High Performance Expert Systems

Todd D. Cherkasky

Work and Technology Institute
1775 K St NW Suite 630
Washington, DC 20006
tdc@wti.org

Abstract

This paper reviews two divergent approaches to the development and application of expert systems in manufacturing and suggests that AI researchers and system designers can more effectively contribute to manufacturing solutions by pursuing high performance design rather than reinforcing traditional technocentric assumptions.

Introduction

To make expert systems more relevant to the manufacturing environment, applied researchers and other artificial intelligence (AI) designers must face the actual problems that arise in manufacturing organizations. While current AI research responds to demands for specialization and flexibility by modeling and automating process planning, scheduling, material handling, and other complicated processes, manufacturers' attention has shifted from exclusively technical concerns to include the complex processes of work organization, interpersonal interaction, and organizational learning. From design for manufacturing (DFM) to integrated process and product development (IPPD), organizational theorists, management scholars, and interdisciplinary design studies researchers recognize that manufacturing solutions require an understanding of the social, cultural, and institutional dynamics underlying technologies of production (Appelbaum & Batt 1994; Cormier 1994; Susman 1992). AI-based systems would better support manufacturing applications if they complemented manufacturers' attention to such factors as work organization and teams and if they built systems that leverage and extend workers' skills.

Technocentrism

The technocentric approach to manufacturing problems is a legacy of an industrial system that achieved production gains by increasing efficiencies in individual tasks, by concentrating information and control toward the top of a multi-layered hierarchy, and by adjusting human activity to the capabilities of new technologies (Howard & Schneider 1994). In technocentric development, investments in technology are assumed to compensate for inefficient, error-prone, and otherwise limited workers. Design proceeds linearly from conception to execution, from engineering to production. Those most closely affiliated with the design and development of machinery—engineers and managers—make all decisions about work organization, plant layout, and workers' activity. Ignoring both the implications of increasingly competitive, segmented markets and the affordances of new technology, technocentric designers overestimate what computers and machinery can achieve on their own and underestimate the social and organizational contributions to industrial production.

High performance

Over the last few decades, management scholars have addressed some of the deficiencies of the technocentric model. In *Technology and the Future of Work*, Paul S. Adler highlights several key factors of successful production that are neglected by the technocentric approach:

> The effective use of new technologies will require a workforce with both higher skills and broader roles.... (and) also requires that the business firm be reconfigured to support a process of continuous learning.... It is becoming increasingly obvious that, to compete effectively, firms need to develop comprehensive long-term strategies for building their "knowledge assets," that is, for jointly managing the interdependent development of the knowledge embodied in technical systems and the knowledge accumulated by employees. Clearly, the success of firms in developing this new approach depends to a great extent on changes in the broader social, political, and institutional context (1992, 13).

Situated in a larger arena than the narrowly focused technocentric model, new approaches to work systems—often characterized as high performance—emphasize continuous learning, a long-term orientation, and an

increased reliance on workers' discretion and judgment. With a goal of improving overall organizational effectiveness over the long term, high performance work systems foster worker participation in technology selection, implementation and customization and provide training to improve technical and process skills. See Table 1 for the eight key elements of high performance, as enumerated by economist Ray Marshall (1991).

Table 1 Eight Key Elements of High Performance Work Systems	
1.	Effective use of all company resources, especially the insights and experience of front-line workers, in order to achieve continuous improvements in productivity.
2.	Acute concern for the quality of products and services in order to satisfy the demands of a consumer-driven marketplace.
3.	A participative and non-authoritarian management style in which workers ... are empowered to make significant decisions by (a) using their individual discretion, experience and creativity, and (b) cooperating with their peers in a mutually supportive atmosphere.
4.	Internal and external flexibility in order to: (a) rapidly adjust internal production processes to produce a variety of goods or services; and (b) accurately comprehend the external environment and adjust to changing economic and social trends.
5.	A positive incentive structure that includes: employment security; rewards for effectively working in groups; decent pay and working conditions; and policies that promote an appreciation for how the company functions as an integrated whole.
6.	Leading-edge technology deployed in a manner that extends human capabilities and builds upon the skills, knowledge, and insights of personnel at all levels of the company.
7.	A well-trained and well-educated workforce capable of: improving a company's work organization and production processes; adapting existing machine technology and selecting new equipment; developing new and improved products and services; and engaging in continuous learning...
8.	An independent source of power for workers—a labor union and collective bargaining agreement—that protects employee interests in the workplace; helps to equalize power relations with management; and provides mechanisms to resolve disagreements that arise because of the inherently adversarial nature of labor management relations.

