Automation and Skill: Three Generations of Research on the Machine-Tool Case

by

Paul S. Adler
and
Bryan Borys

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PAUL S. ADLER and BRYAN BORYS

INTRODUCTION

THE debate over the impact of technology on the quality and nature of work is centuries old. In recent decades, as technological change has influenced an ever-broader spectrum of jobs, debate has intensified. Since the 1960s, numerically controlled (NC = numerical control) machining has often been called as a key witness. With NC the combination of machine and machinist is replaced by a machine, a computer control unit, a human operator, and a programmer. It is a particularly interesting case of technological change since the transition from conventional to NC machining leaves the machining process and the general nature of the product itself largely intact but changes the form and locus of control over the process. It thus provides an opportunity to directly examine the impact of technological change on work.

NC is a particularly interesting case for a second reason: the continuity of debate on its impact over more than two decades of research allows us to trace the evolution of research approaches and theoretical paradigms. Over these decades of research on NC machining and work, research strategies have evolved from task-level analysis of the technological requirements of automation in the

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1960s through analysis of the labor process in capitalist organizations in the 1970s to analysis of the social conventions surrounding skill and the history of specific organizations in the 1980s. Through this evolution, researchers have come to place less emphasis on strictly technological factors and more emphasis on social factors such as politics and ideology.

In this article, we critically review these three generations of research on NC and skill. Along with the shift in focus away from technology, we find a shift in focus toward smaller units of analysis and shorter time frames. Based on our review of the evidence presented in these studies, we offer a hypothesis: while social factors may dominate the determination of skill in the individual organization in the short term, long-run trends and larger organizational aggregates are dominated by technological factors. We thus suggest that the popularity of social over technological explanation in recent research results primarily from a narrowing of the object of research—the answers have changed because the question has changed.

Thus rather than completely rejecting either early technology-focused analyses or recent research focused on social factors, we recommend a reconciliation between the approaches: even if no *one best way* of implementing NC imposes itself in any given plant over any short time period—so that social factors dominate local and short-run analysis—the technological characteristics of the available machinery and the competitive pressure to capitalize on those characteristics are increasingly likely to dominate institutional and social factors as focus shifts from the local and/or short-term to the aggregate and/or long-run trends of the use patterns of automation.

Upon closer examination we suggest that reconciliation of the dominant social determinism and a resurrected technological focus requires addressing four lacunae in existing research on technology and work: misconceptions about technology, lack of consideration of the relationship between the content of work and product characteristics, an outdated and inflexible conception of skill, and a one-sided conception of the relationship between technological change and worker specialization. The following three sections discuss the models dominant in the 1960s, 1970s, and 1980s respectively and identify the increasingly social determinist trend. We confront these theories with the meager evidence available on NC and skill and then suggest a synthesis of the apparently incompatible views. We examine the key elements of this synthesis and in each area, suggest some hypotheses for future empirical testing, and conclude by identifying some policy implications.

JOB EVALUATION STUDIES

Two of the most rigorous studies of machining were conducted in the 1960s.[1] Their common premise was that work is a bundle of tasks representable on distinct, measurable dimensions. Researchers observed actual machining jobs and quantified the changes associated with automation in each dimension. In order to form a composite measure, Crossman and his colleagues weighted an average level of skill in each dimension by the labor hours required in that dimension and by the organization's job evaluation factors. They found that NC jobs required fewer hours of highly skilled work than similar jobs on conventional machinery, leading to the conclusion that there was a modest decline in overall manual and intellectual skills demanded by NC compared to conventional machine tools.

Hazlehurst, Bradbury, and Corlett expanded the range of dimensions of work in machine tool operation to include motor, perceptual, conceptual, and discretionary skills. They found that NC was typically associated with increases in conceptual and discretionary skills but decreases in motor and perceptual skills. Unlike Crossman and his colleagues, Hazlehurst and his colleagues avoided calculating a composite measure of overall skill, limiting their conclusions to statements about each of the skill categories individually.

The Crossman study suffered from a crucial limitation: the apparently arbitrary exclusion of some dimensions of work that are often considered important in machining—responsibility, in particular. The authors justified the omission on the grounds that responsibility did not belong in the *"traditional"* concept of skill. But what if automation increased responsibility requirements, as shown by the Hazlehurst study and by subsequent research?[2] And what if these become important job evaluation and remuneration factors, as in the case of the steel industry?[3] Even when a broader range of dimensions was included, as in the Hazlehurst study, the comparability between NC and conventional skills was not well understood. Are the types of discretionary skill comparable as between the responsibility of a conventional machinist with full control over tooling, machine process, and so forth and the responsibility of the NC operator who must share control over the cutting process with a NC programmer? Moreover neither study presented a robust aggregation scheme. The Crossman study relied on the job evaluation systems' weights of firms. But as Treiman has pointed out, the weighting of job evaluation factors is often much more critical to the results of such studies than the measurement of individual factors, and the weighting system is particularly difficult to determine in any objective fashion.[4]

During the 1960s Williams and Williams conducted a survey of 33 users and 6 producers of numerically controlled equipment. They found that managers who expected to deskill their workforces with NC generally had to change their plans:

> It was generally expected that under Numerical Control the skill level and technical competence required of the machine operator would be considerably less than that of a first-class machine operator. Evidence gathered in this study does not support such a conclusion. On the contrary, the skill and technical knowledge of the operator (and

consequently the wage rate) remain about the same as under conventional equipment. In some cases they increase; particularly when the machine is first introduced.[5]

Rich in empirical data and relatively atheoretical in its approach, this first generation of research and the ambiguity of its results set the stage for the subsequent evolution of the debate around NC.

