PRODUCTION AND OPERATIONS MANAGEMENT
Vol. 10, No. 3, Fall 2001
Printed in U.S.A.

LEAN, GREEN, AND THE QUEST FOR SUPERIOR ENVIRONMENTAL PERFORMANCE*

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We examine the relationship between lean manufacturing practices and environmental performance as measured in terms of air emissions and resource use. We draw on two unique surveys of 31 automobile assembly plants in North America and Japan, which contain information on manufacturing practice and environmental performance, as well as in-depth interviews with 156 plant level employees at 17 assembly plants. Our survey results and interviews suggest that lean management and reduction of air emissions of volatile organic compounds (VOCS) are associated negatively. Lean manufacturing practices contribute to more efficient use of paints and cleaning solvents, but these in-process changes are not sufficient to meet the most stringent air regulations. We found some evidence to support the link between lean practices and resource efficiency. While our survey results were in hypothesized direction, they were not statistically significant. In-depth semi-structured interviews, however, suggest a more robust relationship, and we use them to describe some mechanisms by which all three aspects of lean management (buffer minimization, work systems, and human resource management) may be related to environmental management practices and performance.

(LEAN MANUFACTURING; ENVIRONMENTAL PERFORMANCE; HIGH-INVOLVEMENT WORK; RESOURCE USE)

Introduction

Environmental issues affect corporate strategy and policy at all levels of the organization including business, functional, and operational (Shrivastava 1995a; Starik and Rands 1995; Aragon-Correa 1998). This is reflected in the range of operational issues that have been explored in the operations literature, including supply chain management (Handfield, Walton, Seegers, and Melnyk 1997), product design (Denchant and Altman 1994), remanufacturing (Lund 1994; Hart 1997), and total quality environmental management (Willig 1994; Shrivastava 1995a; Wellford 1992). However, there is recognition that environmental concerns have traditionally been modeled as constraints on manufacturing operations (Angell and Klassen 1999). Yet, researchers have argued that in many ways pollution and inefficiency are the same problems, and that there is a shortage of research linking manufacturing process

* Received February 2000; revision received November 2000; accepted January 2001.

1059-1478/01/1003/228$1.25

with environmental management and performance (McInerney and White 1995; Angell and Klassen 1999).

The goal of this article is to help meet this need by examining whether manufacturing practices and policies associated with superior overall manufacturing performance in the automobile industry contribute to improvements in environmental performance. An advantage specific to studying the automobile industry is that there is a clearly defined set of advanced manufacturing practices known collectively as lean production or "just-in-time" (JIT) manufacturing, which enables us to specify and explore the link between manufacturing practice and environmental performance (Womack, Jones, and Roos 1990; Womack and Jones 1996). We utilize two unique factory-level data sets, along with in-depth interviews to examine the link between advanced manufacturing practices and environmental performance in the automobile industry. We examine the relationship between different characteristics of lean production and measures of environmental performance related to air emissions and resource efficiency.

Background

In this section we describe the relationship between lean production and both environmental efficiency and emissions of volatile organic compounds (VOCS). We develop two hypotheses.

Lean Production and Environmental Efficiency

Environmental efficiency, i.e., the reduction of environmental impact through more efficient use of materials and natural resources in manufacturing, is driven in large part by process and operational decisions that would fall under the category of pollution prevention. While total quality management (TQM) is a useful lens with which to examine such operational decisions relating to the environment (Willig 1994; Shrivastava 1995a), some have argued for an encompassing approach to examining the role of operations in improving environmental performance (Shrivastava 1995b; Klassen and McLaughlin 1996). One such approach is to use the elements of lean production to undertake a broad examination of the role that management systems, practices, and policies play in enhancing environmental efficiency. There are multiple ways to operationalize the concept of lean production. In this paper, we will be using MacDuffie's (1995) methodology. As discussed by MacDuffie (1995), the success of lean manufacturing stems from a combination of practices, policies, and philosophies—a combination that can be divided into three primary areas: Buffer Minimization, Work Systems, and Human Resource Management. Research suggests that all three of these factors are important to the continuous improvement of performance at lean plants (Ichniowski and Shaw 1995; MacDuffie 1995; Pil and MacDuffie 1996).

Lean production is designed to produce small batches of cars. It utilizes a specific set of factory practices that facilitate small lot production with minimal buffers and a corresponding rapid feedback process when there are problems. As such, lean facilities typically have very small end-of-process rework areas compared to non-lean plants. Workers "pull" materials and components throughout the production system. Material is delivered "just-in-time," minimizing work in process, reducing the likelihood of large batches of faulty materials, and reducing in-process waste (Cusumano 1985).

In the lean model, work is based on the principles of continuous improvement, or "Kaizen." Workers are responsible for identifying quality problems found on the production line and, in contrast to mass production, are able to stop the line for such problems. Floor workers are arranged in teams, with a team leader performing a coordinating role in addition to assembly tasks. To enhance the multi-skilling practices needed in the team format, workers also undergo training and job rotation. This is particularly important since assembly workers are given many of the responsibilities that would be assigned to specialists in mass produc-

argued for an encompassing approach to examining the role of operations in improving

tion. Improvement suggestions are offered through a suggestion system or Quality Circles. This involvement of employees at all levels of the organization has been identified as a driver of improvements in environmental efficiency (Kornbluh and Crowfoot 1989; Lawrence and Morell 1995; Florida 1996).