Expert System Development

The contrast between technocentrism and high performance can be seen in the development of a variety of technologies, including expert systems. Whether the end-user expert system is configured as a technocentric or high performance application depends in part on decisions made by applied researchers, designers, marketers, distributors, system integrators, and application engineers. (Individual discretion is influenced to a great extent by institutional determinants as discussed below in "Entry Points for Change.") These developers participate in either the design or implementation (or both) of expert systems in manufacturing environments. The design stage involves knowledge-acquisition and the merger of the knowledge domain with an inference engine. Implementing the expert system requires that it be integrated into the processes of work along with other manufacturing technologies.

Expert system design and implementation

A dominant part of the design of expert systems entails translating an expert's knowledge and experience into a form that the expert system can digest. Knowledge engineers have recognized this process as a serious bottleneck that slows expert system development. Anthropologists that have studied the knowledge acquisition process suggest "that the knowledge engineers' assumptions have some unintended negative consequences for their own practice, for the systems they build, and thus (potentially at least) for the broader society" (Forsythe 1993, 448). These are assumptions about the nature of knowledge, the capabilities of expert systems, and the contributions that workers can make to manufacturing applications.

Knowledge, as it is often viewed by knowledge-acquisition engineers, is asocial and acultural—and thus independent of human interaction. Essentially a commodity, knowledge is elicited from a domain expert by knowledge engineers in what they consider to be a straightforward, common-sense question-and-answer procedure. Knowledge, in this sense, is captured and stored in an ahistorical context for later retrieval and application to manufacturing problems that have well defined parameters. Because "knowledge engineers tend to reify knowledge, often leading to naive and inappropriate elicitation strategies in dealing with experts," they contribute to their own frustrations (Forsythe & Buchanan 1992, 206).

Beyond the practical bottleneck that is created, more severe implications for manufacturing systems result when expert systems are designed without recognition of their limitations. One limitation is an over-reliance on formal models as the exclusive means for solving design problems. Although these models work particularly well for clearly defined problems that anticipate all potential contingencies, the complexity of the contemporary manufacturing environment demands workers' skills and innovations.

> Workers have compensated for inelegant designs and limits in engineering knowledge by employing a range of skills and experience-based knowledge, or even by unsophisticated intervention.... Although the performance of one or several machines might be well understood, when systems are truly integrated and various machinery and electronics interact directly with each other, a higher order of complexity is created. One must predict not only the function and limits of one machine but the conditions created from the interaction of multiple machines and control systems; sometimes effects are created that arise solely from their interaction and could not be found in the operation of one unit in isolation. (Salzman & Lund 1995, 331)

Workers' contributions to production are necessarily overlooked if the knowledge base assumes they do not exist. Their skills and experience will be neglected if knowledge engineers do not realize that knowledge is "distributed through the division of labor, the procedures for getting things done, etc." and that "complete and unambiguous knowledge about expert procedures is unlikely to be transmitted through experts' verbal or written self-reports." (Forsythe 1993, 453)

Defining the role of the eventual operator is thus a central issue for designers of expert systems. According to Jürgen Dorn of the Christian Doppler Laboratory for Expert Systems, the steel "industry has always been very innovative in the application of new production technologies and the latest computer technology.... Despite this rapid automation, the process operator has remained an important link in the production process, and with the introduction of these new control systems, operators are being overloaded with process data." (Dorn 1996)

The operator, increasingly removed from direct experience with the production process, faces a wealth of information generated by programmable controllers, sensors, and other intelligent I/O devices. To deal with this data bottleneck, Dorn suggests that the industry should use "an expert system that acts as a consultant or even as a decision maker...." Here is the crucial choice. Will systems be developed to leverage or to replace workers' experience? While a high performance orientation to manufacturing actively encourages workers' critical input and experience, the technocentric path consistently undervalues human contributions to production.

