

From Fixed to Flexible: Automation and Work Organization Trends from the International Assembly Plant Survey

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March 1996

forthcoming in Transforming Auto Assembly:
International Experiences with Automation and Work Organization,

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Financial support for this research was provided by the International Motor Vehicle Program, and the Sloan Foundation. We wish to also acknowledge the tremendous help of assembly plants from around the world.

The considerable attention given by researchers and managers alike to the diffusion of “lean” or “flexible” production concepts throughout the world automobile industry carries with it the assumption -- often implicit -- that flexible automation is an integral part of this alternative production paradigm. The ample anecdotal evidence available about automation trends in automotive manufacturing is typically based on the newest and most advanced plants of various companies, focusing on their most “cutting-edge” technological installations. What is lacking is more systematic data about how automation use differs across assembly plants around the world, in terms of the relative capital intensity of different parts of the assembly process, the types of automated equipment that are used, and the specific tasks to which automation is applied.

In this paper, we provide a data-driven overview of all these issues, coupled with an exploratory analysis of the factors underlying the adoption of flexible automation. We draw on data that we have collected as part of the International Assembly Plant Study, sponsored by M.I.T.’s International Motor Vehicle Program. These data were collected in two phases, with Round 1 in 1989 and Round 2 in 1993/94. Table 1 contains the regional distribution of plants in the Round 1 and Round 2 samples; 43 plants participated in both phases of data collection.

Table 1: Distribution of Participants in the International Assembly Plant Study

Regional Group*	Round 1 (1989)	Round 2 (1993-94)
Japan/Japan	9	12
Japan/N.A.	4	8
Europe	24	21
U.S./N.A.	16	25
New Entrants	11	18
Australia	6	4
TOTAL PLANTS	70	88
Companies	24	21
Countries	17	20

* JP/JP= Japanese plants in Japan, JP/NA= Japanese plants in North America, Europe=U.S. and European plants in Europe, U.S./NA = U.S. plants in North America, and NE = New Entrant Plants (Korea, Mexico, Brazil, Taiwan)

Previous papers have provided a description of automation trends for the Round 1 data (Krafcik, 1989), have used automation as a control variable in cross-sectional and longitudinal analyses that investigate the impact of flexible production systems on productivity, quality, and product variety outcomes (MacDuffie, 1995; MacDuffie, Sethuraman, and Fisher, 1996; MacDuffie and Pil, 1996), or have treated automation as a factor that potentially influences the adoption of “high involvement” work practices (MacDuffie and Kochan, 1995; Pil and MacDuffie, 1996; Pil, 1996). In this paper, we will emphasize **changes** in the utilization of automation over time, using data from both phases of the assembly plant study, both within and across plants and companies in different regions. Our interpretation of these trends is heavily influenced by our interviews with managers and engineers, conducted during the plant visits we carry out as an integral part of the assembly plant study (MacDuffie and Pil, 1995).

The paper is organized into seven sections. First, we define how we measure automation in the assembly plant study. Second, we describe the overall regional trends in the use of automation from 1989 to 1993/94. Third, we explore the patterns of usage for robotic equipment across regions, emphasizing in particular the significant move by many companies towards the replacement of fixed or “hard” automation with flexible, programmable automation. Fourth, we explore departmental differences in the use of automation, emphasizing the evolution in thinking about the most effective way to automate various tasks in the body, paint, and assembly shops. While automation levels continue to rise in the body and paint shops, a different approach is being taken in the assembly department, the most labor-intensive area of the plant and yet the place where total automation solutions have been most elusive. Fifth, we describe how trends in the adoption of flexible automation are linked to the adoption of flexible work practices that seek to boost worker involvement in production-related problem-solving. Sixth, we summarize what we have learned about the performance implications (in terms of productivity and quality) of the automation trends described here. The seventh section presents our conclusions from these analyses and our speculation about future trends in automotive manufacturing automation.

1. Measuring Automation

Our definitions of automation vary by department. We use automation measures developed by Krafcik (1988; 1989) that in some cases overlap heavily with measures commonly used in the industry and in other cases are unique to the assembly plant study. The body shop is the area of greatest consensus on how automation should be measured. Virtually every plant we have seen measures automation in the body shop as some variant of the percent of spot welds that are placed automatically, although some plants also add measures of the accuracy of aperture fitting, or the extent to which material selection and transport is done automatically. We take the percentage of spot welds that are automated as our baseline measure but we add to it, for plants that do arc welding, the fraction of arc welds that are done automatically. Arc welds are converted to an approximate equivalent number of spot welds (i.e. 1 meter of arc welding equals 150 spot welds, with the average plant using just over 2 meters of arc welding per vehicle).