Human resource (HR) policies are as important as the technical system to the operation of lean production. In contrast to mass production, worker commitment, skill, and motivation are critical to operational success. Some of the means used to ensure this include highly restrictive worker selection emphasizing aptitude and ability to work in a cooperative fashion with others, compensation linked to performance; high levels of training and skill development for both new and experienced workers, and efforts to reduce status barriers between managers and workers (Pil and MacDuffie 1999). While empirical support for the importance of HR to environmental efficiency has been weak (especially with regards to the role of training) (Aragon-Correa 1998), many researchers have argued that careful recruitment and high levels of training and education are critical (Denchant and Altman 1994; Lawrence and Morell 1995; Starik and Rands 1995).

There is significant theoretical, as well as some empirical research suggesting that operational policies and practices can be important determinants of environmental efficiency. We will explore the relationship between the different elements of "lean" manufacturing systems and environmental efficiency, and hypothesize the following:

HYPOTHESIS 1. *Different aspects of lean manufacturing—buffer minimization, work systems, and human resource practices—contribute to improved resource efficiency.*

Lean Production and VOC Emissions

While environmental efficiency is certainly a critical component of environmental performance, there are other important measures to consider (Schenck, Rothenberg, and Maxwell 1993). For example, one of the largest environmental pollutants from the painting process is volatile organic compounds (VOCs). Managing VOCs is one of the primary challenges for environmental managers in assembly plants, and regulations are continuously aiming for lower VOC emissions. When considering approaches to managing VOCs, it is important to look at the "technology portfolio" being used to address pollution reduction (Klassen and Whybark 1999). Environmental technologies and management practices can be classified in one of two categories. First are pollution prevention technologies and management practices, which are structural investments in operations or changes in management practice that involve fundamental changes to basic product or primary process as a means to change material use or reduce material/resource use. A benefit of pollution prevention activities is that they are often "value added" for the firm since they reduce costs through material use reduction or through the avoidance of waste management costs (Porter and van der Linde 1995). The second are pollution control technologies and management practices, which treat or dispose of pollutants or harmful by-products at the end of the manufacturing process. Because these technologies are "end-of-pipe," a final step in the manufacturing process, they are not "value-added" and as such have been associated with worse manufacturing performance (Klassen and Whybark 1999). These latter technologies, however, are often required to meet current and future regulatory requirements or community pressures.

For resource efficiency, reductions are achieved solely through pollution prevention technologies and managerial approaches, value added approaches at which, as discussed above, lean plants will excel. In the case of VOC's, however, while increasing process efficiency and reducing the solvent content of materials through pollution prevention technology and management can reduce emissions, there are limits to this approach. To meet many current and future regulatory requirements, additional reductions require control technology, expensive end-of-pipe abatement equipment such as incinerators. In fact, Aragon-Correa (1998) suggests that firms with leading-edge environmental performance com-

environmental managers in assembly plants, and regulations are continuously aiming for lower VOC emissions. When considering approaches to managing VOCs, it is important to look

bine both prevention and control technologies, rather than rely primarily on prevention technologies. Similarly, automobile assembly plants leading in the area of air emissions reductions need to reduce these emissions through both control technology, such as new abatement equipment, and pollution prevention, such as alternative managerial practices, and paint processes and paint technology (Bailey 1992). As an example, at a plant with one of the lowest VOC emissions in the world, initial VOC reductions were achieved with pollution prevention technologies and management systems. Through material usage reductions, they reduced VOC cleanup emissions from the prime and topcoat paint booths by about 50%. Then, the efficiency of the paint equipment was increased, which provided another 15% reduction in emissions. Even with all of these improvements, however, the plant still had to install booth and oven abatement to meet regulatory requirements.

The downside of abatement is that it is costly, and rarely offers returns. In our research, plants reported spending as much as $28 million on air abatement technology. Saturn Corporation, for example, spent $25 million on emissions control technology for its paint shop, after investing millions more in a water-based painting system (*Environment Reporter* 1992). Abatement equipment, while expensive, is attractive because it serves as a protective "buffer" from future changes in regulation and is less invasive to the production process. Therefore investment in abatement is in direct conflict with the basic principles of lean production, which aims to minimize buffers, focus on value-added investment, and implement continual process improvement. Moreover, lean plants may be more confident in their ability to achieve emissions reductions through process change, decreasing their need to "buffer" their process with excess abatement technology. Thus, plants operating according to a lean philosophy may try to avoid these effective, yet costly abatement technologies in the short term, with the long-term goal of reaching environmental improvements through process change. As a result, despite achievements in pollution prevention, lean plants will still fall behind those plants that use extensive control technology. Thus we will explore the relationship between the different elements of "lean" manufacturing systems and air emissions, and hypothesize the following:

HYPOTHESIS 2. *Plants that operate according to a lean philosophy will be more likely to have higher VOC emissions.*

Methods

We relied on three sources of data for this paper: a survey of environmental performance, a survey of manufacturing performance, and qualitative interviews at 17 manufacturing plants.