Emphasizing the dangers of the technocentric approach, David M. Upton summarizes in the *Harvard Business Review* the case of Mead Corporation's Escanaba paper mill: "The mill's managers ... realized that computerization in itself was no panacea. Some of the machines in the mill were relatively highly computer integrated. 'Even though we had a lot of computers on the plant *(sic)*, sometimes we'd make a couple of hours' worth of production before someone realized that something was wrong. ... It was just too easy to trust that the computers had got it right.' In addition, the opaque computerized systems prevented workers from learning how they might improve operations." (Upton 1995, 80)

As operators' direct experience with manufacturing processes declines, the long-term viability of knowledge domains deteriorates. The danger is that knowledge in expert systems adversely affects manufacturing applications because it remains static (as contrasted with knowledge that is modified by social negotiation), brittle (it neglects common-sense knowledge about the world and contrasting views of different experts), and narrow (when KBS knowledge does not cover a broad enough domain because only one domain expert is used in the elicitation process). (Forsythe 1993)

If, in contrast, knowledge engineers understand the value of workers' experience, they will design systems that depend upon and help augment their skills, thereby making the knowledge base more robust. When these systems are linked to the rest of the manufacturing application, they provide the means for workers to contribute their ideas and to be actively engaged with production processes, thereby ensuring the knowledge-domain's long term relevance and viability.

In the design of expert systems, knowledge engineers and applied researchers shape what counts as relevant knowledge. Similarly, when implementing expert systems, plant-floor supervisors, operators, managers and application engineers make crucial choices that determine the extent to which expert systems conform to technocentric or high performance tenets. The resulting expert system is then linked with other production technologies (e.g., graphical user interfaces, intelligent sensors, supervisory process control software, data acquisition boards, etc.) to become part of the manufacturing environment.

A popular vendor in the machine control industry, Intellution©, has recently acquired Visual Expert©, a Microsoft Windows©-based development and run-time package. Combining the graphical control interface and data acquisition power of Intellution's FIX DMACS with Visual Expert's decision support, Intellution provides a flexible product. Visual Expert can be configured as specified in its product announcement: "It provides step-by-step graphical representations of diagnostic procedures for equipment troubleshooting and minimises *(sic)* the possibility of human error by requiring the operator to log in and follow the instructions displayed on screen" (Expert Systems 1995). In this technocentric configuration, front-line workers execute procedures designed in advance with no opportunity to modify them. Visual Expert's "display builder" and development environment—where the logic structure of pertinent processes are defined—are

unavailable to operators. The Visual Expert application could be configured differently, allowing operators to add nodes and procedures to its logic structure as well as to perform the more passive task of monitoring alarms, temperature, and other process information. The high performance implementation of Visual Expert allows users to be actively engaged with the process, to update the system with real time process improvements, and to ensure that 'the computers got it right.'

Technocentric design and manufacturing trends

Often expert system developers assume that manufacturing applications are more effective if they are controlled entirely by "decision-making" expert systems rather than by workers who are assisted by them. This assumption is readily apparent in documentation summarizing the benefits provided by expert systems. For example, General Electric's Dodger—a diagnostic expert system—"employs a number of AI techniques to analyze eddy current signals and assess trends in material condition. Benefits realized include a high consistency of interpretation and a decreased reliance on human operators". (Klahr & Byrnes 1993) The implicit (and sometimes explicit) statement being made by these researchers and the technologies they produce is that operators, skilled machinists, process engineers, cost estimators and other workers and technical professionals are liabilities to the production process. These personnel are seen as expensive variable costs, as inefficient and error-prone, or as lacking the specialized expertise of more experienced employees (Chorafas 1992; Cunningham & Smart 1993; Hayes-Roth & Jacobstein 1994; Hauser & Hebert 1992; Kowalski et al. 1993).

Although each of these ostensible liabilities offers ample opportunity for technical problem solving, the current manufacturing environment demands an alternative to the technocentric strategy of design. Current manufacturing trends recognize that labor is not the only—and not the most significant—variable cost. Other costs in this category include inventory, purchase price, machine utilization, scrap, etc. Cycle-time reductions and other process improvements stem from continual correctives to work organization and technology configuration, which can be heavily influenced by the input of front-line workers. In high performance manufacturing environments, workers at all levels of the company are understood as innovative contributors to both design and manufacturing solutions. To ensure continual contributions from these workers, high performance work systems emphasize training for both technical and process skills. (See Table 1.)

