.05	0.03
	(1.16)	(1.11)	(0.41)	(−0.26)	(−0.69)	(1.48)	(0.90)
$\Delta V(-4)$	−0.01	−0.01	−0.01	−0.02	−0.03	−0.02	−0.02
	(−0.35)	(−0.37)	(−0.69)	(−0.74)	(−1.09)	(−0.67)	(−0.84)
ΔS	0.67**	0.68**	0.69**	0.92**	0.94**	0.62**	0.63**
	(21.03)	(20.09)	(20.41)	(12.41)	(12.45)	(16.35)	(16.72)
$\Delta S(-1)$	−0.14**	−0.09	−0.07	−0.05	−0.02	−0.09	−0.07
	(−2.68)	(−1.59)	(−1.34)	(−0.40)	(−0.19)	(−1.42)	(−1.26)
$\Delta S(-2)$	0.09*	0.09*	0.08	0.08	0.06	0.08	0.07
	(2.41)	(2.28)	(2.04)	(0.80)	(0.57)	(1.69)	(1.51)
$\Delta S(-3)$	−0.04	−0.04	−0.04	−0.06	−0.05	−0.03	−0.03
	(−1.16)	(−1.20)	(−1.10)	(−0.77)	(−0.64)	(−0.92)	(−0.86)
$\Delta S(-4)$	0.00	0.01	0.01	0.04	0.05	0.01	0.01
	(0.11)	(0.50)	(0.44)	(0.58)	(0.74)	(0.27)	(0.20)
ΔW		−0.02	−0.02	0.00	0.00	−0.02	−0.02
		(−1.60)	(−1.78)	(−0.01)	(0.22)	(−1.31)	(−1.62)
$\Delta W(-1)$		−0.06**	−0.07**	−0.06**	−0.07**	−0.06**	−0.07**
		(−4.68)	(−5.26)	(−3.28)	(−3.53)	(−3.70)	(−4.18)
$\Delta W(-2)$		−0.01	−0.01	−0.06**	−0.06**	0.00	0.00
		(−0.88)	(−1.31)	(−2.93)	(−3.27)	(0.25)	(−0.08)
$\Delta W(-3)$		0.01	0.00	−0.04	−0.03	0.01	0.01
		(0.52)	(0.42)	(−1.72)	(−1.56)	(0.92)	(0.81)
$\Delta W(-4)$		0.00	0.00	0.00	−0.03	0.00	0.01
		(0.00)	(0.22)	(0.00)	(−1.34)	(0.00)	(1.11)
ΔK			0.03		−0.01		0.04
			(1.15)		(−0.15)		(1.52)
$\Delta K(-1)$			0.11**		0.15*		0.10**
			(3.91)		(2.46)		(3.37)
$\Delta K(-2)$			0.06**		−0.01		0.06**
			(2.85)		(−0.08)		(2.80)
$\Delta K(-3)$			0.02		−0.03		0.03
			(1.10)		(−0.50)		(1.32)
$\Delta K(-4)$			0.00		−0.03		−0.01
			(−0.20)		(−0.44)		(−0.34)
R-squared	0.437	0.458	0.476	0.520	0.534	0.466	0.488
SSR	5.907	5.685	5.498	1.628	1.581	3.786	3.630
log$L$	1326	1347	1366	259	262	1125	1144
D.W.	2.00	2.00	1.97	1.99	1.99	2.00	1.97
Nr. of obs.	1107	1107	1107	240	240	867	867

Numbers in parentheses are t-statistics.
* Significant at the 5% level, two-tailed test.
** Significant at the 1% level, two-tailed test.