Survey Design

We used two sets of surveys: one to collect data on environmental efficiency, and the other to capture organizational practice and broader metrics of manufacturing performance. The first survey, the Environmental Practice Survey (EPS), was geared at understanding environmental choices made by the plant via quantitative measures of plant environmental performance. Draft questions were sent out to key informants in the United States and Japan, reviewed with these informants, and then revised for the final version. The instrument was then pre-tested at five automobile plants, two of which were Japanese transplants, two of which were American manufacturers, and one of which was located in Europe. The final survey was then sent to a contact person in each plant, usually the environmental manager. Surveys sent to Japan were translated into Japanese with numerous crosschecks for translation accuracy.

The second survey was an in-depth survey of manufacturing practice and policy at automobile assembly plants, known as the International Assembly Plant Study (IAPS). The IAPS was completed by the plant management team, generally including representatives from

HYPOTHESIS 2. *Plants that operate according to a lean philosophy will be more likely to*

process engineering in the body, paint, and assembly shops, material handling, quality control, senior plant management, and human resources. The resulting data were cross-checked with the plant for completion of missing or incomplete answers, and approximately half the respondents received a 1-day visit to verify the data on-site. The data from the IAPS were utilized to develop metrics of how lean each plant is, as well as non-environmental performance metrics. Additional detail on the IAPS can be found in MacDuffie and Pil (1995).

Data for both surveys were collected in the 1994–1995 time frame. While the two surveys were administered separately, an effort was made to target similar plants. There was an overlap of 32 automobile assembly plants, with 7 plants in Japan and 25 in North America. One plant was eliminated because of its unique body style and painting process, leaving a final N of 31. While this is a relatively small sample, it is similar in that respect to much environmental practice research (Klassen and Whybark 1999). Our data are unique in that the separate surveys provide us with objective metrics by independent observers for multiple measures of environmental performance and management.

For IAPS, the researchers contacted 109 plants from 20 different countries. (In contrast, the environmental survey focused on plants belonging to the Big 3, and Japanese companies operating in North America and Japan.) Eighty-three usable surveys were returned, for a response rate of 76%. The assembly plant survey respondents not included in these analyses are significantly smaller in size (760 vehicles/day versus just over 1,200 for those in the sample), and have significantly worse productivity (30+ hours per vehicle compared to an average of 20.2 for those in the sample). There are no significant differences in the lean indices. The response rate for the environmental survey was 72%.

Descriptive Statistics and Construct Measurement

Table 1 provides descriptions, sources for the key quantitative variables used in our empirical analyses, and the basic descriptive statistics. We have developed three plant-wide measures of environmental performance based on data from the EPS. As a measure of air pollution, we used plant level emissions of volatile organic compounds (VOC) in kg/100 vehicles. Water use was measured in m^3/100 vehicles and energy use in MMBTU/100 vehicles. All three of the measures are plant wide and averaged over 2 years to reduce the influence of extenuating circumstances in a particular operating year.

Table 1 describes our three indicators to capture the different aspects of lean that may contribute to environmental performance. The Buffer Minimization index (BUFFERMIN) measures the degree to which buffers are minimized in the production operations. The Work Systems index (WORK) is a measure of work structures and policies that govern production activity on the shop floor and influence the skill acquisition and development of production workers. Our third index, human resource management practices (HRM), captured the organizational practices associated with employee skill development, and the factors that foster a "psychological contract" between the organization and its employees. For each index, BUFFERMIN, WORK, and HRM, the component items were normalized, summed, and converted into a z-score that is rescaled from 0 to 100. Higher scores indicate a greater level of lean management practice, and the highest score represents the plant that uses the lean practices most extensively (MacDuffie 1995).

To explore the relationship between lean and environmental performance, we introduced a few key controls. We controlled for plant age (AGE), as it can influence the state of the technology in the plant. We recognize that major changes in plant structure and technology can happen after the initial plant structure is put in operation. However, the initial structure does place limitations on plant utilization. We explored collecting data on plant retrofits, but were unsuccessful due to a combination of low response rates, and differences in how plants perceived retrofits. We will utilize the plant's age based on its inception date with the recognition that this is a less than perfect measure. MacDuffie (1995) suggests controlling for production volume (PRODUCTION) as the ability to adopt certain manufacturing processes can

TABLE 1

Variable Measurements and Descriptive Statistics

Variable	Measurement	Source	N	Mean	SD	Min	Max
		Dependent					
Energy use	Average 1992–1993 MMBTU/100 Vehicles	EPS†	30	778	228	337	1,455
Water use	Average 1992–1993 m^3/100 Vehicles	EPS†	30	434	164	150	849
VOC Emiss.	Average 1992–1993 kg/100 Vehicles	EPS†	29	551	163	262	909
		Independent					
BUFFERMIN	Combination of size of repair area, inventory policy (days of parts and frequency of delivery), and size of paint-assembly buffer (z-score, rescaled from 0 to 100, with 0 = most buffered, 100 least)	IAPS‡	30	66.3	20.2	6.8	100
HRM	Combination of recruitment selectivity, training for experienced employees, training for new employees, contingent compensation, and status differentiation (z-score, rescaled from 0–100 where 0 is least use, 100 greatest in overall sample)	IAPS‡	31	48.1	25.4	0	100
WORK	Combination of percent of workforce in teams, percent of workforce in employee involvement groups, number of employee suggestions, amount of job rotation and decentralization of responsibility for quality (z-score, rescaled from 0–100 where 0 is least use, 100 greatest)	IAPS‡	31	47.3	26.2	6.9	91.6
		Control					
Age	Age of plant in years	EPS†	31	35	22	4	94
Daily production	Average number of vehicles produced per day	EPS†	31	1,206	708	430	3,400
Energy cost	Average 1992–1993 $/MMBTU	EPS†	30	8.42	5.62	4.49	29.41
Water cost	Average 1992–1993 $/$m^3$	EPS†	30	0.53	0.37	0.08	1.8
Paint type*	Waterborne top coat, 1 = yes, 0 = no	EPS†	29	12.5% waterborne			
Location*	Location of Plant 1 = Japan; 0 = N.A.	EPS†	31	22% Japan			

