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Integrating Technology and Human Resources for High-Performance Manufacturing: Evidence from the International Auto Industry

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For much of the last decade, technology has held the spotlight as a powerful force that has both promoted dramatic economic restructuring and offered individual firms new strategic opportunities for responding to changing competitive conditions.[1] But the enthusiastic predictions of the early 1980s about the cost-saving and quality-enhancing capabilities of advanced microprocessor-based technologies were matched late in the decade by a chorus of concern about the failure of many technology investments to yield expected performance results (Dertouzos, Lester, and Solow, 1989; Loveman, 1988; Roach, 1987).

These unrealized expectations have brought increasing attention to the organizational context into which new technologies are introduced. According to this perspective, new technological capabilities contribute effectively to improved economic performance only when the organizational skills and flexibility needed for rapid absorption and mastery of these capabilities are present and evolving simultaneously (Adler, 1988; Kochan, Cutcher-Gershenfeld, and MacDuffie, 1990; Walton, 1990).

This chapter carries this line of argument one step further, by summarizing the results of our study in the manufacturing sector of seventy automotive assembly plants representing twenty-four companies and seventeen countries worldwide. The detailed data and statistical analyses that produced these results are presented in several earlier papers (Krafcik, 1989; Krafcik and MacDuffie, 1989; MacDuffie, 1989). Our summary here emphasizes the implications of our findings for the study and practice of organizational change.

Out of our work (and that of our colleagues in the International Motor Vehicle Program) has emerged the concept of a "lean production system," that is, a production system embedded in an organizational context that takes as a premise the existence of a skilled, motivated, and flexible work force, following a logic quite distinct from traditional mass production (Kenney and Florida, 1988; Piore, 1989; Womack, Jones, and Roos, 1990). We find that plants with lean production systems have dramatically better productivity (fewer hours per car) and quality (fewer defects per car) than mass production plants.

We also find that technology is utilized differently in lean and mass production

systems. Under the "organizational logic" of lean production, human resource strategy is integrated with technology strategy (Shimada and MacDuffie, 1987). Policies that develop work force skill, motivation, and flexibility and that promote ongoing problem-solving (or "continuous improvement") activity are seen as critical to the effective use of technology. This contrasts with traditional mass production, in which technological advances are expected to enhance managerial control, reduce labor costs, and minimize reliance on work force capabilities.

Accordingly, we contend that new technological capabilities will contribute more effectively to economic performance in the context of a lean production system than in a traditional mass production context. The chapter describes the "organizational logic" of lean production, explains how technology is utilized in this context, and reviews the analyses supporting this "integration" argument.

THE ORGANIZATIONAL LOGIC OF LEAN PRODUCTION

The model of lean production upon which the assembly plant study is based is drawn from Shimada and MacDuffie's analysis (1987) of the production system in Japanese-owned assembly plants located in the United States, the so-called transplants. The transplants offer a valuable opportunity to consider the structure of the Japanese approach to organizing the production system apart from the cultural context from which it emerged. Shimada and MacDuffie find that the key organizational innovations of "lean production," as developed in Japan, have been transferred nearly completely to the U.S. context, and they conclude that this approach is potentially applicable in any cultural setting.

The key organizational innovations of lean production are those linking the use of buffers and the development and deployment of human resources. We consider these in turn, contrasting the "organizational logic" of lean production and mass production.

Use of Buffers

Mass production uses highly specialized resources (both equipment and people) applied to the high-volume production of standardized products to achieve economies of scale. To ensure that these economies can be achieved, the production process must be protected as much as possible from disruptions (such as sales fluctuations, supply interruptions, equipment breakdowns) by large buffers—of inventory, repair space, extra equipment, and utility workers. These buffers moderate the tight coupling among steps in the production process, creating some slack, which minimizes the impact of contingencies.

In lean production, these buffers are seen as costly, for several reasons. The buffers themselves represent a commitment to resources not directly devoted to production. Inventories must be purchased, stored, and handled. A repair area, which provides a postprocess remedy for problems that would otherwise disrupt the primary production process, must be staffed. Inventory buffers also hinder the move from one product design to another, requiring elaborate planning to ensure that parts from the old design

are used up and replaced by parts from the new design at the same rate that sales of the former product are declining and sales of the new product are increasing.

More important, buffers can also hide production problems or reduce the pressure to deal with them. A key innovation of lean production, pioneered by Taiichi Ono at Toyota, was to see disruptions to the production process as opportunities for learning (Ono, 1988). In this view, organizational slack, in the form of buffers, allows production problems to be ignored or deferred. The minimization of buffers, as exemplified by just-in-time inventory policies, therefore serves a cybernetic or feedback function, providing valuable information that can be used for continuous incremental improvement of the production system (Cusamano, 1985; Monden, 1983; Schonberger, 1982). The term "lean production" is a metaphor for this philosophy about the use of buffers.