Table 5b Regression Analysis of Annual Productivity Changes

	Dependent variable: $\Delta V(t)$ = growth in labor productivity					
	Toyota Group		Nissan Group		Others	
	5.8	5.9	5.10	5.11	5.12	5.13
α	0.03**	0.02	0.03**	0.02*	0.02**	0.00
	(3.16)	(1.95)	(2.68)	(1.99)	(2.47)	(0.46)
$\Delta V(-1)$	−0.05	−0.08	0.09	0.06	−0.01	−0.04
	(−0.81)	(−1.14)	(1.19)	(0.85)	(−0.08)	(−0.46)
$\Delta V(-2)$	−0.14*	−0.15*	−0.21**	−0.20*	−0.16*	−0.18**
	(−2.05)	(−2.38)	(−2.61)	(−2.50)	(−2.51)	(−2.71)
$\Delta V(-3)$	0.00	−0.02	0.04	0.03	0.04	0.00
	(0.04)	(−0.28)	(0.61)	(0.36)	(0.80)	(0.09)
$\Delta V(-4)$	0.02	0.01	−0.01	−0.01	−0.01	−0.01
	(0.92)	(0.56)	(−0.46)	(−0.50)	(−0.18)	(−0.26)
ΔS	0.62**	0.62**	0.61**	0.61**	0.70**	0.72**
	(8.75)	(8.55)	(10.75)	(10.43)	(14.50)	(15.40)
$\Delta S(-1)$	−0.15*	−0.12	−0.26**	−0.25**	0.01	0.02
	(−2.39)	(−1.78)	(−3.95)	(−3.92)	(0.17)	(0.32)
$\Delta S(-2)$	0.12*	0.10	0.14	0.11	0.04	0.04
	(2.00)	(1.66)	(1.80)	(1.47)	(0.63)	(0.63)
$\Delta S(-3)$	−0.07	−0.08	0.03	0.02	−0.07	−0.05
	(−1.19)	(−1.22)	(0.56)	(0.36)	(−1.33)	(−0.89)
$\Delta S(-4)$	0.05	0.04	0.00	0.00	−0.01	−0.02
	(1.06)	(0.89)	(−0.07)	(0.07)	(−0.33)	(−0.45)
ΔW	−0.05**	−0.06**	−0.01	−0.01	0.00	0.00
	(−3.56)	(−3.63)	(−0.71)	(−0.25)	(0.08)	(−0.24)
$\Delta W(-1)$	−0.06**	−0.06**	0.00	0.00	−0.09*	−0.10**
	(−3.63)	(−3.75)	(−0.12)	(0.00)	(−4.24)	(−4.66)
$\Delta W(-2)$	−0.02	−0.03	0.04*	0.02	−0.03	−0.03
	(−1.19)	(−1.48)	(2.08)	(1.15)	(−1.35)	(−1.54)
$\Delta W(-3)$	0.00	0.00	−0.01	−0.02	0.02	0.02
	(−0.17)	(−0.10)	(−0.43)	(−0.84)	(1.22)	(1.09)
$\Delta W(-4)$	0.00	0.00	0.00	0.01	0.00	0.00
	(0.00)	(0.22)	(0.00)	(0.69)	(0.00)	(0.19)
ΔK		−0.02		−0.03		0.09*
		(−0.41)		(−0.54)		(2.32)
$\Delta K(-1)$		0.06		0.05		0.12**
		(1.06)		(0.93)		(3.40)
$\Delta K(-2)$		0.09*		0.11**		0.02
		(2.22)		(2.60)		(0.58)
$\Delta K(-3)$		0.04		0.03		0.02
		(1.17)		(0.64)		(0.70)
$\Delta K(-4)$		0.02		−0.03		−0.02
		(0.37)		(−0.86)		(−0.50)
R-squared	0.422	0.446	0.501	0.523	0.504	0.527
SSR	0.983	0.943	1.080	1.032	3.287	3.132
log$L$	419	425	346	352	632	646
D.W.	2.00	1.99	1.95	1.93	1.97	1.96
Nr. of obs.	293	293	261	261	553	553

Numbers in parentheses are t-statistics.
* Significant at the 5% level, two-tailed test.
** Significant at the 1% level, two-tailed test.

Table 6 Tests of Equality Between Groups*

	Assemblers versus Suppliers	Toyota Group versus Nissan group	Toyota Group versus "Other" Group	Nissan Group versus "Other" Group
Productivity change following change in WIP (ΔW coefficients in Table 5)	**.036**	**.013**	**.027**	**.001**
Change in WIP following change in Productivity (ΔV coefficients in Table 7)	.259	**.001**	**.000**	.113

* Tests were performed by constraining the coefficients indicated (for years t through $t - 3$) to be identical between groups, with all other coefficients allowed to differ. Table gives the p-level by which the null hypothesis of coefficient equality can be rejected, based on a Wald test. (F-test results were very similar.)

second year, with further possible effects in the third year. Moreover, the total magnitude of effect (sum of the coefficients) is larger on average for the assemblers than for the suppliers. These differences were confirmed by tests (shown in Table 6) to determine whether sets of coefficients differed significantly between groups.[13] The test that compares the set of ΔW_{t-i} coefficients between assemblers and suppliers has a p-value of 0.036, indicating that the hypothesis of identical coefficients can be rejected at the 5% level.