Note: * binary variables. † Environmental Practice Survey. ‡ International Assembly Plant Study.

vehicles. Water use was measured in m^3/100 vehicles and energy use in MMBTU/100 vehicles.
All three of the measures are plant wide and averaged over 2 years to reduce the influence
sample)
WORK Combination of percent of IAPS‡ 31 47.3 26.2 6.9 91.6
workforce in teams, percent

differ markedly with the overall production capacity of the plants. This is consistent with findings suggesting technology differences based on plant size (Dunne 1994). We operationalized plant size as the number of vehicles produced per day. Economic theory would suggest that firms will act more readily on environmental indicators that are internalized through resource costs or fees (Hanley, Shogren et al. 1997). For this reason, we controlled for utility costs (water cost and energy cost) when examining water use and energy use. We measured these as the dollar cost per MMBTU and per cubic meter of water. These also helped us capture regional differences in the cost of utilities. For VOC emissions, a dummy variable was introduced to control for the use of waterborne paints (WATERBORNE). Because of its lower VOC content, use of waterborne paints would contribute to lower VOC emissions. A dummy variable for the operating country (LOCATION) was tested to control for gross differences in environmental regulation and culture, but had no significant effect. Regional differences were examined but were found to be insignificant for VOC emissions.

Interview Method

Data on environmental management practice were gathered via semi-structured interviews at a subset of the 31 plants included in the survey sample of 20 plants (Yin 1994). While no plant can be individually identified for confidentiality reasons, 14 plants were visited in North America and 6 plants in Japan. Visits to Japanese plants were 1 to 2 days long, while most visits to North American plants ranged from 3 to 5 days. Visits to four of the North American plants were a month long in duration. In total, 156 plant level employees were interviewed. The purpose of these trips was to gain greater insight into the survey results and to obtain information on the mechanisms by which lean management is related to environmental management and performance. In all plants visited, the environmental, utility, and paint shop managers/engineers were interviewed using a semi-structured interview protocol. Environmental and utility personnel are important because they are often key members of the environmental management team. As paint shop operations account for a large percentage of plant pollutants, interviewing paint shop managers and engineers was critical to understanding paint shop management. When possible, the plant manager, health and safety managers and logistic engineers were interviewed to obtain additional perspectives on overall environmental philosophy, chemical management, and packaging, respectively. The four month-long cases further involved interviews with area managers, quality engineers, process engineers, line workers, team leaders, maintenance personnel, facility engineers, suppliers, waste management staff and cleaning staff, and participant observation in environmental and paint shop team meetings. Additional interviews were conducted with corporate level environmental and research and development (R&D) staff at five companies.

In contrast to the survey, which focused on output-oriented performance measures, interviews focused on management practice, processes, and technologies. For a fuller description of the interview methodology, see Rothenberg (1999). Question categories can be found in Rothenberg's Appendix A. These questions were based on existing literature on environmental management and initial theories formed from pilot studies at two well-known "lean" plants, and one plant with more traditional management practices. As suggested by Miles and Huberman (1994) and Yin (1994), interview data were placed in a comparative matrix, in which the segments were categorized and organized in a matrix in order to explore how the plants differ from one another. In this matrix, a mixture of direct quotes, summary phrases, and data coded for quantitative analysis was used. Matrix categories included level and nature of regulation (for water, air, and solid waste), local environmental issues/demands, environmental management structure, measuring and use of data, worker participation in environmental activities, formal environmental policy and training, supplier relations, role of paint shop personnel in environmental improvements, and approaches to waste reduction (pollution prevention versus abatement) for all pollutant media. For comparative purposes, plants were divided into two categories based on their overall lean score from the IAPS. Taking

the average of the three indices, Buffer Minimization, Work Practices, and Human Resource Practices, "less lean" plants scored below 50 and "more lean" plants scored 50 or above.

Results and Discussion

Survey Results

Table 2 provides the correlations among the measures of environmental performance and the indicators of lean. While all but one of the correlations for water use, energy use, and VOC emissions are in the hypothesized direction, only HRM significantly correlates with water use in the hypothesized direction. Energy cost is negatively correlated with energy use, suggesting that plants facing higher energy costs make greater efforts to conserve energy. The same relationship holds between water cost and water use. Plant age is significantly and negatively correlated with water usage and positively correlated with energy usage, suggesting that older facilities are less wasteful when it comes to water use. Energy cost is positively correlated with both production volumes, and the indicators of lean. One reason for this may be that plants in Japan are more likely to face higher energy costs as well as utilize lean practices. The use of waterborne paints is negatively correlated with VOC emissions.