In the paint shop, there are five main activities that can be automated: electro-coating, primer/surfacer application, interior painting, top coat painting, and application of joint sealer. Electro-coating is inherently automatic and is generally not considered in measures of paint-shop automation. The remaining activities are included by most plants in their measures of automation, although the placement of joint sealer is sometimes considered separately from the paint process itself. We measure the automation level for each activity by looking at the percentage of total surface area that is painted by automated equipment rather than manually -- or for sealer, the percentage of total sealer length applied by automated equipment. Our departmental measure of paint automation weights each activity by its approximate labor content (in percentage terms) in the least automated plants in the sample: a 50% weight for sealer automation, and a 16.67% weight for top coat, interior, and primer/surfacer. Because some paint shop activities tend to be either fully automated or not at all (100% or 0%), the total paint automation measure can increase dramatically if one of these activities becomes automated.

Definitions for automation in the assembly department (comprising trim, chassis, and final assembly lines) vary across different automobile companies. Fujimoto (1992) provides a

good overview of some of the definitions used in Japan. Some plants measure the percent of production steps automated, others look at labor savings, and yet others look at the fraction of overall production time that vehicles spend in automated stations. In order to develop a consistent measure across manufacturers, we estimate the labor required to perform each automated assembly task in relation to the total labor content in the assembly area.

For the overall measure of assembly plant automation, combining all departments, we weight the automation level in the body, paint, and assembly areas by the percentage of total labor content applied to those activities in the least automated plants in the world: 31% for the body shop, 19% for the paint shop, and 50% for the assembly shop. This measure is labeled “Total Automation” and is expressed as the percentage of total production steps that are automated.

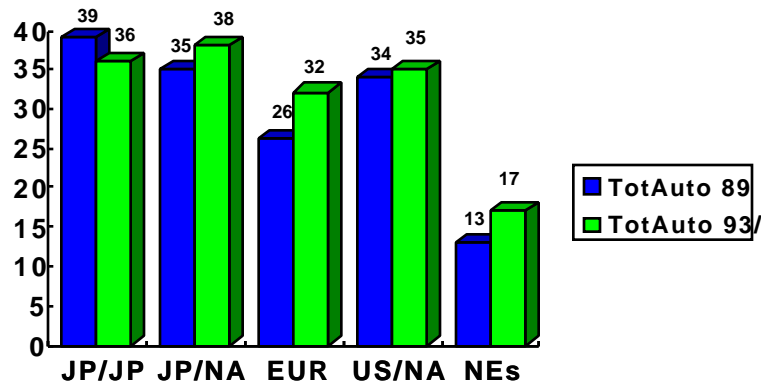
The departmental measures described above do not necessarily make a distinction between “fixed” (or “hard”) automation and “flexible” (or “programmable”) automation. So we also have measures that capture the extent to which flexible automation is being used. In the body shop, we distinguish spot welds applied by “fixed” or “hard” automation from those applied by “flexible” automation. We do the same in the paint shop for various activities. Also, since robots are the most prominent form of flexible automation and can be found in all three departments, we measure the total number of robots used in the plant, adjusted for the plant’s capacity. Robots are defined as having at least three axes of motion, although for some analyses, we further differentiate simple robots (3-4 axes of motion) from more sophisticated equipment with 6 or more axes of motion. This measure is labelled the Robotic Index and is expressed as the number of robots per vehicle produced per hour.

2. International Trends in Automation Usage, 1989 - 1993/94

By the late-1980's, when the Round 1 data were collected, there was a significant disparity in the use of automation across regional groups of plants. Japanese companies were by far the greatest users of automation, followed by the American “Big Three” companies. In

Europe, there were extraordinary efforts at some individual plants to achieve dramatic increases in automation (particularly in the assembly area) by some manufacturers; the Wolfsburg plant of Volkswagen and the Cassino plant of Fiat stand out as well-known examples. But overall, European companies tended to have lower automation levels than Japanese and American companies. Plants in New Entrant countries (e.g. Mexico, Brazil, Taiwan, Korea) tended to use minimal automation, most of it concentrated in the placement of welds that were difficult to place manually, although some individual plants (particularly in Korea) were highly automated.