LABOR PROCESS STUDIES

The first generation's job evaluation approach was primarily concerned with demonstrating the *impact* of technology—that is, the consequences, assumed to be more or less inevitable, of bringing new technologies into the shop. Braverman's "labor process" theory inaugurated a radically new line of analysis, arguing that these consequences were not the inevitable results of technology but of its implementation within a distinctly capitalist labor process.[6] NC was his star witness.

Braverman's attack on "technological determinism" was based on the idea that the way technology is used in capitalist firms in the pursuit of profit generates a "deskilling" tendency. For Braverman, what distinguished the capitalist labor process from the labor process in other forms of society (such as feudal or socialist) was capitalist managers' dual concern over control over a potentially recalcitrant workforce and over reducing wage costs. In Braverman's view, the major motivation for and effect of the implementation of new technologies under capitalist conditions was the Babbage principle:

> The master manufacturer, by dividing the work to be performed into different processes, each requiring different degrees of skill and force, can purchase exactly that precise quantity necessary for each process; whereas, if the entire work is executed by one workman, that person must possess sufficient skill to perform the most difficult, and sufficient strength to carry out the most laborious of the operations into which the art is divided.[7]

The resultant division of labor would simultaneously reduce costs and undercut the shopfloor control of the craft worker.

Applied to the NC case, Braverman thus expected that a plant labor force of conventional machinists could be replaced by less skilled NC operators and programmers. (His theoretical premise does not strictly imply that programmers should be less skilled than conventional machinists, only that a high ratio of operators to programmers would ensure that the average skill level, and thus the hourly labor cost, of the combined operator/programmer workforce would be reduced.) For Braverman, these effects were not due to the nature of NC machinery; it was only because of the specifically capitalist usage of machinery that the degradation of craft work occurs.

An interesting variant of Braverman's proposition is argued by Noble: not only the *implementation*, but also the *design* of new technologies is driven by a "profit and control" motive.[8] Noble's argument thus reasserted a restricted form of technological determinism, one which was very different from that asserted in the first generation of research: more cooperative, noncapitalist labor process would not, in his view, be able to sustain itself without thoroughly redesigning technology to be more convivial to restoration of craft-type worker autonomy.[9]

Shaiken added to this analysis by attempting to show why deskilling is so common even though it may entail a loss of productivity for the machine shop, "once a certain design path is selected it can be very difficult to alter directions."[10] The idea of design inertia allowed him to accept the Braverman/Noble postulate of deskilling while accepting anecdotal but persuasive evidence that deskilling is often not the most profitable option. He argued that the trajectory of machine-tool design toward deskilling is more powerful than the competitive pressures to design more profitable (and potentially skill-upgrading) machine tools. Although Shaiken focuses on inertia in equipment design, one could also imagine that inertia in managerial ideologies as well might hold back the implementation of higher-productivity forms of work organization.

There are three key problems with the labor process analysis of the automation/skill relationship. One is Braverman's conception of control. Braverman's perspective does not recognize that capitalists do not always win their struggles with workers.[11] Machinists, like other workers especially unionized ones, often resist subordination and loss of autonomy in their jobs.[12] Recognizing this resistance opens up a broad field of inquiry as to the impact on implementation patterns of the relative power of the contending players. What has been much less discussed is the fact that removing traditional craft forms of autonomy or decision-making ability from a job does not necessarily undermine workers' power. Braverman assumed, as do his successors and most of his critics, that craft workers, by virtue of their "autonomy," wield more power (or wield power more effectively) than do less-skilled operators. However, the rationalization of the labor process can and does produce new control problems. Workers' machine-tending responsibilities often put them in a position to exercise considerable power, since they "control the controls."[13] Moreover the work of machine tending is not as easily evaluated or proceduralized as that of conventional machine operating, as the majority of the tender's working day is occupied by watching the machine run; it is only when a breakdown is imminent that the tender must perform his/her function.[14]

Braverman's view of control also assumes that worker resistance to managerial direction is detrimental to productivity in capitalist firms. But the reality is that control is not a zero-sum game. Wilkinson, for example, describes how some NC operators—in violation of shop rules restricting programming to staff employees—use the editing capabilities of their machines to create more efficient programs.[15] That superior productivity is often a key bargaining lever demonstrates that control is not the *sine qua non* of management. Burawoy's analysis of worker behavior in a machine shop highlights similar patterns.[16] Freeman and Medoff's analysis of the impact of unions on productivity suggests that collective bargaining agreements, by providing workers with a way to voice dissent, can contribute to productivity.[17]

Apart from an oversimplified conceptualization of control, a second fundamental problem with the labor process approach is that, even if at any given time powerful deskilling tendencies were at work, it remains to be shown that the search for profitable uses of successive generations of technology does not generate a longer-term drift toward higher skill requirements and/or greater worker control. Gordon's formalization of Braverman's argument posits that available technologies create a production possibilities frontier on which capitalists will select the point of lowest worker autonomy and skill;[18] but Gordon ignores the question of the locus of such a point as technological change pushes the frontier outward. Although Braverman cited Bright[19] and others to support his case that successively higher levels of automation tend to reduce skill requirements, none of these studies, for lack of empirical breadth, can be considered an adequate refutation of the commonly held view that automation and skills are positively correlated. On the contrary, most of the labor force surveys cited by Spenner provide *prima facie* evidence for a gradual skill upgrading both through enhanced job content of most distinct occupations and through labor force composition changes.[20]