The organization-centered approach that looks to workers for process innovations is realized in integrated product and process development (IPPD) and design for manufacture (DFM). These manufacturing trends focus on organizational issues that traditional technocentric approaches to manufacturing ignore. IPPD and DFM, for example, stress the importance of communication and teams and they grant authority to those traditionally left out of design processes (e.g., production and maintenance workers, as well as customers) (Thomas 1994; Liker & Fleischer 1992).

These initiatives recognize that continual innovations require the experiential knowledge of human experts—expertise that is based on direct interaction with manufacturing processes. They draw on economic and intrinsic rewards that stem from participatory and skill-based applications of technology. For example, a $500 million plant that produces special order alloy steel was explicitly designed to incorporate the real-time interaction of the experienced operators. The fundamental assumption of this design is that the computer makes recommendations, but does not make decisions automatically. It provides on-line diagnostic capabilities and relies on the critical insights of plant personnel.

> The design of the system was based on an explicit principle of operator control of the process. The system was designed to provide operators with the information and technology necessary to make nearly all production decisions without supervision. It provided operators with a display showing the status of all the heats. At each operation, it provided a computer-calculated "recommended" procedure and an analysis of any operator-proposed changes. There were also manual overrides for all equipment in the process.... (Salzman 1993, 90)

The benefits included "a flow of process improvement ideas" and total system performance that exceeded productivity and quality expectations and industry standards. Several recent studies concur: participation in workplace decisions, including technology design and implementation, increases productivity (Cormier 1994; Potter & Ngan 1996; Levine & Tyson 1990; Keefe 1995).

These insights can be extended to knowledge-engineering, resulting in high-performance expert systems that serve the needs of experts, relying on and supplementing their skills instead of replacing them. Knowledge in "anthropocentric production systems"—the European equivalent of high performance—is understood to include much more

> which has been left to waste and has not ... been exploited yet: creativity, imagination, flexibility, learning from mistakes and the potential to cope with the unforeseen and deal with contingencies. Many of these qualities cannot be programmed in advance nor elicited by tight procedures of command and control or assigned to strictly prescribed tasks nor conserved

in the software of computerised *(sic)* work (Littek & Charles 1995, 6).

Derived from the results of new manufacturing practices, a high-performance, skill-based understanding of what knowledge is considered relevant and how expert systems are implemented will ensure the long term viability of the knowledge domain.

Entry points for change

To ensure the design of high performance expert systems, which criteria must applied researchers, knowledge engineers, system integrators, and application engineers follow? Given the limitations of technocentric design and the performance advantages of skill-based, participative design, we might ask designers to:

- Focus on process and product quality
- Ensure long-term inputs to the system
- Utilize and augment workers' skills

Referring to Table 1, each of the eight key elements of high performance work systems relates to at least one of these three criteria. The concern for quality relies on a high performance approach, which emphasizes overall organizational performance through both process and product improvements instead of a bias towards reducing costs and increasing individual efficiencies (Table 1, items 1, 2 and 5). To ensure long term inputs to the knowledge domain and end-user system by experienced and skilled users, designers must count elements of organizational culture and workers' knowledge of day-to-day operations as relevant to the knowledge domain. Over the long term, workers need to be trained to perform at expert levels to enable continual innovations (Table 1, items 1, 3, 4, and 7). The high performance expert system utilizes and augments workers' skills by providing diagnostic support and integrating human insights interactively with machine "intelligence" instead of pursuing automatic control with operators only reacting to alarms in a crisis (Table 1, items 1 and 6).

These criteria for high performance design are subject to value orientations and structural incentives beyond the level of individual designers. "The combination of a country's or a firm's economic market, employment practices, education system, legal system, social and engineering values, and other factors shape the way it will organize its production process or, for our purposes, technology design." (Salzman & Rosenthal 1993, 46) A shift in design criteria thus requires not only the participation of individual designers, but also organizational and institutional changes.

