Planware has several types of knowledge, all encoded through parameterized theories. The first is knowledge of the scheduling domain, including the constraints on use of the different types of resources, such as reusable or sharable resources. Another type of knowledge is *algorithm knowledge*, such as generate-and-test, branch-and-bound, divide-and-conquer, dynamic programming, and hill-climbing (*see* ALGORITHMS, DESIGN AND CLASSIFICATION OF). By codifying them as parameterized theories, algorithms can be automatically derived for a given very-high-level problem specification, given appropriate domain axioms. A third type of knowledge is *implementation knowledge*, which defines how higher-level constructs such as sets can be encoded as more implementation-level constructs such as lists or bit-vectors.

All of these tools use advanced knowledge representation and automated reasoning capabilities. Although research tools today, they represent the degree of programming automation that may become commercially available within a decade.

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AUTOMATION

For articles on related subjects *see* AUTOMATA THEORY; COMPUTER-AIDED DESIGN/COMPUTER-AIDED MANUFACTURING; COMPUTER-AIDED ENGINEERING; CONTROL APPLICATIONS; ELECTRONIC OFFICE; MANAGEMENT INFORMATION SYSTEMS; ROBOTICS; and TELEROBOTICS.

Automation is the conversion of a work process, a procedure, or equipment to automatic rather than human operation or control. Automation does not simply transfer human functions to machines, but involves a deep reorganization of the work process, during which both the human and the machine functions are redefined. Early automation relied on mechanical and electromechanical control devices; during the last 40 years, however, the computer gradually became the leading vehicle of automation. Modern automation is usually associated with computerization.

This article examines the major phases of historical development and social and economic aspects of industrial automation, focusing on the computerization of production, engineering, and managerial tasks. Other areas of computer-based automation include administrative applications (*q.v.*), communication via electronic mail (*q.v.*), banking applications, medical applications (*q.v.*), and library automation (*see* DIGITAL LIBRARIES).

Phase I: Mechanization and Rationalization of Labor

The mechanization of machine tools for production began during the Industrial Revolution at the end of the 18th century with the introduction of the Watt steam engine, the Jacquard loom, the lathe, and the screw machine. Mechanization replaced human or animal power with machine power; those mechanisms, however, were not automatic but controlled by factory workers. The factory system, with its large-volume, standardized production, and division of labor, replaced the old work organization, where broadly skilled craftsmen and artisans produced small quantities of diverse products. In the late 19th century Frederick W. Taylor rationalized the factory system by introducing the principles of "scientific management." He viewed the body of each worker as a machine whose movements had to be optimized in order to minimize time required to complete each task and thus increase overall productivity. "Scientific management" strictly separated mental work from manual labor:

workers were not to think but to follow detailed instructions prepared for them by managers. The rationalized factory system gave birth to a new managerial class and large clerical bureaucracies. The Taylorist principles served as a basis for Henry Ford's system of mass production. In 1913 the Ford Motor Company introduced a moving assembly line, drastically cutting assembly time. The assembly line imposed a strict order on production by forcing workers to keep pace with the motion of the conveyor belt. Mass production relied on the standardization of components and final products and routinization of manufacturing and assembly jobs. The Ford assembly line became a symbol of efficiency of American manufacturing; for workers and social critics, however, it epitomized the monotony and relentless pressure of mechanized work.

Phase II: Automation of Production

In 1947 the Ford Company brought the term "automation" into wide circulation by establishing the first Automation Department, charged with designing electromechanical, hydraulic, and pneumatic parts-handling, work-feeding, and work-removing mechanisms to connect standalone machines and increase the rate of production. In 1950 Ford put into operation the first "automated" engine plant. Although early automation was "hard," or fixed in the hardware, and did not involve automatic feedback control, this concept provoked great public enthusiasm for "unmanned factories" controlled by "buttons that push themselves," as well as causing growing concern about the prospects of mass unemployment.