Table 3 provides results of regression analyses examining the relationship between VOC emissions and the indicators of lean. Looking only at control variables, use of waterborne base coat is significantly associated with lower VOC emissions. VOC emissions is positively related to all three lean indicators, and is significantly related to WORK SYSTEMS. Thus, Hypothesis 2 is partially supported. This result suggests that there may, indeed, be trade-offs between lean production and environmental performance and underscores the importance of looking at multiple measures of environmental performance. For resource efficiency, regressions were run in a similar formulation. While the relationships are in the hypothesized direction, the regression analyses showed no significant effect of any of the indicators of lean on water or energy use. This may be due to the relatively small sample size (see discussion section below).

We also ran reliability analyses for each of the three constructs on the data used for this paper. The Alphas for the HRM factor was 0.7, for Work 0.69, and for Buffers was 0.37. Given the low alpha for Buffer Minimization, we ran all regressions using first BUFFERMIN, and then the components of this construct (incoming inventory levels, in-process inventory, and repair space). We found that incoming inventory levels was the only variable with a statistically significant role—it was significantly negatively associated with water use and energy use (as

TABLE 2
Correlations

Variable	1	2	3	4	5	6	7	8	9	10
Dependent										
Energy use (1)	1									
Water use (2)	0.152	1								
VOC emissions (3)	−0.101	0.043								
Independent										
Energy cost (4)	−0.385*	−0.133	0.282	1						
Water cost (5)	−0.060	−0.535**	−0.133	0.107	1					
Plant age (6)	0.326	−0.394*	−0.119	−0.141	−0.068	1				
Daily production (7)	0.004	−0.345	0.068	0.669**	0.128	−0.069	1			
HRM index (8)	−0.184	−0.423*	0.184	0.379*	0.215	−0.544**	0.340	1		
Work system ind. (9)	−0.240	−0.266	0.352	0.429*	−0.034	−0.594**	0.440*	0.754**		
Buffer index (10)	0.060	−0.104	0.148	0.442*	−0.084	−0.135	0.530**	0.354	0.479**	1

* Correlation significant at the 0.05 level. ** Correlation is significant at the 0.01 level.

waste management staff and cleaning staff, and participant observation in environmental and

space). We found that incoming inventory levels was the only variable with a statistically

TABLE 3

Regression Analyses for VOC Emissions

Independent	Model 1a (t stat)	Model 1b (t stat)	Model 1c (t stat)	Model 1d (t stat)
Age	−0.133 (−0.808)	−0.051 (−0.265)	0.113 (0.603)	−0.133 (−0.804)
Paint type	−0.525 (−3.25**)	−0.515 (−3.21**)	−0.476 (−3.17**)	−0.510 (−3.10**)
Country (Japan = 1)	−0.073 (−0.446)	−0.137 (−0.757)	−0.302 (−1.648)	−0.127 (−0.636)
HRM index		0.180 (0.857)		
Work index			0.508 (2.275*)	
Buffer index				0.097 (0.493)
F	3.83*	3.027*	4.59**	2.853*
Adj R^2	0.215	0.207	0.317	0.193

Dependent Variable = VOC Emissions per 100 vehicles. * Significant at the 0.05 level. ** Significant at the 0.01 level. *** Significant at the 0.001 level.

incoming inventory decreases, there is more water/energy use). This finding goes counter the hypothesized direction between lean and environmental performance. One explanation for this finding is that many traditional mass-production facilities have reduced their incoming inventory (e.g., for capital investment reasons), without expending similar effort to reduce in-process buffers (c.f., Pil and MacDuffie 1999, p. 52-54).

Interview Results

While our survey results were not definitive, our interviews suggest that all three aspects of lean management, buffer minimization, work practices, and human resource practices influence a plant's approach to environmental management in both positive and negative ways. In this section we try to explain how and why lean practices may influence a plant's approach to environmental management. First, we argue that the "Buffer Minimization" relates not only to reduced buffers in environmental technology and management, but also to an overall approach to manufacturing that requires the minimization of waste, and focuses on the availability of environmental information and continuous improvement in manufacturing processes. This focus, while largely congruent with environmental efficiency, can result in some tradeoffs in other metrics of environmental performance. Second, "Work Practices" involve the participation of workers at all levels improve environmental efficiency. Third, "Human Resource Practices" relate to the increased level of environmental training and greater ability to implement process change because of a broader skill base.

BUFFER MINIMIZATION. Because of their focus on buffer minimization and waste minimization, we found that lean plants view end-of-pipe solutions as a diversion of resources and as an option to be taken only as a last resort. In the case of VOC abatement, lean plants indicated that they were willing to have slightly higher emissions in order to avoid abatement equipment. This type of investment is not value added and, therefore, not in line with the philosophy of lean production. One paint manager at a Japanese transplant explained: "End-of-pipe technologies take a lot of my time and energy while contributing little to productive capacity. I just want to avoid them." In addition, lean manufacturing plants are more likely to reduce their use of end-of-pipe equipment as a hedge against future regulations, and to place greater faith in process improvement as a way to reach future environmental goals. An environmental manager at another lean plant explained, "Instead of asking "how much end-of-pipe technology it should add?", [we] put those resources into increasing efficiency and wait until regulation forces the add on controls."