Figure 1 -- Change in Total Automation in Matched Sample of Plants (n=43)



JP/JP= Japanese plants in Japan, JP/NA= Japanese plants in North America, Europe=U.S. and European plants in Europe, U.S./NA = U.S. plants in North America, and NE = New Entrant Plants (Korea, Mexico, Brazil, Taiwan)

The sample average for Total Automation increased roughly 10% for the matched sample and 20% for the unmatched sample from 1989 to 1993/94. However, the broader trend is one of convergence in automation levels across regional groups. European plants experienced significant increases in automation, while plants in Japan report slight **reductions** in their average automation levels. Several New Entrant plants also increased their automation levels. Particularly in Korea, the boost in automation reflects the fact that new plants are being built with very high levels of automation, possibly as a reaction to rising labor costs. Moving towards

a more capital-intensive production system may also reflect an attempt to limit union influence by some Korean companies.

As Table 2 reveals, automation levels have been on the rise across all departments since 1989. However, the most striking change has been the shift in the type of automation used. The last decade has seen a dramatic replacement of fixed automation with robotics. Indeed, the average number of robots per vehicle/hour increased 60%, from 2.3 in 1989 to 3.7 in 1993/94 for the matched sample of plants. For a plant with an annual production volume of 250,000, this is equivalent to an increase from 144 robots to 231 robots. This trend is most apparent in body shops and, to a lesser extent, in many paint shops. There, the switch from solvent-based to water-based paints has also provided the impetus to increase the use of robotic interior painting. We will review trends in the use of robots in more detail below.

Table 2: Change in Automation Levels by Type in Matched Plants (n=43)

	<u>1989</u>	<u>1993/4</u>
Total Automation	27%	29%
Weld Automation	63%	69%
Paint Automation	36%	39%
Assembly Automation	1%	2%
Robotics (Robots/vehicle/hour)	2.3	3.7

While many European, American, and Japanese plants have added new automation, we have also observed plants in all parts of the world pulling out automation that was either unreliable, underutilized, or exceedingly complex. Problems with equipment reliability appear to be particularly strong in the assembly area or in subassembly areas of the body shop. We have observed instances where plants work overtime, and sometimes even a third shift, because some automated equipment has failure rates as high as 30%. Equipment we have seen removed ranges from tire placement and bolting equipment in assembly to door fitting and welding equipment in

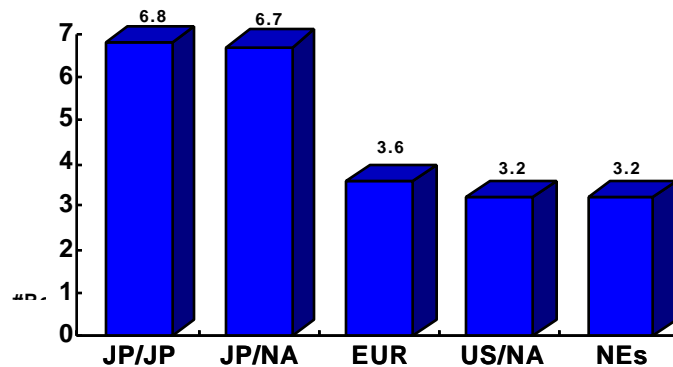
the body shop. That is not to say that these operations cannot be automated. However, poor equipment designs, coupled with some plants' inexperience with preventive maintenance and on-line repair activities, can render some of this equipment more of a liability than a benefit.

There are some plants where robotic equipment sits idle during large portions of the cycle time because there are too many robots operating in too small a space. As a result, several plants have actively scrapped "dead-wood" equipment. Not just excess robots and unwieldy assembly automation are receiving the ax, but so are Automated Guided Vehicles (AGV's), which require that a tremendous amount of space be left empty as they provide unattended transport and variable routing of vehicles between successive operations. The reduction of automation that is underutilized or exceedingly complex in relation to its benefits actually has little impact on the measure of automation in the plants, in part because equipment like AGVs is not measured by most standard automation measures (including ours), and in part because pulling out equipment such as robots that are causing interference can actually enhance the utilization rate of the remaining equipment.

3. Use of Robotics

Although the overall levels of robotics have increased since 1989, large regional variation remains in the extent to which robots are used in 1993/94, as shown in Figure 2:

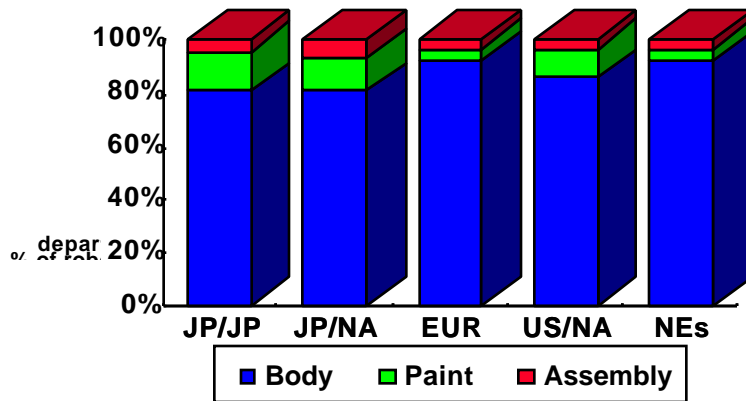
Figure 2: Robot Use by Region, 1993/94



Japanese plants in Japan as well as in North America make the most extensive use of robotics. U.S. plants use robotics the least. The average New Entrant plant has more robots than the average U.S. plant, but the New Entrant average obscures significant variance among plants in this regional group. Some of the Korean plants utilize more robots than plants in Europe and the U.S., and even some of the plants in Japan. On the other hand, plants in countries like Taiwan, Mexico, India, and Brazil, use very few robots.

While there is variance in the number of robots used by plants in different regions of the world, the distribution of robots across departments within the plants is much more similar, with the preponderance of robots used in the weld area. Japanese plants tend to use somewhat more robots in their paint departments, in part because they are more likely to automate interior painting -- an activity that needs robots both for painting and for opening and closing doors and front hood and rear trunk lids.

Figure 3: Robot Use by Department, 1993/94



Although U.S. and European plants generally have the fewest robots, their robots tend to be the most complex. Indeed, nearly 100% of the robots used in many European plants have six or more axes of motion, compared to only 70-75% in average Japanese plants. Some Japanese manufacturers, particularly Honda and Suzuki, have been quite adept at minimizing robotics investment by identifying the cheapest robotics for each task. As a result, many of the robots used by these companies are lighter, smaller, and have fewer axes of motion.

Not only can robots differ in their basic capabilities for movement, but they can also be deployed quite differently from plant to plant. For example, in the welding of subassemblies in the body shop, robots can maneuver weld guns around panels or assemblies being welded, or they can move the objects being welded through stationary weld guns. Robot placement also differs across plants. In the body shops of some plants, robots work in pairs or quads on a vehicle as it comes through, whereas in other plants, as many as 8 or 10 robots can be working at a single station. The advantage of the latter is that the vehicle moves through fewer stations, with more welds applied each time the body is fixed in position by jigs, increasing dimensional accuracy. More welds per station can also mean that robots spend less time being idle. However, as the number of robots working in a given station increases, robots are more likely to get in each other's way (interference), and idle time can increase. Several Japanese manufacturers

have become extremely skilled at designing and placing robots to minimize such interference and to increase the number of welds placed at each station.

Not all robots perform tasks that would be captured by commonly-used measures of automation. For example, over half the plants in our sample use robots for parts transfers and placement in the body shop. Another increasingly popular use is in-line inspection of dimensional accuracy in the body shop, using vision systems fixed to sophisticated robots capable of several axes of motion. Currently, only about 15% of the plants in our sample use robots for that purpose, but we expect that number to increase over the coming years.

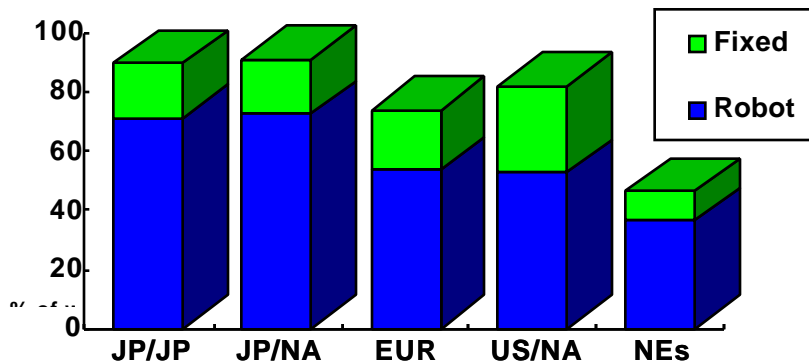
4. Automation Use by Department

Here we review automation trends in the body, paint, and assembly departments.

A. Body shop

In the body shop, levels of automation are very similar across the different regions of the world, as shown in Figure 4. Most plants now exceed 80% automation of total spot and arc welds, and many are approaching 100% automation of spot welds. The exception are some of the plants in New Entrant countries, where funds for capital investment may be scarce and low labor costs reduce the incentive to invest in labor-displacing automation. While most Korean plants have weld automation levels on par with those of other plants in the world, plants in other New Entrant countries automate welds sparingly. Generally, the welds that are placed automatically at these plants are those that require heavy weld guns, and those where accuracy of placement is important because the welds are visible to the customer (e.g. the welding of the roof to body sides).