To meet US Air Force demands for a high-performance fighter aircraft whose complex structural members could not be manufactured by traditional machining methods, a technology of Numerical Control (NC) of machine tools was developed in the early 1950s. NC laid foundation for programmable, or "soft," automation, in which the sequence of processing operations was not fixed but could be changed for each new product style. Commercial NC machines for batch production appeared in the mid-1950s. Designed to military specifications, early NC equipment proved too complex and therefore unreliable, as well as prohibitively expensive, and was applied mostly in the state-subsidized aircraft industry.

The abstract, formal approach of NC, based on mathematical modeling of the machining process, superseded the record–playback technique of direct machine imitation of workers' actions. While the record–playback approach relied on the skill and discretion of the worker, NC technology allowed engineers and managers to exercise greater control over the production process.

Phase III: Computer-Aided Manufacturing (CAM)

The first industrial applications of digital computers occurred in the electrical power, dairy, chemical, and petroleum refinery industries for automatic process control. In 1959, TRW installed the first digital computer designed specifically for plant process control at Texaco's Port Arthur refinery. Early applications were open-loop control systems: gathering data from measuring devices and sensors throughout the plant, the computers monitored technological processes, performed calculations, and printed out "operator guides"; subsequent adjustments were made by human operators. In the 1960s closed-loop feedback control systems appeared. These computers were connected directly to servo-control valves and made adjustments automatically (*see* CYBERNETICS).

In the late 1960s, with the development of time sharing (*q.v.*) on large mainframe computers (*q.v.*), standalone NC machines were brought under Direct Numerical Control (DNC) of a central computer. DNC systems proved vulnerable to frequent failures due to malfunctioning of the central computer and the interference of factory power cables with the data transmission cables of the DNC system.

With the introduction of microprocessors (*q.v.*) in the 1970s, centralized DNC systems in manufacturing were largely replaced by Computer Numerical Control (CNC) systems with distributed control, in which each NC machine was controlled by its own microcomputer. This blending of information and production technologies produced a new breed of machinist-programmer who could operate CNC equipment by generating and debugging NC programs, thus breaking down the traditional distinction between white-collar and blue-collar jobs.

Robotics combined the techniques of NC and remote control to replace human workers with numerically controlled mechanical manipulators. The first commercial robots appeared in the early 1960s. Robots proved very efficient in performing specialized tasks that demanded high precision or had to be done in hazardous environments. To approach the human level of flexibility, robots were supplied with sophisticated techniques of feedback, vision and tactile sensors, reasoning capabilities, and adaptive control. In the 1980s industrial applications of robots slowed down, as their increasing complexity resulted in growing costs and insufficient reliability.

Hierarchical Numerical Control Systems combined DNC and CNC features: they linked each standalone computer controller to a central computer that maintained a large library of CNC programs and monitored production. This approach aspired to replace the human operator's expertise by engineering knowledge formalized in CNC programs. In such systems, human operators generally no longer programmed CNC equipment on the shop floor, and production was brought under remote supervision of a central management-controlled computer.

Flexible Manufacturing Systems (FMS) combined DNC equipment with machines for automated loading, unloading, and transfer of workpieces. These systems permitted varying process routes and sequences of operations, allowing automatic machining of different products in small batches in the same system. Centralized FMS have often proved too complex, however, and they are increasingly subdivided into smaller flexible manufacturing cells (FMC) that include several CNC machines, robots, and transfer devices controlled by a single computer, the "cell controller."

Phase IV: Automated Engineering

In the 1960s large aerospace manufacturers, such as McDonnell-Douglas and Boeing, developed proprietary computer-aided design (CAD) systems, which provided computer graphics (*q.v.*) tools for drafting, analyzing, and modifying aircraft designs. In 1970 Computer-Vision Corporation introduced the first complete turnkey commercial CAD system for industrial designers, which provided all the necessary hardware and software in one package. In the 1970s, combined CAD/CAM systems emerged which used the parameters of a geometrical model created with the help of CAD to generate programs for CNC machine tools and develop manufacturing plans and schedules. While CAD systems are often packaged and standardized, CAM (Computer-Aided Manufacturing) applications tend to be industry-specific and proprietary. With the introduction of Computer-Aided Engineering (CAE) systems for standard techniques of engineering analysis, the whole range of engineering tasks—from conceptual design to analysis to detailed design to drafting and documentation to manufacturing design—became automated. The distinction between blue-collar and white-collar jobs was further blurred, as engineers, clerks, and managers became integrated in an automated office.