Table 5b shows larger differences between groups defined on the basis of company affiliation. Regressions 5.8 and 5.9 suggest that the lag between WIP reduction and productivity gain was about six months shorter for the Toyota group than for other companies. Moreover, Regressions 5.10 and 5.11, which are limited to the Nissan affiliates, reveal that these firms had no significant productivity gains following reductions in WIP. These differences among company groups are confirmed by the test statistics in Table 6.[14] The contrast between Toyota and Nissan groups is consistent with differences in the operations practices of the two assemblers, as discussed by Cusumano (1985).

[13] We implemented these tests by constraining the coefficients of interest to be identical between the two groups being compared, while allowing all other coefficients to differ between the groups. The sum of squared residuals in these constrained regressions, relative to the unconstrained values shown in Table 5, provides the basis for the tests. Table 6 gives significance levels obtained using the Wald test recommended by Geweke et al. (1983).

[14] Differences between the Toyota and Nissan groups are significant at the 5% level, as are the differences between the Toyota group and "Others." Differences between the Nissan group and "Others" are significant at the 1% level.

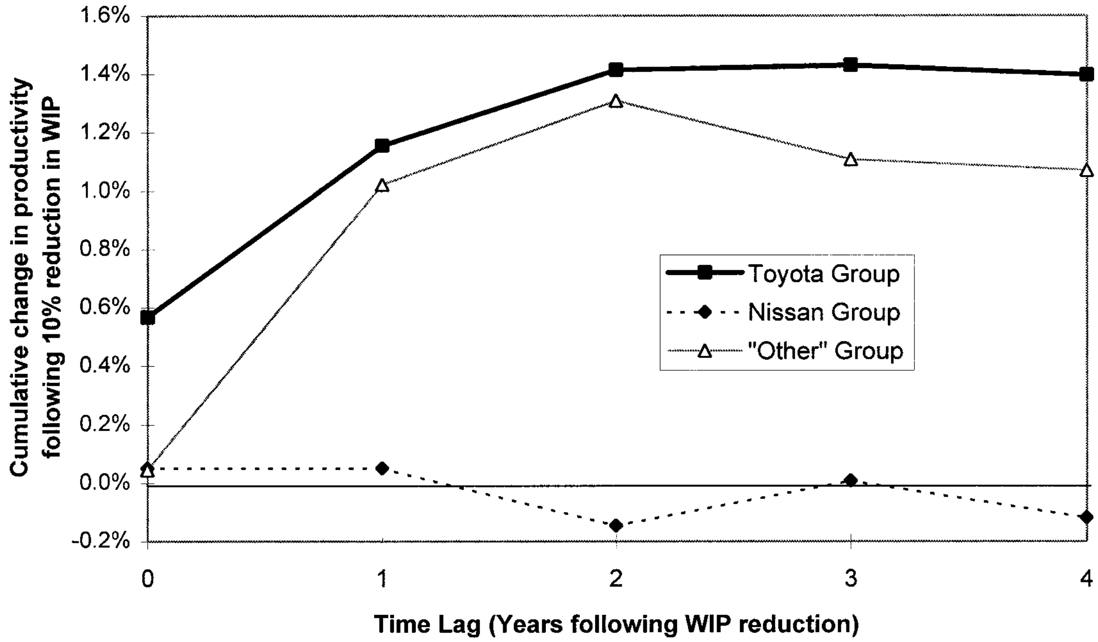
These results are depicted graphically in Figure 3, which plots the cumulative impact of WIP reduction on productivity (obtained by summing the ΔW coefficients in Table 5b). The Toyota and "other" company groupings show similar behavior, although the effects of WIP reduction are more immediate and perhaps more persistent for the Toyota companies. By comparison, the absence of such effects for the Nissan affiliates is striking.

Regression Analysis of Annual Changes in WIP

Tables 7a and 7b give the regression estimates of Equation 2 on the determinants of inventory changes.[15] While these regressions explain only a small proportion of the annual fluctuation in WIP, a number of significant patterns are indicated. The ΔW_{t-i} coefficients are generally negative, revealing a tendency for deviations from trend to return to the trend level. This pattern is especially strong for the Toyota group, where most of the inventory adjustment occurred in the first year, much faster than what is shown for other companies. There was also a strong tendency—particularly in the case of part suppliers—for changes in WIP to track recent changes in sales, as would be expected. The ΔS_{t-i} coefficients in regressions 7.2 and 7.3 sum to approximately unity, implying that increases in sales were ultimately met by

[15] We tested these OLS regressions for simultaneity bias in the ΔV coefficients, using a Hausman test analogous to the one described in footnote 12. Results indicated that the OLS estimates were unbiased. Although tests showed the absence of significant heteroskedasticity, we report t-statistics based on heteroskedastic-consistent standard errors, as in Table 5.