Figure 4: Type of Automation Used for Spot Welds, 1993/94



Despite similarity in the number of welds placed automatically, U.S. plants make much greater use of fixed automation than plants in any other regions. This is feasible only because U.S. plants generally produce only one or two models in their plants, and use dedicated body lines for each model. Similarly, both U.S. and European plants are less likely than their Japanese counterparts to have framing stations where the sides, roof, and underbody are married at once. However, most plants in the U.S. and Europe that have made recent investments in their body shops are likely to have such framing stations, and generally also have the capability to handle multiple body styles and models, although that potential is not always used.

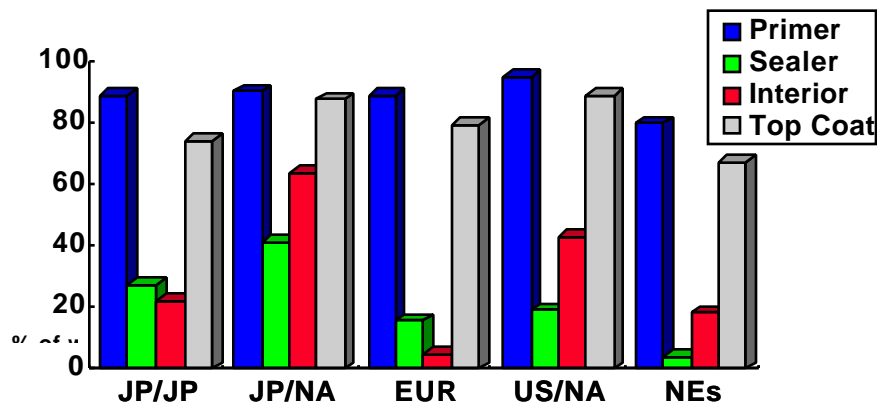
One of the most flexible weld systems is the Intelligent Body Assembly System (IBAS) used by Nissan all over the world. This system uses robots not just for welding, but also for holding the bodies. The framing station contains special robots that can be instantly reconfigured to hold body parts for any number of models or body styles. Indeed, IBAS is capable of handling all Nissan models and body styles, with the exception of truck models. Toyota's Flexible Body Line (FBL) and Mazda's Circulation Body Assembly Line (C-BAL) are similar.

There are also important regional differences in the automation of arc/seam welding in the body shop. U.S. plants generally do this manually, whereas the average Japanese plant automates over half of these welds.

B. Paint shop

As mentioned above, the electro-coating process, in which the vehicle body receives its first coats of protection against rust, is always automated.. After that point, there is greater variance in what plants automate, as Figure 5 shows. Most plants fully automate the application of the primer/surfacer coat, as well as the top coat. Because of the way the automated equipment is set up, either these activities are fully automated or not at all. However, some plants have multiple paint booths, and while top coat may be fully automated in one of those booths, it may be manual in another, thus permitting a plant's overall automation level for top coat painting to be between 0 and 100%. Also, the addition of a two-tone (a second paint color used to provide an accent on certain parts of the body) may be done manually.

Figure 5: Paintshop Automation



There is much greater variance in the extent to which interior painting and the application of joint sealer is done automatically. Interior painting is almost never fully automated, with the exception of plants using a space frame design (where the absence of panels provides easier access to the vehicle's interior). In all but a few cases, production workers provide some degree of finishing touch to the interior painting to cover up areas unreachable or poorly covered by robotic spray.

Joint sealer is applied to seams and joints to waterproof the vehicle and reduce wind noise. The application process is one of the most labor intensive activities in plants that do not automate it. Some plants have turned to automating most of the joint sealer application process, while others have looked for ways to improve tolerances and change body panel designs to reduce sealer content. Sealer spray via robots has become popular at a few plants, particularly those belonging to European and Japanese companies. However, it is not that widespread as yet, with less than half of all plants doing it at all, and less than 15% automating more than half of the sealer application.

The newest plants, and in particular the Japanese transplants in North America, have the greatest amount of automation in their paint shops and are most likely to automate interior painting and sealer application. Thus the likely trend into the future will be steady increases in the overall level of paint shop automation as new investments are made, either in new plants or retrofitting older plants.

There are also other innovations taking place in paint shops that do not alter the level of automation but do fundamentally alter the process of paint application. Perhaps the most significant is the switch to water-based paints from solvent-based paints to reduce Volatile Organic Compound (VOC) emissions. The switch to water-based paints has started in many American, European, and Japanese plants. However, many of the plants upgrading equipment have not yet made the full switch to water based paints. Most are trying it in one of their paint booths with solid colors. Although the technology exists to apply water-based metallic paints, the paint quality is inferior to that achieved with solid colors, so most plants continue to use solvent-based metallic paints.