A third fundamental problem with the labor process approach is its adoption of the craft worker as the norm against which workers in capitalist firms are to be evaluated. This creates two difficulties. First when Braverman wrote of the "secular trend toward the incessant lowering of the working class as a whole below its previous conditions of skill,"[21] he assumed that autonomous, skilled craft work was widespread in early capitalism. Closer examination of the historical record, however, suggests that craft has never been the form of more than a small minority of occupations.[22] The second problem with the craft norm is that it seems to be inherently conservative. Kelley, working in the Braverman tradition and attempting to operationalize and empirically test Braverman's hypothesis, defined "conceptual" demands as the degree of judgment required in planning, selecting tools, and devising methods of work—leaving no room for such demands as the need for the NC operator to understand the structure of the control program.[23] Similarly, her definition of "execution" skills is operationalized in exclusively manual terms. Finally, her third dimension, "breadth" of knowledge required, is operationalized such that even if automation meant that the operator needed to understand entirely new domains like electronic controls, hydraulic load/unload arms, or ceramic cutting tools this increase in scope could never outweigh the fact that at a lower level of automation the conventional machinist knew a broader span of tasks.

This discussion of the labor process model suggests that the most useful way to read this body of research may not be to accept its own definition of its theoretical project as characterizing broad skill trends. On this terrain, its flaws are fatal. If we read it instead as a critique of capitalist/worker power asymmetry—which, when combined with the decentralized decision making of a market economy, sometimes generates deskilling outcomes—we can find in it a wealth of challenging propositions. Subsequent research has certainly benefited both from the conceptual framework positing a basic conflict between managers and workers over work intensity and from the cases describing how, at least in some instances, managers' prerogatives allow them to use automation to deskill jobs.

THE SOCIAL CONSTRUCTION OF SKILL

The third generation of research developed in opposition both to the first generation's assumption that technology inevitably changes the objective characteristics of work and to the assumption of the labor process theorists that capitalist managers choose (and design) technologies primarily on the basis of their capacity to change these characteristics. Theorists in the currently dominant *social construction* school argue that both real skill requirements and the terms used to characterize work as skilled or unskilled are primarily products of complex and often organization-specific social and economic interaction, about which it is difficult, if not impossible, to generalize.[24] NC appears frequently in this research.[25]

Kelly, for example, argues that the conflicts between labor and management within the labor process are conditioned by the competition between firms in factor and product markets.[26] He criticizes the labor process school for assuming that work content and organization are in general more influenced by labor/management conflict within the firm than by these external competitive pressures. Elbaum and Wilkinson compare the American and British steel industries in the late 1800s and argue that beyond the labor-management balance of power, factors such as market characteristics or the legal environment played an important role in shaping work organization.[27] In this broader view, the space for managerial strategic choice of automation-skill configuration is typically larger than Braverman and his followers considered.

The second and somewhat distinct element of the social construction argument focuses on the institutional mechanisms of labeling. Turner argues that workers are considered skilled or unskilled "according to whether or not entry to their occupations is deliberately restricted and not in the first place according to the nature of the occupation itself."[28] In a similar vein, feminist critics point to the sexist elements in the labeling process.[29] Recent research on the prevalence of *tacit skills* has offered an underpinning to this social construction argument: workers commonly employ a range of skills in the accomplishment of their work only some of which are officially recognized.[30]

The theoretical critique of the social construction thesis is more difficult than that of the preceding two schools since it offers so little by way of its own general theoretical propositions, concentrating instead on demonstrating empirical variability in order to undermine other theories' generalizations. Three types of criticism can nevertheless be advanced.

First, and contrary to the social construction thesis, these studies themselves often show, sometimes unwittingly, the real and important dependence of political outcomes on the substantive content of jobs. Elbaum, for example, argues that "[p]ay structure departed from competitive standards in the iron and steel industry because heterogeneous job content afforded different groups in the work force varying bargaining leverage."[31] His study convincingly demonstrates, however, that the principal source of changes in this bargaining leverage was the changing productive roles of different segments of the workforce. Politics clearly plays a role, but by Elbaum's own account, primarily a mediating, not a fundamental, one.

Second the local, industry-specific or period-specific, focus of this research leads it to underestimate the broader structural features of society that condition the probability of any given outcome. As research in the United States and the United Kingdom has shown, unions almost never have the power to change substantially the basic requirements of industrial training or apprenticeships; they almost never manage to block for long the adoption of new technologies; and thus they can influence the rate and details of change but not its overall direction.[32]

Third the social constructionist argument is essentially a negative one directed against the vanity of grand generalization. As such it has the *prima facie* plausibility of all claims that things are more complicated than they seem. But by the same token it suffers from the difficulty of proving a negative proposition. Kelly's theoretical critique is well-taken—Braverman certainly underestimated factor and product market pressures. It remains to be shown, however, that these external pressures systematically counteract the broader deskilling trend hypothesized by Braverman. The local research is certainly interesting and worthwhile, but from the aggregate point of view, perhaps these external factors just generate noise around a longer-term trend. It may well be, as we have suggested, that the deskilling generalization proposed by the labor process school is incorrect. But this can only be established by evidence at the societal, not the organizational, level.