Figure 3 Productivity Change Following WIP Reduction*



roughly proportionate increases in WIP.[16] Most of this adjustment occurred in the year that sales increased.

The conceptual framework outlined in §2 implies that WIP reductions should follow improvements in productivity, although the lag time for adjustment may vary. The regressions in Table 7 provide mixed evidence of such effects. While the ΔV_{t-i} coefficients are generally negative, as expected, none of the individual terms are statistically significant except in the regressions for the Toyota group. (The tests in Table 6 confirm that the Toyota group coefficients are significantly different from the rest of the sample.) Compared with other companies, the Toyota affiliates made faster and more consistent reductions in inventory following improvements in the manufacturing process. Figure 4 illustrates this finding. For the Toyota companies on average, a 1% productivity gain was followed within about a year by a 1.7% reduction in WIP. Other firms also cut their inventories over time (as indicated by the summary ratios presented earlier in Table 2), but without such a tight coupling.

The ΔK_{t-i} coefficients in Table 7 provide additional information on the determinants of WIP. The coefficient for capital investments made during the observation year is strongly positive, implying that WIP inventories rose in response to new investment. This may reflect intentional steps to increase inventory buffers, or alternatively, unanticipated disruption on the factory floor. For the Toyota- and Nissan-affiliated companies, this *post-investment* build up seems to have dissipated fairly quickly, as indicated by the negative coefficients for ΔK_{t-1} and ΔK_{t-2}.

7. Discussion and Perspective

The preceding sections of this paper present various tests for a connection between WIP inventory and productivity, based on historical data for the Japanese automotive sector. In this section we consider the findings in broader perspective.

All the tests show a strong and statistically significant connection between inventory and productivity. None, however, can fully distinguish among the causal links shown in Figure 1. As illustrated in the figure, an association between inventory and productivity can arise in several ways. One chain of causality begins with successful problem solving, which leads to productivity gains (link 2) and subsequent

[16] While sales declines occasionally occurred, the predominant trend was of increasing sales over the sample period.