Development and Deployment of Human Resources

This approach to buffers is inextricably linked to policies that govern human resources. For if the minimization of buffers creates the incentive to identify problems and engage in incremental problem-solving activity, it is the development and deployment of human resources that create the capability to do so effectively.

Workers must be able to identify quality problems as they appear on the line, since there is almost no stock of surplus parts and very little space to put vehicles needing repair. To be able to solve the problems they find (either alone or in a problem-solving group), they must have both a conceptual grasp of the production process and the analytical skills to identify the root cause of problems. This in turn requires a decentralization of production responsibilities from specialized inspectors to production workers and a variety of multiskilling practices, including extensive off- and on-the-job training, work teams, and job rotation within a few broad job classifications.

Furthermore, these skills and abilities are of little use unless workers are motivated to contribute mental as well as physical effort. The attentiveness, analytical perspective, and creativity needed for incremental problem solving cannot be attained through close supervision or the elaborate control systems used to ensure compliance in a mass production system.

Workers will bring those qualities to their jobs only if they believe there is a real alignment between their individual interests and those of the company, and they will commit themselves to advancing company goals only if they believe there is a reciprocal commitment from the company to invest in their future well-being. As a result, lean production is characterized by such "high-commitment" human resource policies as employment security; compensation that is partially contingent on corporate, plant, and/or individual performance; and a reduction of status barriers between managers and workers. The company investment in building worker skills also contributes to this "psychological contract" of reciprocal commitment.

To summarize, in a lean production system the stimulus to achieving cost and quality improvements is the reduction of buffers, which has both a direct effect (e.g., reducing the carrying cost of inventories) and a more significant indirect effect—providing valuable information about production problems and an ongoing incentive to utilize that information in incremental problem-solving activity. While the reduction of buffers can promote this problem-solving approach, it will be effective only when

human resource policies are in place that generate the necessary skills in the work force and create a sense of reciprocal commitment between company and worker.

A "Fragile" System

Shimada and MacDuffie (1987) call attention to an important aspect of lean production's interdependence between the use of buffers and human resource policies. They characterize lean production as a "fragile" system. This is true for both components of lean production. When buffers are minimized, any minor disruption, such as the failure of a supply delivery to arrive on time, can force the entire plant to shut down. Paradoxically, the awareness of this vulnerability can strengthen the production system by providing an ongoing incentive to maintain effective communication and problem-solving skills, both within the plant and in relationships with suppliers (Nishiguchi, 1989).

Lean production is also fragile with respect to its dependence on human resources. As lean production diffuses beyond its source in Japan, it is highly vulnerable to the mass production assumptions and mindsets that have dominated managerial and engineering practice in this century. Unless managers keep the skill levels of the work force high, unless they create a culture of reciprocal commitment in which workers will be willing to contribute to process improvement, unless they accept the premise that technology must be used in a way that complements rather than minimizes the role of human resources, lean production will quickly deteriorate and revert to mass production.

Thus in practice lean production is not weaker or more prone to breakdown than mass production. Indeed, the characteristics of lean production just described often yield a greater resilience and organizational flexibility in the face of changing conditions than do those of mass production. Yet this paradox remains—that maintaining a constant awareness of lean production's "fragility" is in many ways critical to preserving this resilience and flexibility.

TECHNOLOGY IN A LEAN PRODUCTION SYSTEM

The organizational context of lean or mass production systems affects the utilization of hardware technology in several ways. One is the degree to which each production system uses resources—whether hardware or people—in a specialized way. Another, closely related to the first, is the degree to which production processes and tasks remain standardized and fixed over time. A third is the role of the work force with respect to modifying both equipment and task specifications.

A core premise of mass production is that the efficiency of production increases as the division of labor becomes more extensive and the specialization of both machines and jobs increases. This specialization is limited by the market for whatever is being produced. A sufficient volume of a product must be made to keep specialized resources fully utilized, or the inefficiencies of underutilized resources will outweigh the efficiencies of specialization.

Standardized product designs allow for the most extensive specialization of machines and jobs. The greatest efficiencies then result from producing a very large

volume of such a product in very large batches, both because of economies of scale and to minimize setup costs, which are high when hardware is so thoroughly specialized around the requirements of a standard design.

The imperatives for technology under mass production, therefore, are that it be dedicated to a specific product, very efficient in its execution of a highly specialized task, and capable of operating for extremely long production runs. Once a new technology is installed, it should be modified as little as possible if it is to meet these conditions successfully. While this ideal of minimal modification is rarely achieved, it remains the primary orientation and goal of a mass production organization.

Under lean production, there is less concern with the efficiencies of specialization and more concern with the costs of rigidity in the use of technology. General purpose multifunctional or programmable equipment is favored for its ability to switch among product designs at a lower cost in time and money than specialized equipment. Production runs are short, both to provide more opportunities to switch among products and, more important, to speed the feedback that can be provided to upstream processes for problem resolution.