C. Assembly area

The assembly area of the plant is the most labor intensive portion of any car factory, containing, on average, 60% of all production workers. Very few assembly operations are automated. Indeed, in the average plant only 6 assembly steps are automated and most plants

automate less than that. Although each region has its outlier plants, the average automation level in assembly by region ranges from 1.1 to 2.2%.

Table 3: Assembly Operations Most Frequently Automated

	<u>Percent of Plants with Automated Process</u>
1. Windshield Sealer Apply/Install	67%
2. Rear Glass Sealer Apply/Install	56%
3. Tire Disk Wheel	50%
4. Engine Mounting	43%
5. Suspension Assembly	38%
6. Spare Tire Insert	34%

As shown in Table 3, the majority of plants use automated equipment to apply sealer to the windshield and rear glass, and to place them on the vehicle. These two are tasks that are prone to quality problems when performed manually and they are relatively easy to automate. The other operations listed in Table 3 are often fully automated because they are strenuous tasks if performed manually and the robots needed to automate these tasks are relatively simple.

Overall, however, it must be said that progress towards automating the assembly process has been slow, sporadic, and not all that successful. After highly publicized campaigns in the 1980s to automate assembly tasks -- carried out by companies ranging from Volkswagen to Fiat to General Motors -- failed to produce desired results despite massive investments, most companies are approaching assembly automation more cautiously, even in their greenfield plants. Fiat, whose Cassino plant was advertised as being one of the most automated in the world, has taken a step back from automation in the assembly area at its new Melfi plant, and has focused instead on introducing flexible work practices. At Nissan's new Kyushu site, the assembly area was designed to accommodate tremendous amounts of automation, yet it now seems unlikely that Nissan will ever follow through with all of its original automation plans. Toyota, which experimented with highly advanced automation in its Plant #4 at Tahara in the mid-1980s, has

since reduced its emphasis on automation at its new Kyushu plant and its newly retrofitted RAV4 line at the Motomachi plant.

Automation in the assembly area is not limited to the automation of particular tasks on the line. It is exhibited most clearly in the assembly line itself. Gone in most plants are the old chain conveyors that run through the whole assembly area. Instead, newer assembly lines have multiple conveyance systems, with the primary distinction on the main line being between underbody and other work. Off the main line, many plants now have feeder lines for subassembly of dashboards, engine/transmission/strut assemblies, and doors (most plants have moved, or are moving to doors off assembly, where the vehicle doors are removed at the start of assembly, and reattached downstream, after most interior installation tasks have been completed.) In over two thirds of the plants, overhead conveyors are used to permit underbody work to take place outside of the dreaded "pit", and most plants not using such a system are converting to it. More modern lines have "tilt" overhead conveyors to permit easier access to the underbody.

For work on the upper body of the vehicle, there are two main types of conveyors: platform conveyors that only carry the vehicle and conveyors that move both the vehicle and the person working on the vehicle. The latter is found primarily in newer plants. Also found in some plants are accordion hydraulic systems that raise and lower the car as needed. Some companies in the 1980's utilized AGV's to transport the vehicles, but these have fallen out of favor because they are too expensive to purchase and maintain and, as mentioned above, they require too much space. The most dramatic departure from traditional assembly lines, with their synchronous cycle times at each station, is the variable speed conveyance system at Nissan Kyushu, which permits individual cars to move asynchronously through the assembly process, advancing more quickly, more slowly, or stopping, dependent on the requirements of the task performed at a particular station. We see no sign that this asynchronous approach is being adopted by other companies.

We noted earlier that plants have been relatively unsuccessful in attempting to automate most assembly tasks fully. As a result, we now see an alternate trend -- the expansion of what we term "automation assist." These are forms of automation that support the production worker, but do not necessarily replace him or her. There are two primary reasons for automation assist: enhancing ergonomics and reducing extraneous production worker movement. To eliminate the ergonomic strain from installing heavy parts, tools that lift and place parts like seats, tires, and doors are increasingly common. Also important from an ergonomic standpoint are tools that reduce the pressure placed on the wrists when applying the full torque during a bolting operation. Some plants, like Toyota Kyushu for example, let production workers place bolts, screw them on lightly, and then utilize a fixture which automatically applies full torque. Unlike full automation, automation assist tools do not actually install the parts -- they only place the parts in a position where the production worker can more easily install them, or finish off a task started by the production worker.

We have observed various forms of automation assist directed at reducing excess movement by workers. In some plants there are platforms that move under the raised body on which the worker can stand while doing certain underbody tasks. After work on one vehicle is finished, the platform automatically moves the worker back to the next vehicle. There are simple robots that deliver a tray of tools to the worker inside the vehicle for the installation of interior parts, so the worker doesn't have to carry the heavy tools while maneuvering into position. In one instance, we saw a device that physically moves the worker into and back out of the vehicle on a chair at the end of a mechanical arm.