Table 7a **Regression Analysis of Annual Changes in WIP**

	Dependent variable: $\Delta W(t)$ = change in WIP inventory						
	All firms			All Assemblers		All suppliers	
	7.1	7.2	7.3	7.4	7.5	7.6	7.7
α	−0.02	−0.01	−0.03	0.04	0.04	−0.03	−0.05**
	(−1.46)	(−0.93)	(−1.77)	(0.94)	(0.74)	(−1.62)	(−2.53)
$\Delta W(-1)$	−0.15**	−0.16**	−0.15**	−0.22**	−0.21**	−0.11*	−0.10
	(−3.92)	(−4.20)	(−4.00)	(−2.91)	(−2.63)	(−2.44)	(−2.32)
$\Delta W(-2)$	−0.10**	−0.11**	−0.10*	−0.05	−0.03	−0.24**	−0.13**
	(−2.61)	(−2.69)	(−2.41)	(−0.51)	(−0.28)	(−3.59)	(−3.51)
$\Delta W(-3)$	−0.04	−0.04	−0.06	−0.04	−0.05	−0.01	−0.03
	(−1.09)	(−1.00)	(−1.52)	(−0.44)	(−0.58)	(−0.17)	(−0.66)
$\Delta W(-4)$	0.03	0.03	0.03	0.14*	0.15*	−0.02	−0.01
	(0.89)	(0.77)	(0.96)	(1.98)	(2.05)	(−0.53)	(−0.37)
ΔS	0.69**	0.82**	0.81**	0.37	0.36	0.91**	0.91**
	(8.84)	(6.72)	(6.86)	(1.34)	(1.28)	(6.49)	(6.67)
$\Delta S(-1)$	0.04	0.09	0.06	0.08	−0.02	0.08	0.05
	(0.56)	(0.80)	(0.48)	(0.32)	(−0.06)	(0.60)	(0.36)
$\Delta S(-2)$	−0.01	−0.03	0.03	−0.52	−0.41	0.08	0.13
	(−0.11)	(−0.22)	(0.25)	(−1.51)	(−1.18)	(0.62)	(1.03)
$\Delta S(-3)$	0.17*	0.23*	0.22*	0.07	0.05	0.26*	0.26*
	(2.15)	(2.07)	(1.98)	(0.24)	(0.16)	(2.17)	(2.11)
$\Delta S(-4)$	0.06	0.05	0.04	−0.08	−0.06	0.12	0.10
	(0.79)	(0.54)	(0.43)	(−0.41)	(−0.29)	(1.23)	(1.05)
ΔV		−0.19	−0.20	0.00	0.04	−0.21	−0.24
		(−1.59)	(−1.75)	(−0.01)	(0.22)	(−1.30)	(−1.59)
$\Delta V(-1)$		−0.09	−0.12	0.08	0.08	−0.16	−0.20
		(−0.89)	(−1.10)	(0.42)	(0.41)	(−1.27)	(−1.49)
$\Delta V(-2)$		0.01	−0.05	0.23	0.15	0.02	−0.04
		(0.05)	(−0.46)	(1.02)	(0.62)	(0.13)	(−0.30)
$\Delta V(-3)$		−0.09	−0.08	0.17	0.22	−0.19	−0.20
		(−0.91)	(−0.86)	(0.80)	(1.01)	(−1.66)	(−1.77)
$\Delta V(-4)$		0.00	−0.01	0.00	0.23	0.00	−0.06
		(0.00)	(−0.14)	(0.00)	(1.83)	(0.00)	(−0.88)
ΔK			0.32**		0.39		0.30**
			(4.42)		(1.63)		(4.23)
$\Delta K(-1)$			−0.06		−0.25		−0.04
			(−0.87)		(−1.32)		(−0.53)
$\Delta K(-2)$			−0.01		−0.14		0.02
			(−0.05)		(−0.71)		(0.14)
$\Delta K(-3)$			0.15*		0.13		0.14*
			(2.14)		(0.64)		(2.13)
$\Delta K(-4)$			−0.10		−0.18		−0.05
			(−1.54)		(−0.91)		(−0.80)
R-squared	0.123	0.128	0.152	0.147	0.175	0.157	0.182
SSR	56.13	55.82	54.22	14.75	14.26	39.32	38.16
log*L*	79.7	82.7	98.7	−5.8	−1.7	110.7	123.7
D.W.	1.99	1.99	2.00	2.07	2.10	1.99	2.00
Nr. of obs.	1107	1107	1107	240	240	867	867

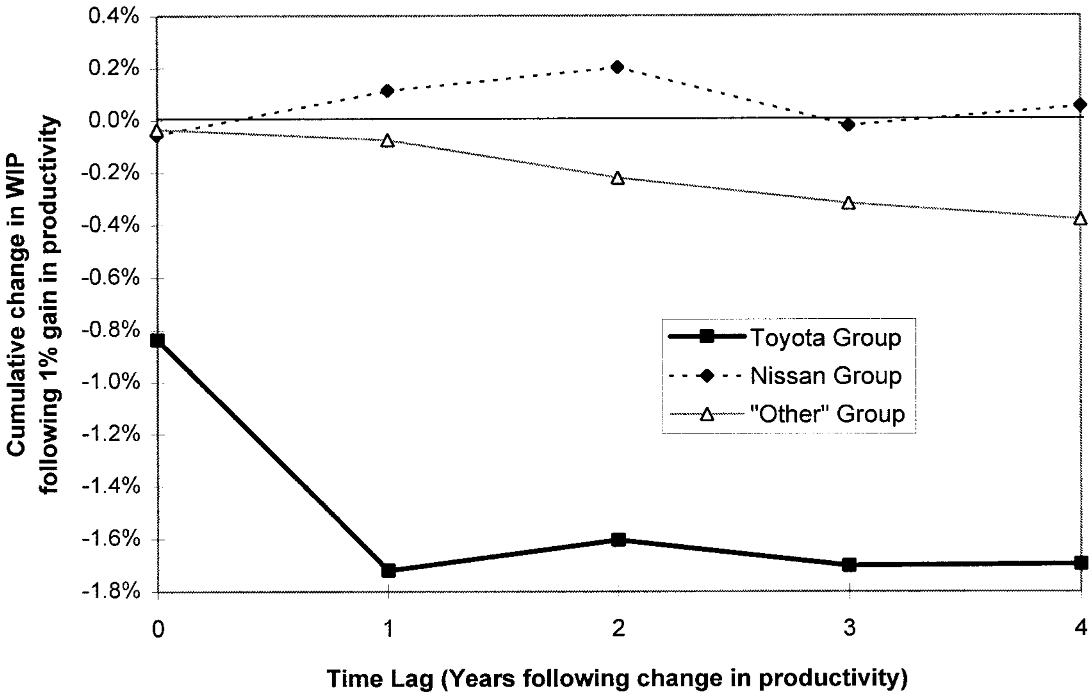
Numbers in parentheses are *t*-statistics.
* Significant at the 5% level, two-tailed test.
** Significant at the 1% level, two-tailed test.