Most significantly for this discussion, the incremental problem-solving orientation in lean production is also applied to hardware technology. Each type of production equipment has its own idiosyncrasies that keep it from being used at full capacity; the more complex the equipment, the greater the idiosyncrasies. In both mass and lean production settings, operators, maintenance personnel, and engineers all learn over time how to minimize the impact of these idiosyncrasies.

Under mass production, the acquisition and application of this "working knowledge" about equipment glitches is constrained by the broader imperatives of specialization, standardization, and high-volume production (Hirschhorn, 1984; Kusterer, 1984). But under lean production, workers and engineers apply their problem-solving abilities to the task of improving equipment performance over time. This process of incremental improvements is commonly referred to in Japanese plants as "giving wisdom to the machine." It means that production technology need not be automatically subject to decay and depreciation but can actually appreciate in value over time.

For example, under mass production, the installation and "debugging" of a new technology are handled by staff specialists or vendors, whereas these responsibilities are often given to workers under lean production. This means that the important learning from this initial period is retained among those who will operate (and seek further improvement in) the equipment over time rather than being taken along to the next plant or customer.

Another crucial aspect of giving wisdom to the machine is the continual modification of job specifications by the work force. In some cases, these are jobs that relate directly to the use of technology, such as equipment setup times. Minimizing setup time is crucial to achieving small-lot production and the rapid feedback it provides. Therefore, workers and engineers work to improve the layout, fixtures, and procedures involved in, for example, changing a stamping press die. This type of die change once commonly took several hours (and still does in some mass production plants). But most Japanese plants and an increasing number of U.S. plants have managed to reduce this die change time to under ten minutes, often without any major capital investment.

The same principle of continual process improvement applies to all job specifications under lean production, whether directly related to technology or not. Here, too,

mass production seeks to specialize and standardize as much as possible, for greater efficiency. The specification process is assigned to industrial engineers, who follow the rationalization prescriptions of Frederick Taylor to assign an appropriate work time to each process step. Workers can ease the demands of their job if they successfully fool the industrial engineer into setting a task cycle time that is greater than what they actually need to do the job.

Under lean production, workers have a major role in determining specific work procedures and methods. While production levels and the basic framework for the production process are determined by engineering requirements, teams of production workers have responsibility for developing, recording, and modifying job specifications. These specifications are extremely detailed, as much as any industrial engineering time study, but with the crucial difference that workers, rather than managers or engineers, take charge of their revision (Cole, 1990; Krafcik, 1988b; Monden, 1983).

We previously noted a tendency for mass production plants to rely on more specialized equipment and for lean production to use more general purpose equipment. It is perhaps more significant that the differences in the approach to technology in these two systems often persist regardless of the type of hardware being used. In other words, under mass production, general purpose equipment tends to be used as if it was specialized equipment intended for long, unvarying production runs. Conversely, under lean production, specialized or dedicated equipment tends to be subject to the same processes of incremental modification as general purpose equipment.

Thus there are two reasons to believe that technological capabilities will be utilized more effectively under lean production than mass production. First, the organizational context of mass production, with its prerogatives of high volume, specialization, and standardization, leads to a relatively static or rigid use of technology (Abernathy, 1978). This can be true even when the technology is inherently flexible, as with robotics and other microprocessor-based programmable equipment (Jaikumar, 1986). Second, the problem-solving orientation and skills of the work force under lean production facilitate the process of introducing *any* new technology and also yield valuable modifications over time.

RESEARCH QUESTIONS

The foregoing discussion lays out the difference in organizational logic between lean production and mass production and develops the hypothesis that the link between the minimization of buffers and the extensive development of human resource capabilities under lean production contributes significantly to such manufacturing outcomes as high productivity and high quality. It also advances the "integration" hypothesis that advanced technologies will contribute more effectively to manufacturing performance under lean production than under mass production. We next review the empirical evidence on these two hypotheses.

THE INTERNATIONAL AUTOMOTIVE ASSEMBLY PLANT STUDY

The International Automotive Assembly Plant Study was initiated in 1986. By May 1990, we had visited ninety assembly plants, representing twenty-four assemblers in

sixteen countries, and seventy of those plants had responded to our survey. Almost all of the auto-producing regions of the world and all the major assemblers, with the exception of those in the Soviet bloc and China, participated in our study.

Although this chapter reports primarily on the relationship of technology and production organization to manufacturing performance, the assembly plant study was designed to address the role of other explanatory variables as well, such as model mix complexity, parts complexity, scale, and product design age. A summary of the complete multivariate analysis of these factors can be found in Krafcik and MacDuffie (1989) and MacDuffie (1991). Some of these control variables are significant, but none of them change the basic results described here. Of these, product design age was most influential. We believe that this variable is a proxy for "design for manufacturability," that is, newer products are more likely to have been designed with ease of manufacture in mind. This supports our belief that design for manufacturability has an important effect on assembly plant productivity and quality. Indeed, this is an issue we intend to study intensively in our future work.[2]

Our sample consists of sixty-two plants, all in the volume (as opposed to luxury/specialty) product category. The regional distribution of these plants (and, for U.S. plants, the region of the parent company) is presented in Table 13.1.