Phase V: Automated Management

Among the earliest applications of information technology was the automation of information-processing tasks. The first stored-program digital computer purchased by a nongovernment customer was UNIVAC (*q.v.*), installed by GE in 1954 to automate basic transaction processing: payroll, inventory control and material scheduling, billing and order service, and general cost accounting. Large clerical bureaucracies, which processed huge amounts of data generated in mass production and mass marketing, became a primary target of automation and job reduction in the 1960s and 1970s. By 1970 the profession of bookkeeper was almost completely eliminated in the USA. In the mid-1960s the first management-information systems (MIS) appeared, providing management with data, models of analysis, and algorithms for decision-making; eventually they became a standard tool for operation control, management control, and strategic planning.

Phase VI: Computer-Integrated Manufacturing (CIM)

In the late 1980s an integration of the automated factory and the electronic office (*q.v.*) began. CIM combines flexible automation (robots, numerically controlled machines, and flexible manufacturing systems), CAD/CAM systems, and management-information systems to build integrated production systems that cover the complete operations of a manufacturing firm, including purchasing, logistics, maintenance, engineering, and business operations. CIM emphasizes horizontal links between different organizational units of a firm and provides the possibility of sharing data and computing resources, making it possible to break the traditional institutional barriers between departments and create flexible functional groups to perform tasks more speedily and efficiently.

Social and Economic Dimensions of Automation

Views of automation range between two extremes—unabashed optimism and utmost pessimism. The optimists believe in a technological utopia, an imagined bright future in which machines will relieve people of all hard work and bring prosperity to humankind. The pessimists view machines as instruments of subjugation and control by a ruling elite, argue that automation leads to the degradation of human beings, and depict the future as a grim technological dystopia. Both sides view automatic technology as an autonomous force determining the direction of human history. Automation itself, however, is a social process shaped by various social and economic forces. This process may take various directions and may have diverse consequences depending on the socioeconomic and organizational choices made during automation.

The Productivity Paradox

While productivity in major industries in the USA rose sharply during production automation in the 1950s and 60s, its growth has slowed significantly since the 1970s, precisely at the time of widespread computerization of the factory and the office. The link between computerization and productivity remains problematic. The advantages most commonly associated with computer-aided manufacturing include increased production rates, better product quality, more efficient use of materials, shorter lead times, reduced work hours, and improved work safety—all factors leading to higher productivity. Among its main disadvantages, analysts usually cite the high cost of designing, building, and maintaining computerized equipment; vulnerability to downtime; relatively low flexibility compared with humans; and worker displacement and emotional stress—all leading to lower productivity. It is particularly difficult to compare directly productivity before and after computerization, since it brings with it not merely technological, but also organizational change which transforms the entire nature of production and brings with it the most benefits and losses.

As manufacturers who introduced computer-aided manufacturing systems affirm, the largest payoff from computerization comes not from speeding up old operations but from making work organization more flexible and efficient. On the other hand, if computers are used to conserve old inefficient organization, computerization can only accelerate negative trends. As John Bessant has remarked, "When you put a computer into a chaotic factory the only thing you get is computerized chaos" (quoted in Ayres, 1991–1992, Vol. 4, p. 94). Most successful manufacturers streamline operations before computerization, following the dictum, "Simplify, then automate!" Efficient computerization takes far more than merely installing a computer: it requires changes in the entire workstyle.

Worker Displacement, Skill, and Working Conditions

A leading concern among workers, labor leaders, and social critics has been the issue of worker displacement—a loss of work, transfer to a different job, or geographic dislocation—due to automation. Such categories as welders, carpenters, insulators, machinists, and clerical staff have been most heavily affected. At the same time, automation creates new highly-skilled jobs in programming, operating, and maintaining computerized production machinery. Workers need extensive retraining programs, however, to prepare for such jobs.