Table 7b Regression Analysis of Annual Changes in WIP

	Dependent variable: $\Delta W(t)$ = change in WIP inventory					
	Toyota Group		Nissan Group		Others	
	7.8	7.9	7.10	7.11	7.12	7.13
α	0.08*	0.04	−0.03	−0.04	−0.04	−0.05
	(2.11)	(0.98)	(−1.09)	(−1.32)	(−1.83)	(−1.91)
$\Delta W(-1)$	−0.27**	−0.25**	−0.08	−0.05	−0.13*	−0.13*
	(−3.58)	(−3.58)	(−1.13)	(−0.70)	(−2.42)	(−2.47)
$\Delta W(-2)$	−0.11	−0.10	−0.05	0.01	−0.17**	−0.17**
	(−1.43)	(−1.29)	(−0.64)	(0.13)	(−3.36)	(−3.37)
$\Delta W(-3)$	0.01	−0.04	−0.10	−0.11	−0.06	−0.07
	(0.08)	(−0.65)	(−1.24)	(−1.47)	(−1.34)	(−1.36)
$\Delta W(-4)$	0.11	0.14*	0.04	0.06	−0.06	−0.06
	(1.83)	(2.26)	(0.56)	(0.89)	(−1.24)	(−1.27)
ΔS	1.03**	0.95**	0.90**	0.70*	0.63**	0.67**
	(4.04)	(3.86)	(3.80)	(3.30)	(4.01)	(4.39)
$\Delta S(-1)$	0.44	0.49	−0.29	−0.24	0.10	0.09
	(1.48)	(1.54)	(−1.35)	(−1.20)	(0.70)	(0.60)
$\Delta S(-2)$	−0.56	−0.47	0.12	0.20	0.09	0.11
	(−1.59)	(−1.38)	(0.60)	(0./95)	(0.53)	(0.59)
$\Delta S(-3)$	0.05	−0.03	0.23	0.19	0.41*	0.42*
	(0.18)	(−0.11)	(1.27)	(1.02)	(2.30)	(2.37)
$\Delta S(-4)$	0.08	0.05	−0.02	0.00	0.07	0.07
	(0.39)	(0.29)	(−0.11)	(0.02)	(0.60)	(0.56)
ΔV	−0.84**	−0.84**	−0.18	−0.06	0.01	−0.04
	(−3.50)	(−3.31)	(−0.74)	(−0.25)	(0.08)	(−0.24)
$\Delta V(-1)$	−0.68*	−0.88**	0.28	0.17	−0.03	−0.04
	(−2.46)	(−3.08)	(1.19)	(0.82)	(−0.21)	(−0.29)
$\Delta V(-2)$	0.14	0.11	0.15	0.09	−0.12	−0.14
	(0.62)	(0.47)	(0.71)	(0.41)	(−0.78)	(−0.93)
$\Delta V(-3)$	−0.03	−0.10	−0.29	−0.22	−0.08	−0.10
	(−0.16)	(−0.47)	(−1.30)	(−1.04)	(−0.59)	(−0.71)
$\Delta V(-4)$	0.00	0.01	0.00	0.07	0.00	−0.06
	(0.00)	(0.07)	(0.00)	(0.95)	(0.00)	(−0.66)
ΔK		0.36**		0.53**		0.17
		(2.64)		(3.40)		(1.68)
$\Delta K(-1)$		−0.27*		−0.12		0.06
		(−2.10)		(−0.99)		(0.55)
$\Delta K(-2)$		0.45		−0.31*		0.00
		(1.34)		(−2.36)		(−0.04)
$\Delta K(-3)$		0.26		0.34*		0.01
		(1.56)		(2.49)		(0.10)
$\Delta K(-4)$		0.04		−0.22		−0.05
		(0.30)		(−1.50)		(−0.57)
R-squared	0.198	0.266	0.180	0.277	0.156	0.164
SSR	15.18	13.90	12.90	11.37	24.50	24.28
log*L*	17.9	30.8	22.1	38.5	77.1	79.5
D.W.	1.95	1.97	1.97	1.9	2.04	2.04
Nr. of obs.	293	293	261	261	553	553

Numbers in parentheses are *t*-statistics.
* Significant at the 5% level, two-tailed test.
** Significant at the 1% level, two-tailed test.