Social constructionist arguments often cite as supporting evidence research on international differences in technology utilization patterns, claiming that it demonstrates the viability of culturally determined forms of work organization in broader aggregates.[33] But their interpretation of these differences is flawed: within-country variance in NC skill configurations is typically high and the profitability of more productive configurations may encourage shifts over time in national average practices. Furthermore, worldwide patterns can also be affected when firms in the less productive countries lose market share to imports from the more productive countries. The international comparison studies ignore the impacts of both these longer-run trends. Indeed these studies are often so firmly embedded in the social constructionist approach that they do not even attempt to measure the relative productivity of different configurations nor do they try to track changes in utilization patterns over time. The qualitative assessment of productivity in these studies is unanimous, however, leaving no doubt that German firms are more productive than their English or French counterparts, that they have not seen NC as a deskilling opportunity, and that the higher skill profile of German firms is a major source of this productivity advantage.[34]

Perhaps the most useful way to read the social construction research is as a guide to the complexity of the models required to make sense of local/short-term dynamics: the analysis of a given plant or industry must certainly go beyond both the simple technological determinism of job evaluation and the broad-gauge social determinism of the labor process school. But whether automation in the aggregate and in the longer run does have a specifiable impact on work remains a valid concern.

SOME SUGGESTIVE DATA

Apart from the properly theoretical difficulties, the key problem with the NC skill debate is that all this theorizing has proceeded without any systematic data.

The consequences of skill requirements for wage rates may yield an indicator of the basic dynamics involved. Following standard economic theory, we might hypothesize that since skill is a scarce and productive factor owners will in general pay a premium for more highly skilled workers.[35] It is true that the hypothesis that skill requirements are reflected in wages is subject to the same debates that surround the theory of skill as socially constructed (see the previous section). Moreover, alternative hypotheses are difficult to ignore: larger or more profitable firms might be both more willing to invest in NC and more able to pay higher wages, regardless of NC's skill requirements and of the skill of the workers; wages may reflect the capabilities of the incumbent workers more than they do the current technical requirements of the job. It is, however, difficult to believe that if we take a large enough sample, a major reduction in skill requirements due to

NC would not generate some perceptible downward pressure on the relative wage levels of NC operators.

We examined wages for a sample of over 80,000 machining jobs in the machine-tool industry, a major employer of machinists. The average wage for Class A journeymen machinists in 1981 in the Bureau of Labor Statistics sample was $9.72; for NC operators it was $9.51; for Class B conventional machinists, $8.54; and for Class C conventional machine operators, $6.41.[36] Both with and without controlling for location, wage differentials between Class A, Class B, and Class C machinists were statistically significant, but there was no significant wage differential between Class A machinists and NC operators.[37] Comparable data for other years indicate the same general relationship: NC operator wages are not statistically significantly different from Class A machinist wages but are significantly higher than those of Class B machinists.

Without a rigorous analysis of the other effects on wages (unionization, urban versus rural location, plant and firm size, and so forth), we cannot make strong claims about the skill levels represented by these wages. Nonetheless, and even assuming only a very approximate correlation of skill and wage levels, this result suggests two surprisingly strong conclusions. The first conclusion is based on the premise that NC is not only introduced into Class A machinists' positions but often also into those of conventional Class B and Class C machinists.[38] To the extent that Class B and C machinists are recruited for work on NC, our wage data suggest that the overall effect on skill requirements is neither negative nor neutral but very likely positive since it must be drawing the average shop workforce profile (Classes A, B, and C combined) closer to a Class A profile.

The second conclusion to be drawn from the wage data is that since NC programmers' salary rates are on average roughly 30 percent higher than the rates for Class A and NC machinists,[39] the Babbage principle does not hold: the average hourly wage rate for operators and programmers combined goes up, not down, with NC (even though the ratio of programmers to operators is typically quite low). If NC is profitable, it is not because it allows reductions in wage rates but rather because it allows increased output value per labor hour.

The wage data seem thus to support the conclusion one might draw from the less theoretical and more pragmatic elements of these three generations of research: firms usually muddle through to the conclusion that vendors' promises are exaggerated and that deskilling is unprofitable.[40]

RECONCILING THE THREE GENERATIONS OF RESEARCH

Rather than concluding that the above analysis directly contradicts any of the three previous generations of research on NC technology and work, we believe that it points to a potential reconciliation. First we have shown that each of the three generations of research has a different domain of interest: job evaluation research was aimed at explaining broad changes in skill levels across all relevant organizations in the entire economy; labor process theory analyzed the dynamics of technology in specifically capitalist organizations; social constructionism focused on case histories of specific industries or plants. Second each generation differs on the scope of the causal mechanisms invoked: job evaluation research focused narrowly on the impacts of technology and technical-economic factors; labor process theory expanded the explanation to consider the impact of political forces; social constructionism introduced a broader range of factors including the institutional, cultural, and symbolic (see Figure 1).

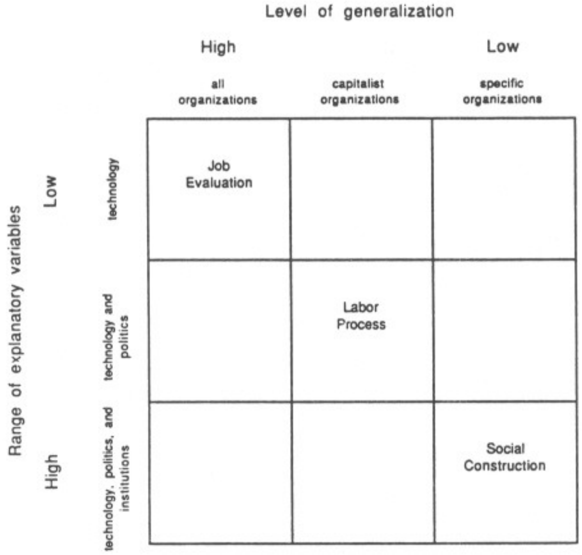

Figure 1. The scope of previous research.