Three key institutions that can help the design environment to prioritize high performance criteria over technocentric ones are government, professional societies, and labor unions. Government's role is to help guide technological development by providing public funds and institutions for basic and applied research, among other resources and regulations. Ultimately, however, technologies do not develop autonomously guided by some natural internal logic; and thus government can not merely prod technologies along a single linear trajectory. Although there are significant constraints to social control over technological development[1], choices made by funding agents, researchers, and designers facilitate certain social arrangements and constrain others. Government, as a means for reconciling diverse values and opinions, must make normative assessments of what technologies should be developed and provide a research agenda that supports all of the society's stakeholders.

With this responsibility in mind, top-level policy makers from the federal government have been emphasizing a high performance approach to technological innovation and new work systems. They encourage workers to master knowledge-intensive skills via continual training and education, as a way to help them maintain secure jobs in the global marketplace. In general, they see technical, specialized knowledge as the key to personal, corporate, and national success. Secretary of Labor Robert Reich, for example, sees a promising future for "symbolic analysts," knowledge workers who leverage their value to the globally competitive firm based on problem-solving skills and data analysis. (Reich 1991) In *Technology for America's Economic Growth*, the Clinton administration recognizes that "the new growth industries are knowledge based. They depend on the continuous generation of new technological innovations and the rapid transformation of these innovations into commercial products the world wants to buy. That requires a talented and adaptive workforce capable of using the latest technologies and reaching ever-higher levels of productivity." (Clinton & Gore 1993) These technologies, including knowledge-based systems, can be developed with either technocentric or high performance assumptions. One entry point for change towards the latter is a technology policy for high performance design. (Jarboe & Yudken 1996)

Another significant means for influencing the design context involves designers as professionals. Individually and through professional associations, designers are in a good position to contribute to the high performance agenda

[1]e.g., technological momentum, inherent physical properties of materials and machines, emergent organizational and institutional imperatives, etc. (Clark et al. 1988; Hughes 1983; Winner 1977; Winner 1995)

outlined here—one that includes work organization and the critical judgment of users. By broadening the design problem to include both technical and social processes, individual technical professionals can join other designers from a variety of disciplines to expand their skills. Often, professional societies serve this networking function. They also encourage joint work between, for example, engineering societies and other professional groups, including those from the social sciences and education. Professional associations also often shape educational and training curricula for their members, affecting both eventual and incumbent designers' assumptions. New programs, in interdisciplinary engineering design studies—informed by the participation of engineering professionals and the endorsement of their societies—address the issues of re-training, attracting under-represented students to the field, reducing the effects of artificial disciplinary boundaries, challenging traditional curriculum and accreditation standards, discussing socially relevant issues, and expanding exclusive, linear definitions of design processes. (Schumacher 1995) Reinforcing an expanded view of design through educational change, civic professionalism encourages a high performance orientation to design. According to William Sullivan, author of *Work and Integrity* "the role of professional expertise ... is being redefined away from providing discrete technical interventions. Instead, professionals are giving continuing attention to the institutional and cultural infrastructure needed to sustain a modern society." (1995, 237)

One of these institutions, effective labor unions, provides the necessary resources and structure to help developers meet each of the three design criteria for high performance expert systems: quality, long-term inputs to the knowledge domain and larger manufacturing application, and an emphasis on workers' skill. Unions provide an environment where workers can feel secure enough to critique existing procedures, to contribute to innovations that increase performance. (Table 1, item 8.) With an explicit recognition of the various interests in the workplace, workers and designers will more seemlessly negotiate inevitable disagreements because they will have a reliable, well structured means towards solution. Ex-Secretary of Labor Ray Marshall concurs that if this labor-management dynamic "is good and effective, it is inherently adversarial. In the best of circumstances, both sides have different perspectives and are going to disagree about some things. How high are my wages going to be? Whose going to run things? Disagreement is inevitable and healthy. But a functioning adversarial relationship provides a way to resolve differences." (Marshall 1991, 12)

Equally important for the design context, the union provides a liaison between workers and engineers—a structured process for regular, two-way communication.

Besides providing the structure for processes to run smoothly, unions offer a variety of resources. From a local to international level, through strategic partners and consultants, unions support workers' needs to be effective participants in the design process. They encourage continual learning for workers and increased training and education in both process and technical skills. Unions provide conferences and seminars on workplace technologies and can tap the resources of consultants on workplace change and technology choices and applications.