Figure 4 Change in WIP Following Productivity Gain**



inventory reduction (links 3 and 4). In this case WIP reduction plays no role in stimulating productivity, but is purely a response to successful problem solving. Could this be the dominant chain of causality underlying the empirical results? The tests in §§4 and 5 are silent on this issue, but the analysis in §6 is informative. One piece of evidence is the finding of a relatively weak connection between productivity gains and subsequent inventory reductions, except within the Toyota group. By comparison, the links in the opposite direction (WIP reductions preceding productivity gains) appear larger and more pervasive. These precedence relations suggest that the dominant path leads from WIP reduction to productivity growth, rather than vice versa.

Ambiguity nevertheless remains with respect to the exact mechanisms linking inventory reduction to productivity gains. To what extent does it occur via links 1 and 2 (embodying the "rocks in the river" metaphor for JIT), as opposed to link 5 (inventory reduction economizes on working capital and other inputs)? We expect the former to be more important, for a number of reasons. Schonberger (1982) and others have argued that the benefits associated with link 5, which are primarily savings in inventory holding costs, are comparatively small. In the Japanese automotive industry we estimate that these holding cost economies amounted to at most one-third of the average productivity gain.[17] Moreover, most of the holding cost savings would be immediate, whereas we typically observe the productivity gain with a lag.

These assessments are based on the assumption that the WIP-productivity connection reflects the outcome of successful problem solving activity. To some extent, though, the observed correlations could stem from factory setbacks. Unanticipated problems may cause a temporary drop in productivity (link 2) and a build-up of WIP inventory (links 3 and 4). While such effects may be present in our data, they are likely to be comparatively small. One reason is that such setbacks should have an immediate impact on both productivity and inventory, whereas the analysis shows signif-

[17] In our sample, the WIP/value-added ratio peaked at 16.3% in 1967, falling below 10% from 1977 onward. Assuming a 15% ratio and a 15% annual holding cost, a 10% reduction in WIP amounts to a holding cost savings equal to 0.225% of value-added. This is less than one third of the estimated productivity gain.

icant lags. Moreover, in the Japanese automotive industry the strong prevailing trend was toward WIP reduction and productivity growth, rather than vice versa.

One issue that warrants greater discussion is the precise interpretation of the time structure associated with the coefficients in the Granger causality tests. Given that some variables are end-of-year stocks while others are annual flows, a shift of one-half year is appropriate in some cases.[18] In Table 5, for example, the lag between WIP reduction and productivity gain was likely to have been about six months shorter than what would otherwise be implied by the regression coefficients. Suitable adjustment suggests that productivity gains were almost immediate for the Toyota companies, as compared with a lag of about one-half year for non-Toyota suppliers, and one year for assemblers. In Table 7, the flow variables such as ΔV are shifted by six months in the opposite direction. Here, the coefficients for ΔV_t and ΔV_{t-1}, which are statistically significant for the Toyota group, should be interpreted as reflecting lags of 0.5 and 1.5 years between productivity gains and subsequent inventory reductions.[19]

To put the findings in perspective, it is helpful to compare the magnitude of productivity gains attributable to inventory reduction with the gains attributable more broadly to other factors. The WIP coefficients in Tables 4 and 5 suggest that as a rough approximation, each 10% reduction in WIP contributed to an average increase of about 1% in labor productivity. Producers that made substantial inventory reductions (as identified by our algorithm) cut their WIP / sales ratio by about two-thirds, on average. Combining these estimates leads to the conclusion that, for such firms, the aggregate productivity gain attributable to inventory reductions was typically about 10%. In other words, labor productivity was 10% higher at the end of the sample period, as compared with the hypothetical case where the firm would have made no inventory reductions at all.[20]

While a 10% productivity differential is appreciable, it is important to recognize that from 1970 to 1980, when most of the inventory reductions were occurring, labor productivity for the sample companies grew at an average annual rate of 9%. Thus, the estimated effects of inventory reduction correspond to less than one-tenth of the total productivity gains recorded during the 1970s.