In order to obtain a better measure of a plant's commitment to process change versus end-of-pipe abatement, we asked each plant to characterize the ways in which they reduced pollution in the past year. As shown in Table 4, "pollution prevention" includes value-added

... reduced buffers in environmental technology and management, but also to an overall approach to manufacturing that requires the minimization of waste, and focuses on

TABLE 4

Waste Management Strategy (Averages from Each Category)

Lean Score	N	% of Water Waste Reduced in Past Year through Pollution Prevention	% of Air Emissions Waste Reduced in Past Year through Pollution Prevention	% of Solid Waste Reduced in Past Year Through Pollution Prevention
TOTLEAN <50	8	44	37	94
TOTLEAN >50	12	44	53	94

activities such as recycling, material changes, process change, and energy recovery. In the case of air pollution, lean plants reported achieving 53% of their air emission reductions in the past year through pollution prevention, while less lean plants reported 37%, indicating that lean plants place a greater emphasis on pollution prevention over abatement equipment. We can see that for water waste, lean plants had an approach similar to that of less lean plants, with approximately 44% of the water waste improvement being made through pollution prevention. This outcome was strongly influenced by the extremely stringent water regulations in Japan in comparison to the U.S. (most plants emit drinkable water, which one plant manager proved to us by drinking a cup). When looking only at plants in North America, however, leaner plants in North America did take a more preventative approach as compared with less lean plants in North America (63 versus 43%). For solid waste, we found little difference between the plants, as most waste is recycled or incinerated (incineration was coded as abatement if there was no energy recovery).

Other goals of lean production can also conflict with environmental performance. For example, because water use in some processes is critical to product quality, lean plants may trade off greater water consumption in those areas for superior quality. This is particularly the case in the paint shop. One plant in Japan, for example, chose not to adopt a water saving process in the paint shop because of quality concerns, even though it was being used with success at a U.S. plant. One environmental manager explained how difficult it was to get buy-in for a water recycling project in the wet sanding area:

> We looked at the cost of plumbing the water to 20 microns or smaller—at that level you would not need to worry about contamination. We talked to paint engineers and especially quality people. They had a lot of fears. They feared that there would be oil in the water—so we used in-line oil and grease analyzers. They were afraid of dirt—so we decided to run it back through the dionizer. They were afraid of bacteria—to deal with that we exposed the water to UV light.

While the focus on buffer minimization and waste minimization may conflict with some aspects of environmental performance, they can contribute to environmental performance. As explained by an environmental manager at a Japanese transplant, "The very basis of the [lean] system is to always reduce waste. Of course, it applies to a lot of things, such as reducing costs and space. But it is the same concept." Minimal buffers, for example, allow instant feedback of problem conditions during production and relate to an overall philosophy of waste reduction. A manufacturing manager at a lean plant explained:

> Narrowing inconsistencies is a primary goal of [our company]. Because of this focus, managing waste is easier to do. Every time we make a change, the indicators of manufacturing performance show the impact of that change. [With this type of focus,] it's easier to monitor wastes and then reduce them.

One of the advantages of low buffers is that they allow for rapid feedback of data. For this feedback to happen in a timely manner and the lean process to function properly, there must be adequate measurement and use of data related to important process outcomes, such as efficiency. In our interviews, we found that workers in lean plants measured and posted material and natural resource use data more often than less lean plants. As shown in Table 5, plants that scored above 50 on the Total lean index measured solvent-laden cleaners, purge

process in the paint shop because of quality concerns, even though it was being used with success at a U.S. plant. One environmental manager explained how difficult it was to get

TABLE 5

Data Measurement and Use Questions (Averages from Each Category)

Lean Score	N	Number of Energy Meters in Strategic Locations[‡]	Number of Water Meters in Strategic Locations	Frequency Chart and Post Water Use Dept. Level[*,‡]	Frequency Chart Energy Use Dept. Level[*,‡]	Frequency Post Energy Use Dept. Level[*,‡]	Frequency Measuring Cleaning Solvent[†,‡]	Frequency Measuring Purge Solvent[†]	Frequency Measuring Topcoat[†]
TOTLEAN <50	8	0.7	1.7	0.3	0.3	0	2.4	3.4	3.4
TOTLEAN >50	12	4.3	3.4	1.8	2.2	2.4	4	3.9	3.9

* Coding: 0 = Never; 1 = Once a year; 2 = Between once a year and once a month; 3 = Between once a month and once a week; 4 = Once a week; 5 = More often than once a week. † Coding: 1 = Less often than once a week; 2 = At least once a week; 3 = At least once a day; 4 = At least once a shift; 5 = At least every hour. ‡ T-Test indicates significant difference in means.

material, and top coat more often than those with lower lean scores. Our interviews suggested that these types of data are critical to any solvent management and voc reduction program, and reinforced the notion that lean plants place a greater emphasis on reducing emissions through process change. In the area of energy and water, leaner plants on average had a greater number of water and energy meters in critical locations, were more likely to chart and post water and energy data on the departmental level, and posted these data more often, although this relationship was stronger for energy-related activities than for water. Because of the high utility costs in Japan, these comparisons were also made looking only at plans in North America—the differences persisted.

The difference observed in water and energy management practices underscores the complexity in the relationship between lean production indicators and environmental efficiency. A resource is only a valuable resource to the extent it is perceived as such by an organization. In most plants we visited, water and energy use were perceived and managed differently. Most manufacturing staff clearly regard energy use as a valuable resource. Many of the U.S. plants visited, for example, have had plant-wide energy conservation committees in operation for decades. In contrast, water use was usually relegated to the facility staff or to interdepartmental teams on an "as-needed" basis. At three U.S. plants, water use reduction was outsourced to water treatment suppliers, further removing it from core processes and personnel. Similarly, many more plants posted energy use as a basic performance measure in multiple areas of the plant, than they did water use.