Perhaps the most prominent and popular form of automation assist are carts that carry parts and tools. They move along beside the vehicle from the time it enters a work station to when it leaves and then are returned, either automatically or manually, to the starting position. By having the parts and tools move with the vehicle, the production worker saves considerable amounts of walk time, thus reducing both the physical demands of the job and wasted motion. These are quite popular with workers and often have acquired nicknames -- for example, "line-

side limo's" and "dollies" in some U.S. plants, "Viking ships" in some Japanese plants, and "les servantes" in some European plants. The most interesting aspect of most forms of automation assist, and in particular, the line-side limo's, is that they are low-cost forms of automation, generally developed in-house by teams of engineers and production workers.

5. The Role of Flexible Workers

While we mostly focus on trends in the use of automation, we will also briefly discuss the relationship between the use of flexible automation and the need for flexible workers. To consider this relationship fully, we must first take stock of the strategic goals that firms need flexible automation to pursue. Flexible automation allows for multiple products to be built in a single plant and/or for rapid model changes (both major and minor) over time. Investing in flexible automation thus facilitates strategies of more product variety and shorter product life cycles. Robotic weld and paint equipment can also be adjusted more easily to accommodate incremental process improvements or engineering changes.

How do these strategic goals relate to the firm's approach to work organization and workforce flexibility? The link between flexible work organization and flexible automation is hardly technologically determined. Robots do not require teams to operate effectively, nor multiskilled workers. But the decision to invest in flexible automation and the decision to invest in new forms of work organization are increasingly interconnected.

There are many ways in which flexibly-deployed workers capable of effective problem-solving are critical to achieving the strategic goals associated with flexible automation. In plants building many different models, workers have heightened responsibility for accommodating greater product complexity without productivity or quality penalties, mastering a higher variety of tasks, making sure the right parts go on the right vehicle, working with team members to find the most efficient layout for parts and tools, and identifying the product-specific quality problems.

Then, to accomplish rapid changeovers from one model to another, work methods must be revised and well-tested in advance to avoid quality problems during product launch. Workers

who are accustomed to job rotation within and across teams and to involvement in *kaizen* activities that refine work methods over time are critical resources in achieving an effective changeover. Programmable automation also lends itself more readily to worker involvement in making incremental process changes. The ease of minor reprogramming by workers (which can often be done by physically "teaching" the robot where the new weld spot should go by moving the weld tip to the exact spot) removes the technical barriers to incremental change -- unlike fixed automation, for which any changes require engineering involvement and substantial cost.

Analysis of regional trends for both flexible automation and flexible work organization (MacDuffie, 1996) reveals that plants using flexible forms of work organization (e.g. teams and job rotation) and emphasizing high levels of workforce training are likely to implement flexible automation most heavily. (Note that this relationship does not necessarily hold in the reverse, i.e. plants that implement flexible automation are not necessarily more likely to implement, subsequently, flexible work organization (Pil and MacDuffie, 1996.)) In contrast, there remains a strong association between plants that rely heavily on fixed automation (e.g. U.S. "Big Three" plants) and more traditional approaches to work organization. The importance of "fit" between technological and organizational capabilities is particularly well-supported by the extremely high level of both kinds of flexibility at the Japanese plants in Japan and North America. While the presence of good "fit" does not conclusively indicate the direction of the causality, it is worth noting that Japanese plants have had flexible work organization much longer than they have had programmable automation. This suggests, as previously mentioned, that the presence of flexible work organization can help make investments in flexible automation more feasible and/or cost-effective.

6. Performance Implications

Here we briefly summarize our findings, reported elsewhere (MacDuffie & Pil 1996), on the relationship between our automation measures and economic outcomes of productivity and quality. Automation in both the body and paint shops bears a strong relationship to plant

efficiency in terms of labor productivity . As automation increases, labor requirements clearly decrease. This is not true for full automation of production steps in the assembly area. Full automation of assembly steps is expensive and the equipment often requires significant maintenance labor which offsets savings in direct labor. As a result, automation in the assembly area is generally only done when there are significant quality or ergonomics gains. However, automation assist appears to offer significant performance improvement in the assembly area for relatively little capital investment.

In terms of quality, while Round 1 analyses showed no relationship between the level of automation and the level of defects, in Round 2 we find that increases in automation are consistently associated with improved quality (measured using the J.D. Power Initial Quality Survey data), even controlling for work practices, scale, product complexity, and vehicle design age. We surmise that this difference between Round 1 and Round 2 is the result of companies learning how to use their new automation more effectively, to eliminate automation that is overly complex or plagued by too much downtime, to avoid automation that offers relatively little benefit in relation to its costs, and to support their use of flexible automation with investments in flexible work organization and human resource policies.