Research in the upper-right-hand corner of Figure 1, insofar as it provides one-dimensional explanations of localized events, has low generalizability and so has not generated a major research stream. Research in the lower-left-hand corner, on the other hand, would need to be the kind of "total history" advocated by Braudel;[41] it calls for a breadth of intellectual culture that discourages more specialized researchers. Research thus tends to be carried out on the diagonal—in attempting to broaden the scope of causal mechanisms invoked, researchers have narrowed the scope of the phenomena explained.

This analysis suggests that there is no necessary contradiction or incompatibility between these approaches—including a broader variety of factors leads naturally to a greater detail in our image of NC and thus to a greater awareness of local variation. But there is a trade-off: this broadening of scope introduces a degree of complexity that cannot but impede efforts at long-run, aggregate generalization. This is where the confusion between difference and disagreement arises: although the broadening of scope opens fruitful new lines of inquiry focused on sources of variability, it does not invalidate the older narrower focus on the sources of similarity.

Figure 2 presents one way of integrating these approaches. The top part of the figure represents the short-run dynamics of automation and skill: in the short run, the effectiveness of various forms of work organization is unproven, competition has not been allowed to select the more effective plants, and thus local economic and political conditions systematically affect the power of labor relative to management. Over time, however, these institutional and local factors will change and both organizational adaptation and competitive selection will reduce the number of *outliers* as shown in the bottom half of Figure 2. In this view, the fundamental relationship between technology and skill—in our hypotheses an increase in skill demands made by technological change—may be discerned through the *noise*.

We believe that whatever long-run, aggregate generalizations can be culled from the data could be particularly useful to both theorists and practitioners. However, we need to reexamine the long-run aggregate focus resurrected from the first generation of research in light of issues raised by subsequent generations. Thus in the remainder of this paper we present a series of hypotheses designed to explicate and operationalize this reconciliation.

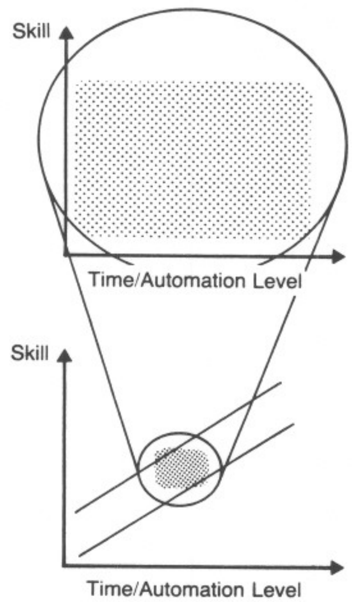

Figure 2. Automation and skill in the short run and long run.

TOWARD A MORE ROBUST THEORY

The Nature of Technology

One of the principle handicaps of much previous research has been its reliance on a mythical image of machine-tool automation as moving toward a completely stable, prespecified process through the embodiment in machinery of an ever-larger fraction of the worker's task set. Such a scenario makes deskilling appear almost inevitable. Four problems with this image need correction.

First programs and machine tools are far from completely reliable and error free. In many domains automation seems to shift the profile of uncertainties such that, even if the more automated process experiences fewer breakdowns or errors and the total cost of breakdowns/errors is reduced, the remaining contingencies can have a higher average unit cost of detection and correction. The implications for skill requirements of such a shift in the contingency profile are considerable since it is no longer cost effective to "inspect quality in"—operational effectiveness and economics demand greater worker mastery of the process.[42]

A second and related factor is the association between increased automation and the evolution of the worker's skill profile. The specific effects of automation on machining skill are discussed in detail in the following section. At this point we wish to emphasize a more general relationship. It is likely that there is a significant correlation between (a) the degree of difficulty experienced by engineers in attempting to automate an operation and (b) the complexity of the skill requirements of the operation. There are certainly some exceptions to this generalization; the handling of soft materials and visual pattern recognition are often very simple tasks for workers but very difficult to automate. These exceptions help explain why low-skill jobs such as machine feeding and data entry are often found at the interstices of automated systems. But the intellectual, creative, and social functions that account for the complexity of highly skilled work are as yet well beyond the reach of even the most advanced technology.[43] Moreover as the machine takes on more tasks, the worker's task is augmented by the need to control a more complex machine. Successive waves of automation can thus be expected to reduce workers' low-skill workload, leaving them with a higher overall skill level.

A third factor undermining the association of automation and process stability is the *flexibility* associated with computer-automated manufacturing. Computer-based automation may encourage more variability in the plant's production process as it is used to respond to environmental demands for flexibility. The shift from conventional to NC does in fact tend to reduce batch sizes and accelerate new product introduction.[44] In this scenario, increasing automation both allows the plant to adapt to changing conditions and increases the amount of change within the plant, both of which typically have important skill upgrading ramifications.[45]

Finally skill requirements are increased by automation's tendency to feed on itself. The shift to NC creates the opportunity for implementation of computer numerical control (or CNC, which allows programming to be done on the machine). CNC, in turn, allows the linkage of systems of machine tools into flexible manufacturing centers and these in turn can be linked in flexible manufacturing systems. The requirements of increasingly rapid process change, as well as the requirements of the new forms of automation it brings, can be expected to increase skill requirements.[46]

These arguments lead us to the following propositions:

- Proposition 1: The frequency of operating incidents (machine crashes, defective parts, and so forth) is negatively associated with the level of automation, but the average severity of the remaining incidents increases.
- Proposition 2: This new profile of operating incidents within the production process will be better managed by decentralization of expertise and authority; this high-skill configuration will be adopted over time as the productivity gains realized outweigh managerial fear of loss of control.
- Proposition 3: Low-skill operations tend to be automated before high-skill operations.
- Proposition 4: NC operator expertise and authority are positively correlated with productivity and profitability.