METHODOLOGY AND OPERATIONALIZATION[3]

Productivity

We define productivity as the hours of actual working effort required to complete a group of designated assembly plant "standard activities" on a product standardized by size, option content, and product manufacturability in the welding and painting areas. These adjustments *do* take into account differing levels of vertical integration, worker relief periods, and absenteeism. No adjustments are made for differing levels of automation, plant scale, or assembly area manufacturability. The bulk of the plants in this survey assemble products ranging in size from Ford Escort to Ford Taurus.

Quality

We used the U.S. market 1989 J. D. Power Initial Quality Survey to develop an index which reflects only those defects that an assembly plant can affect, ignoring such areas as engine performance and reliability. The emphasis therefore is on fit and finish of

Table 13.1 Composition of volume assembly plant data

Regional Category	*n*
Japan (J/J)	8
Japanese-parent plants in North America (J/NA)	4
U.S.-parent plants in North America (US/NA)	14
Europe (All/E)	19
New Entrants, including East Asia, Mexico, and Brazil (All/NE)	11
Australia	6

body panels and trim pieces, paint quality, and integrity of electrical connections. In those cases where plants in the survey do not sell products in the United States, we used internal company quality data correlated to J. D. Power figures to increase the size of the quality data base.

Production Organization Index

This index is the average of two component measures of production organization: Use of Buffers and Human Resource Management (HRM) Policies. When combined into the Production Organization Index, a high score indicates a lean production system and a low score indicates a mass production system.

The *Use of Buffers Index* measures a set of production practices that are indicative of overall production philosophy. It includes the percentage of assembly floor space allocated to final repair, the capacity of the in-process buffer between the paint and assembly areas, and a measure of inventory policy that reflects the level of inventory stocks and the frequency of parts delivery to the line. A high score for this variable indicates a minimal use of buffers and a low score indicates an extensive use of buffers.

The *HRM Policies Index* captures a wide variety of work structures and personnel practices that affect the development and deployment of human resources. Six variables reflect shop floor work organization: how direct assembly tasks are organized (the extent to which work teams and job rotation are used); how indirect tasks traditionally handled by functional specialists are allocated (the extent to which quality inspection and statistical process control are assigned to production workers); and the level of worker participation in problem-solving activity (the percentage of the work force involved in employee involvement groups and the number of production-related suggestions received and implemented).

Four other variables measure policies that affect the "psychological contract" between employees and the organization: the recruiting methods and hiring criteria used in selecting the work force, the extent to which the compensation system is contingent upon performance, the extent to which status barriers between managers and workers are present or absent, and the level of ongoing training offered to experienced production workers, supervisors, and engineers. A high score for this variable indicates a high-commitment, multiskilling bundle of HRM policies; and a low score indicates low-commitment, specializing policies.

Technology Measures

We use two complementary technology measures, the Robotic Index and Total Automation. The *Robotic Index* is the number of robots in the welding, painting, and assembly areas adjusted for the scale of the plant. Since robots are often a new investment and are by definition flexible, the Robotic Index captures these aspects of a plant's technological intent or strategy. It does, however, miss the often substantial investments plants make in fixed automation.

Our other technology variable, the *Total Automation Index*, captures the level of both flexible and fixed automation. Total Automation measures the percentage of direct production steps in the welding, painting, and assembly areas that are automated. As such, it is essentially an indicator of the total automation stock in the plant. Unlike the

Robotic Index, it does not indicate the characteristics of the automation, i.e., old or new, flexible or fixed. Also, since it measures the percentage of total direct production steps that are automated, we can expect it to be somewhat correlated with our productivity measure, which reflects the labor hours required for nonautomated direct production steps (along with all indirect and salaried/administrative labor hours). However, this allows for a conservative test of our hypothesis that a high technology level will not produce high performance in a plant lacking a lean production system.

THE SIMULTANEOUS ACHIEVEMENT OF HIGH QUALITY AND HIGH PRODUCTIVITY

Although traditional manufacturing doctrine propounds that high levels of quality and high levels of productivity are incompatible, our study results show otherwise. We divide the sample into four performance zones (Figure 13.1) and find a surprising number of plants that achieve better than average productivity and quality performance, with an overall correlation between these outcomes of .36 (p = .007). Further, we have identified a small group of "world-class" plants that simultaneously achieve very high levels of productivity and quality.[4]