We find some empirical support for the idea that some companies are learning how to gain more fundamental performance advantages from their use of new technology. When flexible automation, as captured by our Robotics Index, is used in conjunction with flexible work organization and human resource practices such as work teams, problem-solving groups, high levels of training, there is a positive interaction effect -- i.e. productivity and quality improve by more than the sum of the impact of the automation or the new work practices on their own.

7. Conclusion

The common perception that the diffusion of flexible production concepts is linked to the increased utilization of flexible automation is mostly accurate, although data from Rounds 1 and 2 of the International Assembly Plant Study reveal a more nuanced story across departments

within assembly plants and across regions. Worldwide, automotive assembly plants experienced a moderate increase in automation from 1989 to 1993/94, with increasing convergence in average automation levels across regional groups. Important regional differences remain, however, not only in the amount of automation found in the body, paint, and assembly departments but in the relative use of flexible versus “fixed” or “hard” automation.

Japanese plants in Japan and North America continue to install the most automation in their plants, on average, followed by plants of the U.S. “Big Three”, European, and Korean companies. Automation levels in the weld shop often exceed 90% in the advanced industrialized countries, while automation in the assembly area remains consistently low, between 1% and 2%, in these same plants. Paint shops show the most change over these five years and the most regional variation.

While overall automation has not increased dramatically since 1989, the more striking trend is the substitution of flexible automation (primarily robotic equipment) for fixed automation. This change in the makeup of the tool stock, even where overall automation levels remain relatively stable, reflects the high levels of product complexity that many plants now handle (due to a combination of the company’s product strategy and its export activity) as well as steady improvements in the price/performance ratio for flexible equipment. This helps explain some of the regional variation in the use of flexible automation. Japanese and European plants use robotics the most and also have the highest levels of product variety and export activity. U.S. plants of the “Big Three” companies have worked to reduce their (already relatively low) levels of product variety and still do little exporting, and accordingly continue to rely much more heavily on fixed automation than plants in any other region.

Innovations in assembly plant automation have also emerged in ways not easily captured by traditional measures of automation. Perhaps the most important of these is the rapid proliferation of different types of automation assist in the labor-intensive assembly departments of plants around the world. In contrast with previous efforts to automate assembly tasks fully, which proved to be expensive, subject to frequent downtime, and difficult to adapt to different

products, the automation assist approach minimizes investment costs, relies on simple and reliable technologies, and can be customized to different work stations. Automation assist is also often welcomed by workers because it does not aim to replace their jobs but to support them, it can improve ergonomics and reduce fatigue associated with excess walking time and workers can often be involved in the design and implementation process for these installations.

We consider briefly the links between flexible automation and a flexible workforce and the performance consequences of the increased use of flexible automation. Achieving the full benefits from flexible automation with respect to various strategic goals appears to require a skilled, motivated, and flexible workforce, and the assembly plant data reveal an increasingly close correspondance between flexible automation utilization and the adoption of new work practices. While automation levels have consistently been strong predictors of labor productivity at the plant level, the relationship between automation and quality outcomes has changed over time. In Round 1, there was almost no association between automation levels and quality, but in Round 2, the relationship is strong, suggesting that many companies have learned -- mostly through adjustments in their mix of automation to achieve the best match of tool to task -- how to gain improved quality as well as productivity. Finally, we find some synergistic interactions between investments in flexible automation and investments in a flexible workforce. Performance improvements are greater when both kinds of investment are made than could be predicted by summing the individual contributions of each type of investment.

In summary, we find that the conception from the early 1980's that full automation would sweep the automobile industry and make production workers obsolete is long-gone. While a few infamous examples of rash over-investment in automation are best-known, we found that company after company has concluded through their own initiatives that massive increases in assembly automation are not cost-effective. Instead, the industry has witnessed a tempered investment in automation overall, the steady replacement of fixed automation by flexible automation, the elimination of unreliable or overly complex technology installations, and the development of low-cost initiatives like automation assist.

We expect that over the coming years, companies will increasingly recognize the variety of ways in which flexible workers and flexible automation can serve as important complements to each other. The strong emergence of automation assist in diverse plants around the world is just one of many indicators in this direction. It may well be that the strategic goal of flexible production is best achieved when companies recognize the complementarities between these two factors and allow their investment plans for automation and corresponding investments in employee training and new forms of work organization to evolve accordingly.

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