The Interaction between Skill and Product Characteristics

In thinking about automation and skill, it is tempting to focus narrowly on the question: "all else held constant, what is the relationship between machine-tool automation and operator skills?" Indeed, as we noted in the introduction to this article, machining is an attractive research domain since the modest changes in product characteristics permit us to study this question. But product characteristics such as part complexity, batch size, frequency of new product introductions, and number of part families are important mediators of NC's skill effects, and there is strongly suggestive evidence that worker skill is required to capitalize on these characteristics.[47]

Given these differences in product characteristics, should analysis focus on the impact of automation on the skill requirements associated with the production of a *given* set of products or should it focus on the total impact of automation on skill requirements—both the *direct* effect (for a given set of products) and the *indirect* effect (as automation affects skill via changes in the typical product mix)? One might argue that indirect effects are small, since standardization is seen by some to be the general trend of modern industry. On the other hand, Piore and

Sabel highlight a trend toward "flexible specialization," in which new technologies (especially those that are microprocessor based) reduce the cost penalties associated with the more varied product lines.[48] In fact, Sorge, Hartmann, Warner, and Nicholas found that many firms are using CNC to produce smaller batches.[49] And in the United States Putnam shows that the NC users he surveyed typically have more part design changes per year, smaller lot sizes, and more complex product designs than do the nonusers.[50] The arguments for including the indirect effects of automation on skill are therefore strong, especially if the adoption of automation is being driven by its ability to change the cost differentials between small and large batches and between less and more complex products. Including these mediating effects may uncover an upgrading trend as machine shops using NC with higher-skilled workers to capitalize on these product characteristics outperform those shops where less-skilled labor prevents them from achieving such gains.

These arguments lead us to the following empirical propositions:

- Proposition 5: Use of NC is positively correlated, *cæterus paribus*, with greater part complexity, higher frequency of new product introductions, and smaller batch sizes.
- Proposition 6: Part complexity, frequency of new part introduction, and smallness of average batch size are, *cæterus paribus*, positively correlated with skill levels.
- Proposition 7: Workers on NC equipment may not be more highly skilled than those on conventional machine tools when product characteristics are held constant, but will be more highly skilled when the influence of product characteristics on skill requirements is allowed to mediate the automation/skill relationship.

Reconceptualizing Skill

If we want to characterize the relationships between the plant, its technology, and the skills of its labor force, we need a more robust concept of skill. As Spenner summed up in 1983: "All designs for studying skill transformations—whatever their theoretical motivation—stand to gain by more explicit and comprehensive treatment of skill.[51]

The definition of skill implicit in the job evaluation research is that skill is a bundle of capabilities each of which contributes to the overall skill of a job independently of the others and each of which is identifiable and measurable independently of the others.[52] As discussed above, this approach must overcome the difficulties of capturing qualitative change and constructing aggregate measures of skill.

A second notion of skill is the one embedded in the labor process analysis: "the concept of skill is traditionally bound up with craft mastery—that is to say, the combination of knowledge of materials and processes with the practiced manual dexterities required to carry on a specific branch of production."[53] This approach focuses on two key dimensions: substantive complexity and autonomy/control.[54] Our concern here is that the concept of autonomy is both too broad—there are other dimensions apart from substantive complexity identified by job evaluation that one would like to examine separately—and too narrow—it assumes that if autonomy is reduced by increased horizontal interdependence, this amounts to deskilling/degradation, which we shall show later to be a debilitating assumption.

A third notion of skill as *satisfying work* is implicit in Braverman's concern

> that work has become increasingly subdivided into petty operations that fail to sustain the interest or engage the capacities of humans with current levels of education; that these petty operations demand ever less skill and training; and that the modern trend of work by its "mindlessness" and "bureaucratization" is "alienating" ever larger sections of the working population.[55]

But skill is not necessarily synonymous with job satisfaction. That some workers dislike the stress and difficulty of some highly skilled jobs, while others enjoy the minimal demands of low-skilled work, is neither a surprising nor a controversial result.[56] More importantly, the case of refinery control-room operators shows that it is not at all obvious that the most fruitful definition of skill would necessarily exclude the possibility that automation increases factors along most dimensions of skill while reducing precisely those factors that correlate most strongly with satisfaction and interest.[57]

A fourth definition of skill is the social constructionist definition: skilled work is whatever gets labeled as skilled where labels primarily reflect the interests of powerful actors. We have seen, however, that political power and the opportunity to wield it are usually strongly conditioned by underlying technological and economic factors. We do not wish to exclude such labeling effects; they can be characterized as a superstructure of the skill definition process primarily reflecting—but partly autonomous of—underlying technological and economic forces influencing the definition of skill.

Our own approach to defining skill begins with the notion of human capital. Human capital theorists conceive of skill as the result of an investment that workers must make in order to gain access to higher-paying jobs.[58] The time and money spent on schooling and apprenticeship by individuals is treated as an investment in the individual's marketability in the labor market. This idea of human capital may stretch the noneconomist's imagination, but the notion on which it rests is sound: skill is valuable in production, hence employers will pay a premium for it; how much they will need to pay depends on (*inter alia* but importantly) the cost of acquiring the skill. This model offers a simple quantitative measure of the substantive complexity dimension of skill: the resources used in training on and off the job.