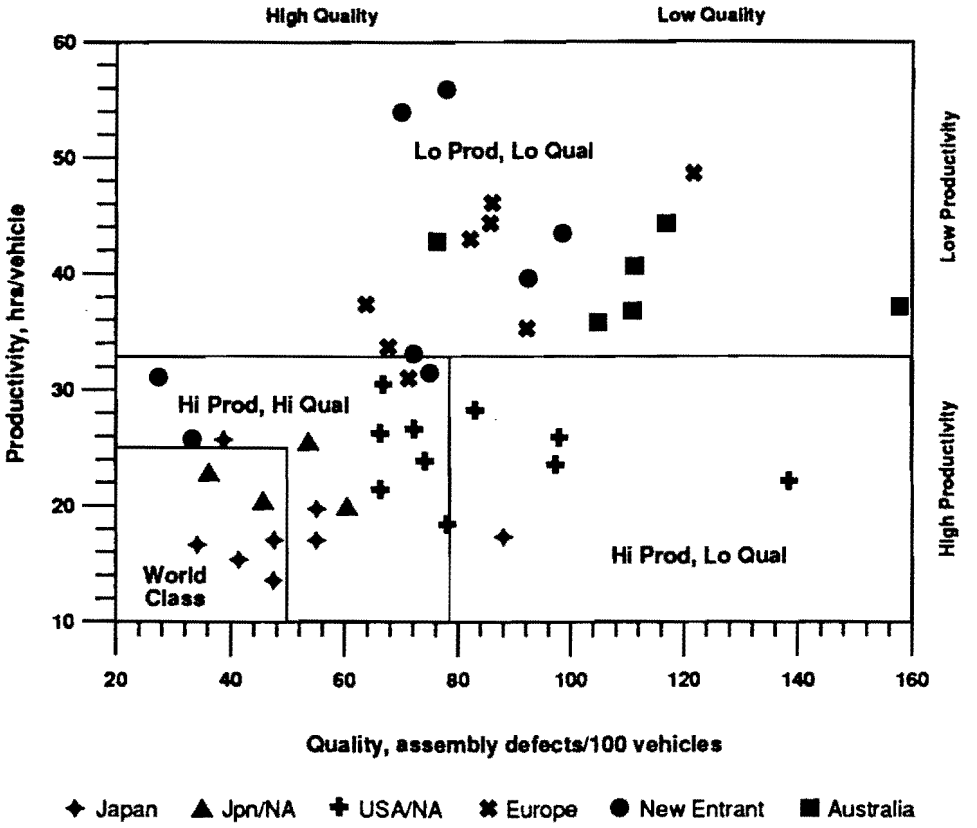


Figure 13.1 Productivity/quality performance zones.

Note that the simultaneous achievement of better than average quality and productivity is not limited to plants in Japan; six American, one European, and three New Entrant plants join five Japanese-parent plants in this zone. On the other hand, the world-class performance zone contains only Japanese plants—four in Japan and two in North America. One striking manifestation of the relationship between these outcomes is the small number of plants with above-average quality and below-average productivity, or below-average quality and above-average productivity. For the majority of the plants in our sample, quality levels and productivity levels are closely linked.

PRODUCTION ORGANIZATION, TECHNOLOGY, AND MANUFACTURING PERFORMANCE

As indicated previously, we derive the Production Organization (ProdOrg) Index as the average of two component measures, Use of Buffers and Human Resource Management (HRM) Policies. We argued that these two measures were conceptually interrelated. As Figure 13.2 shows, they are highly interrelated statistically as well.

The ProdOrg Index is strongly correlated with performance results for this sample of plants, with a simple correlation of $r = -.59$ ($n = 57$, $p = .000$) with productivity (hours per vehicle) and a simple correlation of $r = -.63$ ($n = 45$, $p = .000$) with quality (defects per 100 vehicles). This indicates that about 36 percent of the variation in both productivity and quality for this sample of plants can be explained by this organizational measure alone.

As a test of the separate effects of the two production organization components on performance, we examined the correlation between the ProdOrg Index and our key outcome variables, controlling successively for each of the components (Table 13.2).

The greater the drop in the correlation between ProdOrg and productivity when controlling for one component, the greater the role of that component in accounting for the overall relationship. Thus, Use of Buffers and HRM Policies contribute almost equally to the strong relationship between ProdOrg and productivity. With quality as the outcome measure, however, the HRM Policies measure is the most influential component, with the Use of Buffers measure contributing much less to the overall relationship. Although we would have expected Use of Buffers to contribute as much to quality as to productivity results, these findings are broadly supportive of the earlier arguments about why a lean production system is able to achieve high productivity and quality outcomes. It does suggest that it may be possible to minimize buffers for purely

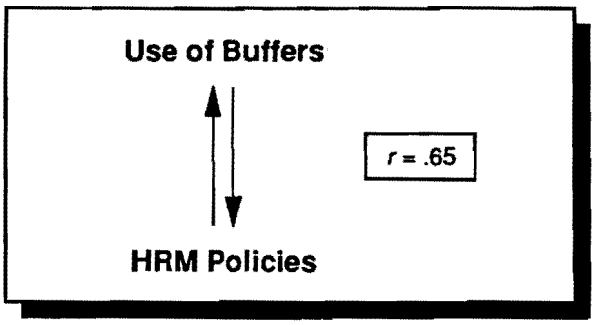


Figure 13.2 Correlation of production organization components.