One explanation is that because of the lower costs of water, as compared to other resources, the plants were not organized in terms of both technology and management practice, to focus on water use. An environmental engineer at a lean plant explains:

> I do have a theory about [why they are managed differently]. Energy use is 10× the cost of water. We have meters all over the place for energy because the cost is higher. There has just not been a priority put on water. It's something that people don't really see that much of and it's out of sight.

The difference in management and perception also relate to technical differences between energy and water use in the plants. Technically, energy use reduction opportunities overlap with almost all plant operations and are accessible to most workers. Substantial energy savings can be achieved by turning off equipment or using less energy-intensive equipment. Water reduction, however, often entails a substantial change in the design of a particular process and the water flows in the plant. Additionally, as discussed earlier, in the minds of many employees, water remains more closely linked with product quality.

The approach to environmental management itself is also influenced by this focus on buffer minimization. The environmental management function has traditionally been seen as a way to "buffer" the plant from changes in environmental regulations (Maxwell, Rothenberg, Briscoe, and Marcus 1997). Environmental staff would have minimal interaction with plant staff and were often placed in offices that were physically isolated from the rest of the plant. This approach to environmental management conflicts with the philosophy of buffer minimization found in lean production. In lean plants, there was a concerted effort to increase the level of interaction between environmental and other plant staff. For example, as seen in Table 6, most striking was that environmental managers in lean plants took a more "hands-on" approach to management, with managers in leaner plants reporting to spend an average of 59% of their time on the plant floor in comparison to the 28% reported by the less lean plants. As one environmental manager explained, "working the floor" was the key to successful environmental management; it helps increase buy-in, explain environmental concerns (e.g., why it is important to purge paint guns in a specific manner), and harness new ideas regarding environmental performance.

Work practices. The lean practices indicated by the second indicator of lean production, work practices, also seemed to influence the way in which environmental performance was managed in the firm. We saw greater levels of worker participation in environmental activities in lean plants. For example, as seen in Table 6, plants with higher lean scores generally had greater participation from floor workers in areas such as chemical use monitoring and reduction and solid waste reduction. Much of this participation took place through formal suggestion programs and quality circles. The suggestions and Quality Circles that the plants used as examples with us addressed such issues as reducing cleaner use, reuse of cleaning rags, reuse of scrap material, energy conservation, and systems for packaging waste separation. An environmental manager at one Japanese transplant explained the role of workers in environmental management:

> Yes, the [lean] production system is an outstanding manufacturing philosophy, but all of these systems and techniques within it remain nothing but a collection of great ideas unless the right people make it happen. This is particularly true in environmental affairs. We give team members every opportunity to want to care [about environmental performance] by getting them involved in the decision-making process. We believe that the people who do the work are the most qualified to figure out how to do it even better. . . . The whole key to environmental performance is people.

At one plant, a closer look was taken at participation practices, details of which can be found in Rothenberg (1999). In this plant, 744 suggestions from the suggestion program were reviewed, coded, and analyzed. We found that 8.5% of the suggestions had potential for a positive environmental impact. An interesting observation was that hourly specialty staff such as workers on "special projects," and quality and maintenance personnel, rather than line workers were important in initiating suggestions resulting in large environmental improvements. However, floor level workers were often important in their ultimate implementation.

As discussed earlier, in parallel with these work practices is an environment in which

TABLE 6

General Management Practice Questions (Averages from Each Category)

Lean Score	Degree to which Problem Solving Circles Contribute to Solid Waste Reduction*	Level of Involvement of Production Workers in Monitoring Chemical Usage[*,†]	Level of Involvement of Production Workers in Reducing Chemical Usage[*,†]	% Time Environmental Manager Spends on Shop Floor[†]	% Employees Trained Regarding Plant Environmental Policy
TOTLEAN <50	1.4	1.7	1.5	28	30
TOTLEAN >50	3.2	3.7	3.2	59	55

* Coding: These questions were structured questions asked on a scale of 1–7. † T-Test indicates significant difference in means.

in operation for decades. In contrast, water use was usually relegated to the facility staff or
to interdepartmental teams on an "as-needed" basis. At three U.S. plants,
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workers are encouraged to continuously innovate and implement process change. In traditional plants, production quantity is always the number one objective, even with a tradeoff in terms of quality or cost. A paint engineer from a plant based on the mass production model explained, "The truth is that when the line stops, [paint managers] will dump gallons of paint in order to get the line going again. They will do just about anything to get it started." In several lean plants, however, engineers and environmental managers discussed the importance of their freedom to experiment with new technologies to achieve environmental improvements, even at the risk of hampering production. An environmental manager at a lean plant explained how the willingness of the paint shop managers to experiment with new processes and technology was important to lowering solvent use in the paint shop.