But our analysis of skills clearly must address the more *qualitative* aspects of work requirements. We need some framework for understanding the qualities that training is designed to elicit. We propose to capture these qualities with four dimensions, rather than the single autonomy/control dimension used by labor process analysts.

1. The question of operator *responsibility* and the difficulties in theorizing it have been discussed in our review of the job evaluation approach. With the passage to NC, these responsibility requirements not only increase in degree, but also change in form. Due to the greater value of the equipment, greater complexity of the product, and higher throughput typically associated with NC, it is no longer possible to interpret the operator responsibility requirement as simply a matter of how much effort is applied. An attitude—a sense of responsibility for the integrity of the whole process—is demanded.[59]

Thus NC may or may not result in an increase in the traditional form of responsibility—that for effort. It does, however, significantly raise the level of a qualitatively different form of responsibility—that for outcome. While piece-rate systems ostensibly reward workers on the basis of outcome (i.e., output), the traditional technologies they typically employ permit a close coupling between worker effort and outcome; thus working harder brings both more output and added rewards. The coupling between effort and outcome is looser in an automated system, however. Workers in an automated system are required to take a wider view of their role in the production process; working smarter becomes more important than working harder.

2. The task of monitoring an NC machine requires not only a working knowledge of the physics of machining, but also the ability to follow the control program. A more *abstract* understanding of the technology is needed if the operator is to be able to recognize potential problems before they result in expensive machine crashes (as both the Crossman and Hazlehurst studies recognized). This abstractness arises from the greater sophistication of the technology and corresponding removal of the operator from direct involvement in the metalcutting process. As the machinist's task moves from machining to monitoring, less emphasis is placed on the experience-based physical reflexes acquired in apprenticeship and greater emphasis is placed on conceptual understanding of metal cutting and tool programming. That some conventional machinists might feel such a shift to be a loss even if others see it as a challenge is entirely understandable; for the theorist to side with the former over the latter seems to betray a romantic conservatism.[60]

3. The degree and pattern of horizontal *interdependence* is also greatly affected by increased automation.[61] The passage to NC increases the interdepen-

dence across more specialized activities such as planning, programming, and supervision. Here we find that the classical analysis of technical interdependence has important ramifications for work content as well as organization.[62] The reciprocal interdependence fostered by automation calls for substantially broader social skills, which then become increasingly important elements of skill comparison. As Belitsky found in his case study, "the greatest challenge is not in training people to do their jobs but in training people to work with other workers."[63]

4. A final qualitative dimension is the extent to which training is a one-time, up-front investment rather than an ongoing process of continual upgrading. Evidence from surveys by Majchzrak and Jacobs suggests that the accelerating rate of technological change makes such continuity of training an increasingly important characteristic of machine-tool operator jobs.[64] With NC both new products and new and more advanced process technologies will come at an accelerating rate. As a result pay-for-knowledge types of remuneration[65] might be increasingly common at higher levels of automation.

We face, to some extent, the same problem faced by the job evaluation researchers: machine-tool automation reduces some skill components while increasing others. While we recognize the incommensurability of these dimensions of skill, we offer two suggestions. First, a more refined notion of skill will allow researchers to identify more subtle forms of both deskilling and upgrading than is possible within previous frameworks, regardless of their ability to construct overall scales. Second, wages provide a useful proxy for net skill requirements: wages are the way the labor market forces skill level comparisons.

Empirical support for our dimensionalization of skill can be found in Cain and Treiman's factor analysis of 44 measures of job requirements across a sample of occupations from the *Dictionary of Occupational Titles*(DOT).[66] Their exploratory analysis generated factors that correspond remarkably well with our theoretical scheme. Their first factor, substantive complexity, corresponds to the quantitative, human capital dimension encompassing amount of training. Their next two factors, motor skills and physical demands, correspond to our abstract-cognitive *versus* manual-experiential dimension. The fourth factor, management skills, corresponds to our responsibility dimension. Their fifth factor, interpersonal skills, corresponds to our interdependency dimension. Our final dimension, need for continual training, is not captured in the underlying DOT characteristics, and their final dimension, working conditions, bears little relation to skill.

It would be possible to verify these arguments by empirical testing of the following propositions:

- Proposition 8: Through the shift in the profile of operating incidents (Proposition 1), NC changes the form and increases the amount of responsibility required of workers. This dual proposition can be tested using data on job evaluation systems operative in machine shops. The qualitative shift in the form of responsibility may be measured by the redefinition of responsibility away from effort to results measures, while the quantitative shift in responsibility may be measured by the increased weighting of responsibility relative to other job evaluation categories (typically training, effort, and working conditions).

- Proposition 9: NC increases the abstractness of work since the effective functioning of the operation requires that the operator understand the program guiding the cutting tool; this abstractness can be measured as the ratio of theoretical training to on-the-job training and experience typically required.
- Proposition 10: NC increases the interdependence of workers, measured (a) by the amount of time spent in discussion by operators, programmers, and other support staff; (b) by the redesign of organizational structures and rules to handle these new interactions; and (c) by the importance of social/interpersonal skills in hiring criteria and training programs.
- Proposition 11: The development of machining automation will be associated with greater frequency of retraining; as a corollary, we might also expect an increasing proportion of the more automated firms to adopt pay-for-knowledge policies.
- Proposition 12: Changes in these dimensions will generate increases in the training time requirements of the typical NC operator compared to the conventional machinist; these increases will more than offset reductions in experience-based manual learning, with a corresponding increase in overall job evaluation scores averaged over a large number of shops.
- Proposition 13: Wages of NC operators will, controlling for local labor market conditions, firm size, and unionization, be higher on average than wages of conventional machinists. This wage differential will be primarily accounted for by a difference between these two groups along the qualitative dimensions of skill outlined above.