Table 13.2 Correlations between production organization and key outcomes

	Correlation of Production Organization with:	
	Productivity (hours/vehicle)	Quality (defects/100 vehicles)
No controls	−.59	−.63
Controlling for Use of Buffers	−.25	−.37
Controlling for HRM Policies	−.24	−.23

cost reduction purposes, thus improving productivity, without changing the organizational processes that lead to high quality. The use of buffers must therefore be matched with HRM policies that improve a plant's capability for ongoing problem solving, as argued earlier.

The two technology measures also have statistically significant correlations with both outcomes. The simple correlation of Total Automation with productivity is $r = -.67$ ($n = 62$, $p = .000$) and with quality is $r = -.41$ ($n = 46$, $p = .002$). For the Robotic Index, the simple correlation with productivity is $r = -.55$ ($n = 62$, $p = .000$) and with quality is $r = -.41$ ($n = 46$, $p = .002$). Despite the differences in these measures, they result in similar characterizations of the technology levels of a given plant, as shown by the high simple correlation between them of $r = .81$ ($n = 62$, $p = .000$).

TESTING THE INTEGRATION HYPOTHESIS FOR PRODUCTIVITY AND QUALITY

Having considered the separate relationships of production organization and technology to performance, we now analyze their combined effect to assess the integration hypothesis.[5] We first examine the relationship between technology and both outcomes for subgroups of mass production and lean production plants, formed by using the sample average for the ProdOrg Index (44.6). Table 13.3 shows that the correlation between Total Automation and both productivity and quality is much stronger for the lean than for the mass production subgroup.

We then further subdivide our sample by using the sample average score for Total Automation (24.4 percent), generating four quadrants that reflect all possible combinations of technology and organizational context. In Figure 13.3, we show the average productivity and quality outcomes for each quadrant.

Table 13.3 Correlation between total automation and performance outcomes

	Productivity (hours/vehicle)	Quality (defects/100 vehicles)
LeanProd plants ($n = 21$)		
Total Automation	−.79 ($p = .000$)	−.39 ($p = .053$)
MassProd plants ($n = 36$)		
Total Automation	−.56 ($p = .000$)	−.25 ($p = .101$)

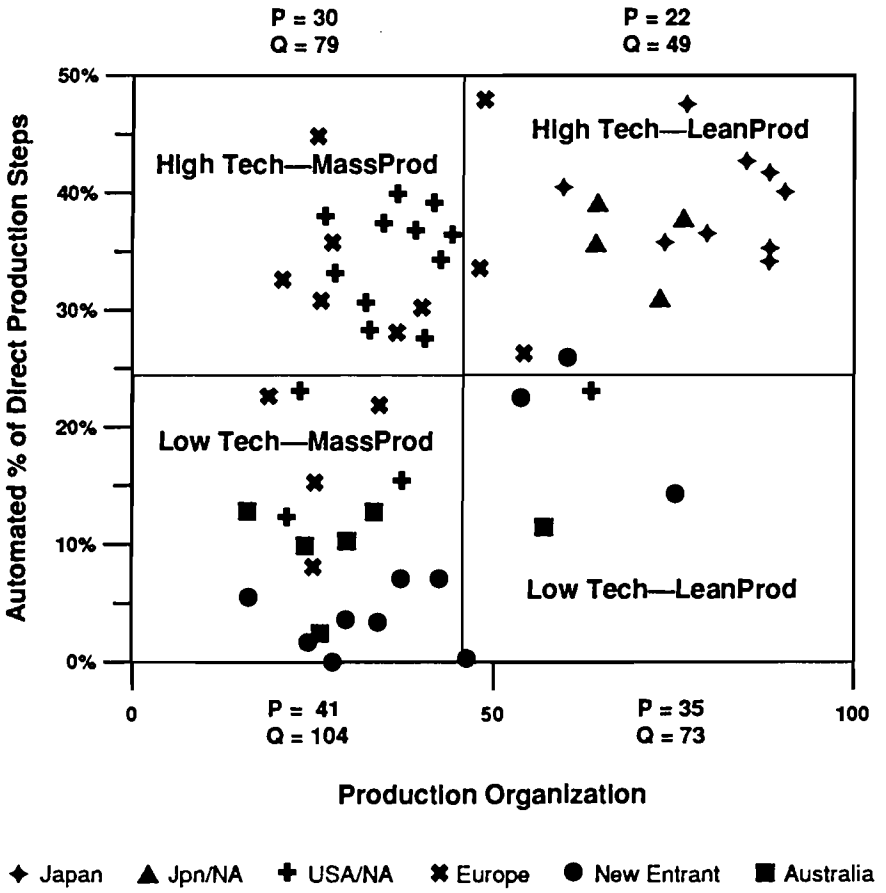


Figure 13.3 Level of automation versus production organization.