The cumulative impact of WIP reduction on labor productivity can also be compared with the effects of increased capital investment. From 1970 to 1980, real fixed capital per worker rose by 5.1% per year on average across the sample. Using an elasticity of 0.15, which is suggested by the regression coefficients in Tables 4 and 5, this increase in capital intensity translates into a labor productivity gain of about 10% over the course of the decade. Thus, the productivity gain that can be linked to inventory reduction during the 1970s may have been roughly the same magnitude as the gain from increased capital investment. Taken together, these estimates suggest that most of the rapid growth in Japanese automotive productivity during the 1970s was derived from manufacturing process improvements not directly related to capital investment or inventory reduction.[21]

[18] Assume for purposes of illustration that a reduction in WIP inventory leads to an immediate gain in productivity. The dependent variable in Table 5, ΔV_t, is the change in value-added per worker (a flow measure) between year $t-1$ and year t. The explanatory variable, ΔW_t, is the change in the stock of WIP inventory, measured from the end of year $t-1$ to the end of year t. A reduction in WIP made at the midpoint of year t would be followed by an immediate rise in the firm's value-added, but the increase in productivity, a recorded by ΔV_t, would appear half in year t and half in the next year. In the regression analysis of ΔV_t one would observe coefficients of equal magnitude for ΔW_t and ΔW_{t-1}, with coefficients of zero for the additional lagged terms. This is approximately what is shown for the Toyota group (regressions 5.8 and 5.9).

[19] This raises the possibility that ΔV_{t+1} should be included as an explanatory variable in Table 7. When tested, this measure had a negative coefficient that was weakly significant but comparatively small.

[20] A similar computation can be made using the estimates of relative labor productivity growth in Table 3. Firms that made substantial inventory reductions (based on the 4% criterion) experienced productivity growth during this period that was, on average, about 1.5% above the growth rate of other firms. Multiplying this figure by an average reduction period of about 6–7 years (consistent with Figure 2) yields a total differential productivity gain of about 10%.

[21] During the 1970s various manufacturing practices, such as quality circles and total quality control, became widely adopted in the Japanese automotive sector.

8. Conclusions

The findings of this study shed light on the linkages between WIP inventory and productivity. We have considered alternate paths of causality and have derived quantitative estimates of effects. The results are complementary with the large body of case study evidence on the implementation of JIT manufacturing. Indeed, our work demonstrates that quantitative analysis of public company data can provide insights for researchers and practitioners in operations management, a field with little tradition of statistical data analysis.

Our findings suggest that for most companies in our sample, inventory reductions were followed by productivity gains. We find more limited evidence of effects in the opposite direction. In quantitative terms, each 10% reduction in inventory led to an average gain of about 1% in labor productivity, with a lag of about one year. Firms that made substantial inventory reductions enjoyed a period of annual productivity growth significantly higher than that of other companies on average. Typically, these firms also saw an increase in their productivity rank.

While these effects were widespread in the Japanese auto industry, inter-firm differences are apparent, particularly between the Toyota and Nissan groups. For the firms affiliated with Toyota the inventory-productivity linkage appears very tight: productivity gains followed quickly after inventory reductions, and inventories were cut soon after the achievement of productivity gains. For the Nissan affiliates, however, neither of these effects was observed. "Other" companies in our sample showed a significant link in one direction only (from inventory to productivity), and with a longer lag than that detected for the Toyota group. Despite these differences in estimated effects, over the two decades of sample coverage most of the companies in the sample achieved major inventory reductions, and all attained substantial productivity growth. Taken jointly, these observations support our hypothesis that many Japanese firms relied on inventory reduction as a driver for process improvement, although some utilized other approaches and methods.

While broadly consistent with prior research, these findings offer new and quantitative insights regarding the effects of JIT implementation. Nevertheless, important caveats apply. The findings presented here are aggregate estimates, far removed from details of the shop floor where JIT implementation actually takes place. Such details undoubtedly matter, and the estimates obtained in this study are averages that mask heterogeneity across individual firms, plants and processes.

Most importantly, it is well known that inventory reduction is only one component of JIT; related activities (such as setup time reduction and statistical process control) are essential. It may be impossible, and perhaps not meaningful, to distinguish the impact of WIP reduction from that of these other activities. Indeed, the WIP reductions observed in this study may serve in part as a proxy for these other activities, with which they are correlated. Thus, the quantitative findings of this study should be kept in perspective and regarded as rough benchmarks only.[22]

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