Finally, labor unions provide a source of stability and long-term commitment that is not always found among managers and other professionals. In many corporations, managers and engineers are rotated from plant to plant as part of the overall business strategy. In contrast, workers and their union representatives are more likely to spend their entire career in one location. They possess an extensive knowledge of the everyday contingencies and interactions. In addition, because their own financial futures are tied to the success of the plant, they are deeply committed to its success.

High Performance Expert Systems and Manufacturing

This paper has identified two viable means for creating expert systems that solve practical problems in manufacturing applications. It has outlined the deficiencies of the technocentric approach to expert system development and highlighted the benefits of pursuing high performance design.

Robert Thomas, an MIT Sloan School of Management scholar on manufacturing and organizational studies, confirms that "the human and social systems that make up organizations ... can be eliminated. That is, work can be automated. Organizational policies can be tightened and more closely monitored. People can be made to go away. But the social costs of unemployed and underemployed people and skills will be quite high ... and ... organizational costs will take the form of a diminished ability to innovate—a risky strategy to pursue in a global economy that demands innovation and change." (Thomas 1994, 247)

Expert system developers must realize, as Dorn has for the steel industry, that "despite even more pervasive automation in the future, human experts will remain unavoidable for production control ..., because new production failures that cannot be handled adequately by a system occur quite regularly." (Dorn 1996, 21) As production operations require the participation and intervention of human experts, expert systems should be

designed to operate interactively with workers and to complement, not replace, their knowledge and experience.

In current manufacturing applications, however, developers of expert systems too easily impart the technocentric perspective that humans are the weak link. In doing so, they limit options for the design of systems using intelligent machines—resulting not only in harm to workers, but also to their firms. In 1988 Shoshana Zuboff published *In the Age of the Smart Machine*, a classic study that highlighted how workers could take advantage of computer-based control technology to contribute productively to the manufacturing process. Zuboff's contribution to the study of work-life quality was to recognize the "informating" capabilities of computer-based programmable logic controllers. She noted correctly that shop-floor technologies of the 1980s, while intensively automating manufacturing processes, actually generated information about the processes they controlled. So, Zuboff suggested that instead of de-skilling workers, managers ought to encourage workers to develop intellective skills—the ability to reason and analyze information.

Although the capabilities of new manufacturing technologies continue to increase—even intellective skills can now be handled by intelligent machines—their implementation is not determined by the force of autonomous technological development. These technologies are consciously developed, with decisions being made throughout the complex product development process. Therefore, Zuboff's lesson for managers and designers is relevant today as well. She outlined the tendency for managers to design programmable logic control technology to reinforce technocentric assumptions. The managers, therefore, sacrificed opportunities for alternative arrangements that were more flexible, productive and able to synthesize the strengths of both humans and machines. Since that time manufacturing managers have begun to recognize the value of high performance skill-based design. In contrast, the technocentric emphasis of current expert systems development suggests that human needs and contributions to the production process may be neglected, threatening future manufacturing productivity and flexibility.

References

Adler, P. S., ed. 1992. *Technology and the future of work.* New York: Oxford University Press.

Appelbaum, E. and Batt, R. 1994. *The new American workplace: Transforming work systems in the United States*. Ithaca, New York: ILR Press.

Chorafas, D. N. 1992. *Expert systems in manufacturing.* New York: Van Nostrand Reinhold Publishers.

Clark, J., McLoughlin, I., Rose, H. and King, R. 1988. *The process of technological change: New technology and social choice in the workplace.* Cambridge: Cambridge University Press.

Clinton, B. and Gore, A. 1993. *Technology for America's economic growth: A new direction to build economic strength.* Washington, D.C.: U.S. Government Printing Office.

Cormier, D. 1994. Comments on the relationship between worker participation and productivity. Paper given at University of Notre Dame Department of Economics Institutions Workshop, October 5. Notre Dame, IN.

Cunningham, A. and Smart, R. 1993. Computer-aided parts estimation. *AI Magazine* 14(3):39-49.

Dorn, J. 1996. Expert Systems in the Steel Industry. *IEEE Expert* 11(1):18-21.