> The biggest thing the managers did was empower the people and support us. Because, you know, we had flack from the line. You know, not all the kaizens [improvements] would work. We would do something on the weekend and sometimes it wouldn't work—so we picked it up and fixed it and the managers did not cut anybody's head off. It is a big force when you empower somebody. Then, you just go at it and don't worry about it if something goes wrong. We just see what went wrong and make sure it won't happen again. [The managers here] are willing to try—and not all companies are willing

HUMAN RESOURCE MANAGEMENT. Last, environmental practices were supported by human resource practices associated with lean production. As discussed earlier, workers in lean plants are trained to chart, graph, and statistically analyze production data. This appeared to facilitate employees' ability to understand data on material use and identify solutions. In one lean plant, for example, an engineer stated, "I would like to see more detailed use of information on plastic waste and reuse. Sometimes there is a dollar number that is reported, but that does not tell how much waste is being produced." In comparison, engineers in traditionally run plants were overwhelmed by poorly managed information. "I don't need more information," one engineer stated, "I need to figure out how to use all the information I am getting now!" As seen in Table 6, workers in lean plants received more environment-focused training, such as hazardous material training, and general training on plant environmental policy, recycling, and pollution prevention.

Conclusions and Future Research

In both our quantitative and qualitative analyses, we found a complex relationship between lean manufacturing and environmental performance that depended on the measure of environmental performance being examined. As suggested by Hypothesis 2, with regard to air emissions, we found that there may be tradeoffs between lean manufacturing techniques and VOC emissions. To achieve mandated levels of air emissions in the United States, automobile assembly plants need to rely on advanced pollution abatement equipment, as well as on process improvements. Plant interviews further clarified this relationship. Lean plants are more likely to resist the large capital expenditures for pollution abatement equipment that would reduce emissions beyond what is required by current regulation.

There is some evidence that several lean plants have shown willingness to compromise some of their lean management principles in order to reduce their emissions. They have started to increase painting batch sizes (the number of similar color vehicles painted in a row) in order to reduce VOC emission in the plant, although it conflicts with the "just-in-time" philosophy of the plant. In Japan, plants have also altered their "just-in-time" delivery system to reduce congestion and urban air pollution (Cusumano 1994).

Our results support Hypothesis 1, but not as strongly as we expected. Our multivariate analyses examining the association between lean production and energy and water use were in the right direction but did not show statistically significant results. Our qualitative analysis, however, presents more convincing evidence of complementarities (Milgrom and Roberts 1994; Pil and MacDuffie 1996; Rothenberg 1998) between lean management practices and environmental efficiency goals. All three aspects of lean production—buffer minimization, work systems, and human resource practices, lead to management practices that were more

supportive to improvements in resource efficiency. First, lean plants aim to minimize waste and buffers, leading not only to reduced buffers in environmental technology and management, but an overall approach to manufacturing that requires the minimization of waste and accessibility of environmental information. While this philosophy may result in some tradeoffs in environmental performance when control technologies are needed for superior performance, it is largely congruent with resource conservation. Second, worker participation in continuous improvement serves to improve environmental efficiency. Third, the human resource practices in lean plants encourage higher levels of environmental training and provide the skills needed for identification and implementation of waste reduction opportunities. An interesting finding in the qualitative analysis was that this relationship will be stronger for those resources plants perceive as more valuable.

Our reliance on "global" indicators of lean may be one reason we did not find statistically significant results in our regression analysis. Certain lean plants are implementing environmental management practices (e.g., training, measurement of resources use, and environmental managers with multiple responsibilities), which may not be related to these overall lean practices and strategies. Future research should rely on measures of environmental management practice, similar to those used in our semi-structured interviews, to capture the environmental aspects of lean production.

We recognize that there are several limitations to this study. We have only a relatively small sample of 31 plants for the multivariate analysis. Both the EPS and IAPS had larger samples of plants, and the EPS was designed to be complementary so that the data could be pooled efficiently. This could not be fully implemented because we were unable to obtain commitments from the companies to attain an identical sample. To address this issue we have recently placed an integrated survey into the field that combines manufacturing and environmental measures.

Despite sample limitations, this is the most comprehensive examination of the relationship between lean production and environmental performance and management in the automotive sector. The study relied on extensive surveys and in-depth interviews with more than 150 managers in Japan and North America. In contrast to King and Lenox (2001), we believe that these relationships are strongly influenced by the sector and technical options within the sector's "technology portfolio." In this case, it is clear that mandated emission levels can not be achieved through prevention technologies only. This relationship deserves further investigation to determine their generalizability to assembly plants across industries in industrial countries.

Our findings about the potential tradeoffs between lean production and environmental performance are of interest to researchers as well as managers in industry. With respect to researchers, this study points to the complexity of the relationship between manufacturing management practice and environmental performance. In particular, it stresses the necessity to distinguish between environmental management practices and environmental performance, and between various environmental performance metrics. Theories that suggest a simple "win-win" relationship do not accurately reflect these complexities.

With respect to managers, of utmost concern is how to balance pressures for improved environmental performance and more traditional measures of performance as many plants adopt lean management practices. This paper suggests that while lean practices can influence environmental management practices and perhaps improve resource use, they will not be able to address all environmental issues. The complexities uncovered, both in our quantitative analyses, and qualitative findings, suggest the need for further research to deepen our understanding of the links between advanced manufacturing and environmental performance.[1]

The authors thank the participating companies, Lotte Bailyn, Tom Kochan, Maureen Scully, John Paul MacDuffie, Charlie Fine, Daniel Roos, Joel Clark, Frank Field, The Sloan Foundation, The MIT International Motor Vehicle Program, and the Center for International Business Education and Research at the Katz School of Business for assistance and support.

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