Another risk is the danger of employees losing essential working skills as work becomes increasingly mediated by the computer. With automation, the worker has gone through a series of transformations—from a direct producer of goods and services to the operator of production equipment to the programmer of the computer that operates and controls that equipment. Engineering changed from hands-on tinkering with machinery to the use of standard design and analysis procedures that tell the computer how to design and build a needed part. Management evolved from direct supervision of labor to "management by numbers," based on numerical data reports and pre-programmed computer algorithms for decision-making. When operators must step in and take control in case of an emergency at an automatically controlled nuclear power plant, would they possess the necessary skills if their training and daily experience mainly concerned work with a computerized control system?

Because of the high cost of downtime, efficient maintenance and fast repairs become crucial in automated production, which places a great burden of responsibility and tight time constraints on maintenance and repair crews. Computerized equipment can be used to enhance the flexibility of work organization, leaving one in charge of planning one's work time, but it may also be used to impose a strict and inflexible work regime on factory and office workers by closely monitoring their performance. As a result, automation can make work either easier or more exhausting and stressful, depending on the type of work organization.

Technocentric vs. Human-Centered Approaches

Historically the predominant approach to automation has been technocentric: a goal of automation is to reduce and ultimately entirely eliminate human participation in production and eventually arrive at an unmanned factory. From this standpoint, workers are seen as a source of potential errors, disturbance, and unreliability; on the other hand, automatic machinery is viewed as inherently more precise, reliable, and controllable. The technocentric approach extends the principles of Taylorist work organization to modern information-processing and production systems. It is based on further subdivision of labor, with more complex and intelligent tasks trusted to flexible computer systems and simpler tasks left to low-skilled workers who assume a residual role. Skill gradually passes from people to machines, and control functions are also transferred in the same direction.

The technocentric approach faces a fundamental paradox: it aspires to replace human skill with highly flexible computerized machinery, but this machinery requires even more human skill to operate, maintain, and repair it. Instead of "freeing" production from the "human element," automation only increases the importance of highly qualified, versatile, and motivated workers. Accidents at the nuclear power plants at Three Mile Island and Chernobyl testify that automation does not eliminate the possibility of human error; it only makes this error more costly.

The Taylorist logic of seeking productivity by accelerating the pace of work may not apply in a computerized workplace. With computerization, companies do not simply automate, but "informate" their operations. Computer-based control of production becomes an information-processing task; workers turn into analyzers of information rather than simple machine minders. Improving the quality of this analysis, instead of speeding up workers' movements, becomes a crucial problem of automation.

An alternative approach aspires to change the workforce from being part of the manufacturing problem into part of the solution. Instead of taking skills, responsibility, and control away from the worker and absorbing them into the machine, human-centered CIM systems mobilize the intellectual resources of all employees. Leading Japanese companies, such as Matsushita and Toyota, achieved much greater productivity gains from automation than their American competitors by decentralizing control and reorganizing the factory layout into production islands controlled by semi-autonomous multi-skilled teams responsible for all operations. Reversing the Taylorist trend of subdivision of labor, the human-centered approach integrates functions and skills in flexible teams, where workers can rotate jobs and choose the optimal order and pace of work. Instead of being forced to follow instructions handed to them from above, workers are motivated to play a greater role in decision-making by programming CNC equipment on the shop floor. In the late 1960s and early 1970s only a handful of American companies, such as Procter & Gamble, Cummins Engine, and Gaines Foods, realized that greater productivity did not come automatically with more sophisticated equipment but required profound organizational change. In 1974 Volvo built a highly productive plant at Kalmar, Sweden, which implemented the "sociotechnical systems" approach, elaborated in Britain. Based on group assembly instead of a conventional assembly line, this new design gave workers more initiative, flexibility, and control over product quality. In the 1980s major American manufacturers began experimenting with worker involvement in decision-making, a recent example being GM's Saturn project. The human-centered approach finds a source of productivity in more efficient utilization of human abilities, rather than in the utopian efforts to eliminate people from production.

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AUXILIARY MEMORY

See MEMORY: AUXILIARY.