As Figure 13.3 shows, Low-Tech–MassProd plants take, on average, 41 hours to build a vehicle with a poor quality level—over 100 defects per 100 vehicles—whereas plants in the High-Tech–LeanProd quadrant have the best performance, taking only 22 hours—just over half as many hours—to build a vehicle with superior quality performance, with an average of about 50 defects per 100 vehicles. Plants in the High-Tech–MassProd group perform at the intermediate level of 30 hours per vehicle and 80 defects per 100 vehicles; the very few plants in the Low-Tech–LeanProd group have similarly intermediate results.

We now examine the integration hypothesis for overall manufacturing performance—the simultaneous achievement of high productivity and quality. Table 13.4 shows the average values of key explanatory variables, using the four performance zones found in Figure 13.1.

Total Automation is very low (15 percent) for the low-productivity–low-quality group, jumps up to 30 percent for the high-prod–low-qual and high-prod–high-qual groups, and increases modestly to 36 percent for the world-class group. The amount of technology does not, therefore, significantly differentiate among the top three performance groups. The Production Organization Index and its two component measures, in

Table 13.4 Averages for key variables by overall performance zone

Zone	*n*	Total Automation (% auto steps)	Production Organization (100 = Lean)	Use of Buffers (100 = Minimal)	HRM Policies (100 = HiComm)
Low-prod–low-qual	19	15.6	32.2	43.3	26.2
High-prod–low-qual	6	31.6	35.1	44.4	30.4
High-prod–high-qual	15	29.3	53.8	60.7	50.4
World class prod and qual	6	36.4	81.7	87.0	79.1

contrast, *do* differ significantly across the top three groups, with the best performing group having the most lean production system, the most minimal buffers, and the most high-commitment HRM policies. These findings confirm that the best overall manufacturing performance results when relatively high levels of automation are combined with a lean production system.

CONCLUSIONS

Support for the Integration Hypothesis

We find that both production organization and technology are important factors in explaining manufacturing performance when considered separately but contribute most significantly to high productivity and high quality when they occur together. This provides broad support for the "integration" hypothesis, which posits that a lean production system is a necessary condition for effectively utilizing high levels of automation.

To summarize our findings, the correlation between technology and performance is much stronger for LeanProd plants than for MassProd plants. High-Tech–LeanProd plants dramatically outperform Low-Tech–MassProd plants, with the latter group requiring 86 percent more hours per vehicle and yielding 112 percent more defects per 100 vehicles. But High-Tech–LeanProd plants also substantially outperform traditional plants with comparably high levels of technology—the High-Tech–MassProd plants require 36 percent more hours per vehicle and yield 61 percent more defects per 100 vehicles than this top-performing group. Furthermore, the technology measures are correlated much less with quality than with productivity, in contrast with the Production Organization measure, which is equally strongly correlated with both outcomes.

Finally, when considering overall performance (productivity and quality together), we find that technology has an important role in boosting performance as plants move from very low levels of automation to moderate levels, even in the context of a mass production system. But the performance gain in moving from moderate to high levels of automation appears to occur only when combined with the organizational, human resources, and manufacturing practices of a lean production system.

Implications for Organizational Change

While our analysis is cross-sectional, our observations of the industry suggest that the assemblers with the best manufacturing performance have approached the integration

of technology and production organization by establishing a lean production system *first*, to provide a solid foundation, and then have moved to higher levels of automation. These assemblers have then been able to capitalize more quickly on new technological capabilities because their production systems facilitate learning and continuous improvement.

The value of these organizational capabilities extends to other aspects of lean production not addressed in this chapter, such as design for manufacturability. The high level of employee suggestions and of group problem-solving activity under lean production is a valuable source of ideas for design improvements and is a crucial part of the two-way flow of communication between design and manufacturing that is so critical to achieving easy-to-assemble products. Moreover, the multiskilling practices of lean production at the plant level, such as job rotation and high levels of ongoing training, are also applied at the corporate level, yielding design engineers and project managers who bring extensive manufacturing experience to their task.

As noted earlier, our study finds that lean production, despite its source in Japan, is fully transferrable to other cultural and national settings. Both the Japanese transplants in North America and a growing number of U.S.-owned and New Entrant plants (though almost no European plants) have established that the principles of lean production have universal value.

Yet the switch from mass production to lean production is far from simple. Because the bundle of practices and policies that make up lean production are so closely interrelated, transitional states between mass and lean production, in which some aspects of both systems are in place, are treacherous. When some production crisis challenges a plant in transition, the overwhelming pull is to revert to tried and true mass production principles by, for example, restoring buffers, reinstituting quality inspection, or recentralizing control over job specifications. Yet everything we know about organizational change also suggests that an abrupt shift to lean production, in response to what employees may perceive as a short-lived management fad, is also likely to be doomed to failure.