Automation and Specialization

The major focus of the previous studies of NC skills has been the machine operator. But NC inevitably brings with it additional requirements for planners, programmers, specialized maintenance workers, and fixture- and toolmakers. An individualistic concept of the labor process is increasingly problematic when productivity and effectiveness are determined not only by individuals' skills and technology but also by the coordination of specialized tasks.

First attention must be refocused on the skill requirements of the "collective worker," encompassing shopfloor coordination and technical functions, rather than only on the operator. Even if future research were to find that NC operators were less skilled than conventional machinists (contrary to Proposition 12 and contrary to the currently available evidence), it would not prove whether the shift from a single machinist to the combination of operator and programmer represents an increase or decrease in the *total* skill requirements of the plant.

Second we need to be clearer about the impact of specialization on the content of any single job. For a given level of technology, an increase in the division of labor will typically reduce average skill requirements. But the analysis is entirely transformed when such specialization is accompanied by increased automation. When NC allows tool path control to shift from the machinist to the programmer, it is not necessarily the case that the operator's job is deskilled. Subtractions from the operator's task set are counterbalanced by the addition of new tasks: controlling the more powerful machine, managing the new interdependence with a specialized programming function, and keeping up with the increase in abstract knowledge that accompanies automation. It is therefore not adequate to assume that NC operators are more skilled than conventional machinists only if they do their own programming (as does Kelley, for instance).[67]

Empirical propositions which follow from these arguments include:

- Proposition 14: NC typically increases the division of labor in the shop (at least insofar as it typically introduces a specialized programming function), which increases the amount of interdependence between employees (restating Proposition 10).
- Proposition 15: The increase in specialization that accompanies NC does not lower the skills even of the lower-skilled jobs (restating Proposition 13) but instead introduces more highly skilled tasks to each occupation (programming or program editing compared to blueprint reading, more complex maintenance, and higher operator skills as discussed in Proposition 13).
- Proposition 16: Controlling for local labor market conditions, firm size, and unionization and including direct and support labor, the average hourly labor cost associated with NC machining is higher than that associated with conventional machining. This difference will be associated with an increase of skill in the NC shops not only for operators (Proposition 13) but also for programmers and maintenance personnel.

POLICY IMPLICATIONS

Our effort to reconcile job evaluation, labor process, and social constructionist models rested on the distinction between the dynamics operative at the local level over the short term and the long-term dynamics at the aggregate level. Policy conclusions, however, require that we consider more carefully whether the latter are likely to be felt as tangible realities at the plant level. The hypothesis underpinning the previous section's analysis is that close examination of the individual plant will indeed reveal a pattern of productivity differences associated with different work/automation configurations.

The policy implications of our skill upgrading diagnosis are thus substantial. Five important challenges to managers, workers, and unions follow from changes in each of the work dimensions we have identified:

1. As *substantive complexity* increases, both generic and firm-specific skill requirements tend to increase, but firm-specific skill requirements may increase more rapidly. With automation the need and the opportunity to tailor routines to specific local conditions is multiplied and firm-specific skill requirements thus become more important. This implies increased pressure on firms to design effective internal labor markets and career ladders.
2. As the scope of worker *responsibility* increases in automated systems, firms must find ways of eliciting and sustaining a much higher degree of commitment on the part of workers—workers from whom all that was previously demanded was a "fair day's work for a fair day's pay." More participative decision-making processes may be required to sustain enthusiasm for these new responsibilities.
3. The increasing *abstractness* of automated work poses two distinct challenges. The increased level of general and scientific knowledge required demands new training methods and more extensive classroom programs. The weaknesses of the public education system become increasingly costly. The second challenge is the problem of boredom. Automated work tends not only to be abstract in the sense of *general* but also abstract in the sense of *lacking a tangible object of effort*. Workers in automated systems are often required to work *in* and *around* the system (the way professionals and managers do), rather than work *on* the system, as do most blue-collar workers. This lack of tangible contact often leaves automated work boring—a common complaint of NC machinists.[68] At the same time that responsibility for outcomes weighs more heavily on workers, motivation to be attentive is reduced by the boredom of work. Participation policies may help, but work-time reduction may also be required.
4. Another major challenge is posed by the interdependencies brought about by automation. Traditional forms of remuneration and workers' traditional self-image based on individual effort are modified by increased dependence on others for one's own success. Both pay systems and workers' attitudes must evolve toward a new, perhaps more fragile, balance of individual and group if teamwork is really going to work.
5. A final challenge is posed by the *professionalization* of operators who increasingly need to play a proactive role in continually updating their skills. This professionalization will exacerbate pressures to turn the authoritative relationship between managers and operators into a more collaborative one.

In sum NC creates substantial challenges for traditional management policies and practices and opens new opportunities for workers to play a more active role in shaping the organization of production. Machining may not be fully representative of other cases of automation. We badly need more aggregate statistical studies that grapple directly with the big picture. But close attention to individual cases like machining can help clarify the questions and the stakes.

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