Expert Systems. 1995. Added expert systems. *Expert Systems* 12(1):68.

Forsythe, D. E. 1993. Engineering knowledge: The construction of knowledge in artificial intelligence. *Social Studies of Science* 23(3):445-477.

Forsythe, D. E. and Buchanan , B. G. 1992. Nontechnical problems in knowledge engineering: Implications for project management. *Expert Systems with Applications* 5:203-212.

Hauser, R. D. and Hebert, F. J. 1992. Managerial issues in expert system implementation. *SAM Advanced Management Journal* 57(1):10-15.

Hayes-Roth, F. and Jacobstein, N. 1994. The state of knowledge-based systems. *Communications of the ACM* 37(3):27-39.

Howard, R. and Schneider, L. 1994. Worker participation in technological change: interests, influence, and scope. In *Critical studies in organization and bureaucracy*, ed. by F. Fischer and C. Sirianni, 519-544. Philadelphia: Temple University Press.

Hughes, T., Park. 1983. *Networks of power*. Baltimore, MD: Johns Hopkins.

Jarboe, K. P. and Yudken, J. 1996. Smart workers, smart machines: A technology policy for the 21st century, Washington, D.C.: Work & Technology Institute.

Keefe, J. 1995. The role of transformational union leadership in workplace restructuring, Briefing Paper, 95-01, Washington, D.C.: AFL-CIO Human Resources Development Institute.

Klahr, P. and Byrnes, E. 1993. *Innovative applications of artificial intelligence 5*. Menlo Park, CA: AAAI Press.

Kowalski, A., Bouchard, D., Allen, L., Larin, Y. and Vadas, O. 1993. Pitch expert: A problem-solving system for kraft mills. *AI Magazine* 14(3):81-98.

Levine, D. I. and Tyson, L. D. A. 1990. Participation, productivity, and the firm's environment. In *Paying for productivity*, ed. by A. S. Blinder, 183-243. Washington DC: The Brookings Institution.

Liker, J. K. and Fleischer, M. 1992. Organizational context barriers to DFM. In *Integrating design and manufacturing for competitive advantage*, ed. by G. I. Susman. New York: Oxford University Press.

Littek, W. and Charles, T., eds. 1995. *The new division of labour: Emerging forms of work organization in international perspective.* New York: Walter de Gruyter.

Marshall, R. 1991. The eight key elements of high performance work systems. In Proceedings of High Performance Work and Learning Systems, 3-14. September 26-27. Washington, D.C.: AFL-CIO Human Resources Development Institute.

Potter, E. E. and Ngan, Y. K. 1996. Estimating the potential productivity and real wage effects of employee involvement, Washington DC: Employment Policy Foundation.

Reich, R. B. 1991. *The work of nations*. New York: Vintage Books.

Salzman, H. 1993. Skill-based design: Productivity, learning, and organizational effectiveness. In *Usability: Turning technologies into tools*, ed. by P. S. Adler and T. A. Winograd, 66-95. New York: Oxford University Press.

Salzman, H. and Lund, R. 1995. Engineering principles and production technology: Automation and skill-based design in the US. *International Journal of Vehicle Design* 16(4/5):314-338.

Salzman, H. and Rosenthal, S. R. 1993. *Software by design: Shaping technology and the workplace*. New York: Oxford University Press.

Schumacher, J. A. 1995. Engineering and society: The art of design, Interim Report, EW-20263-94, Troy, NY: Rensselaer Polytechnic Institute.

Sullivan, W. M. 1995. *Work and integrity: The crisis and promise of professionalism in America*. New York: HarberBusiness.

Susman, G. I., ed. 1992. *Integrating design and manufacturing for competitive advantage.* New York: Oxford University Press.

Thomas, R. J. 1994. *What machines can't do: Politics and technology in the industrial enterprise*. Berkeley: University of California Press.

Upton, D. M. 1995. What really makes factories flexible? *Harvard Business Review*.

Winner, L. 1977. *Autonomous technology*. Cambridge, MA: MIT Press.

Winner, L. 1995. The enduring dilemmas of autonomous technique. *Bulletin of Science, Technology, and Society* 15(2-3):67-72.

Zuboff, S. 1988. *In the age of the smart machine: The future of work and power*. Basic Books.