The most important first step for plants contemplating a move to lean production is education—managers, supervisors, engineers, and workers alike must understand the crucial (and not always obvious) differences in philosophy from mass production, in such areas as quality control, the use of buffers, process standardization, task specialization, and the role of the work force. Also important is the idea that work structures such as teams and quality circles are valuable only to the degree that they bring about changes in daily activities—especially the degree to which they promote ongoing problem-solving efforts from employees. Finally, those leading this change effort must understand the risks involved: lean production is a "fragile" system whose strength is realized only through prolonged efforts to minimize its vulnerabilities.

We have found that this education is best accomplished through access by managers and union officials to a learning example—a lean production plant—through either joint ventures and other forms of strategic alliance or just geographical proximity. The transplants have provided this example for U.S. companies, whereas European companies have remained mostly insulated. But for production workers, direct training in such lean production "basics" as statistical process control, the job specification process (and other tasks traditionally assigned to industrial engineers), and "hands-on"

mastery of new technologies (setup, programming, preventive maintenance) are even more effective.

Once an understanding of the principles of lean production is achieved and training is under way, the change process can best be implemented through incremental steps that make clear to all the linkages between the policy of buffer minimization and the increased decentralization of responsibilities to shop floor workers (and the associated need for continued skill development). We have known some plants that have steadily closed down portions of their repair areas by roping them off or painting the floor a different color, creating more "off-limits" space by the week. Still other plants have tried to simulate the conditions of a just-in-time inventory system, even before achieving such arrangements with their suppliers, by delivering from parts storage to the line on a small-lot, high-frequency basis.

Production crises may challenge the transition to a "lean" use of buffers, but there are many other developments that can threaten the culture of "reciprocal commitment" so necessary to lean production. Demonstrating a commitment to employment security (if not an absolute "no-layoff" policy), although tough to do in the cyclical U.S. auto industry, is probably essential for lean production to take hold. We believe that the Japanese transplants have gained considerable loyalty from their U.S. workers each time they have not resorted to layoffs during a period of volume decline. Other pitfalls include the retention of visible status barriers differentiating managers and workers; compensation policies that award management bonuses in years when worker bonuses are not given; abuses of management discretion over job assignments within broad job classifications; and reliance on formal grievance mechanisms rather than informal, close-to-the-source dispute resolution.

Finally, the common separation (and even opposition) of technology strategy and human resource strategy under mass production must give way to an "integrated" perspective. As our data show, it is only through such integration that the high productivity and quality necessary for competitive success can be achieved. Many observers have noted the potential of new technologies to either enhance or constrain individual and organizational capabilities. Lean production provides the context in which the former scenario can be realized. Recognition of this fact may be the first step for any company (or country) concerned with both economic achievement and human development.

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NOTES

1. This chapter summarizes some of the key results from the broader research project on manufacturing performance conducted by John F. Krafcik and John Paul MacDuffie under the

auspices of the M.I.T. International Motor Vehicle Program. The project grew out of Krafcik's case study of the NUMMI plant, where he developed the initial methodology for measuring assembly plant productivity and quality and from Shimada and MacDuffie's comparative case studies of Japanese manufacturing techniques found in Japanese assembly plants in North America. After Krafcik's M.S. thesis tested several hypotheses about assembly plant performance for a small sample of plants, Krafcik and MacDuffie combined forces to expand the sample and to develop and test a more complete model of the technological, human, and organizational determinants of manufacturing performance.

2. See Womack et al. (1990) for a discussion of product development processes under lean production and the link to assembly plant performance.

3. For more details on the methodology for calculating productivity and quality, see Krafcik (1988a); for the production organization index, see MacDuffie (1989); for the technology variables, see Krafcik (1989).

4. The lines separating the high and low productivity and quality zones are drawn at the sample average values for the 46 plants for which we have both kinds of data—33 hours per vehicle and 78 defects per 100 vehicles. The plants in the low-productivity–low-quality zone whose quality level is slightly better than the sample average were both few in number and virtually indistinguishable on most variables from those with worse-than-average quality. The "world-class" zone includes plants with productivity levels better than 25 hours/vehicle and quality levels better than 50 defects/100 vehicles.

5. From this point on, we present results that use the Total Automation measure of technology. This measure is more comprehensive and tends to show a stronger link between technology and performance outcomes than the Robotic Index, thus providing a more conservative test of the hypothesis that a "mass production" organizational context limits the performance contributions of technology.

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COMMENTARY BY RANGANATH NAYAK

I'd like to start by encouraging continuation of this research by delving deeper into the question of what makes a high-tech–lean production system possible. This fascinating piece of analysis explains the principles of productivity and quality, yet I wonder what it is that makes a high-tech–lean production system possible in some organizations and not possible in others.

In the tradition of consulting, I decided to look at some analogies. I examined a world-class basketball team, a world-class dinner, and a world-class automobile. What makes them world class? One thing I found in all three of these is that apart from the ingredients, which must be good, there is also a master chef, a talented coach, or a very good designer who provide some sort of conceptual integrity to the thing that is being