Proceedings of ICOOMS’92: International Conference on Object-Oriented Manufacturing. pp. 19-36. Calgary, 1992

Manufacturing in the Knowledge Economy

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Manufacturing as a process of fabrication is normally considered part of the industrial sector of the economy and not part of the post-industrial, or knowledge, sector. However, the knowledge economy is critically dependent on modern manufacturing technology for its existence, and modern manufacturing has come into being as a result of developments in information technologies. This presentation analyzes manufacturing as a knowledge science in which ‘knowledge’ is applied to raw materials or components to produce a product, and in which, increasingly, the knowledge is itself subject to automatic processing. This formulation allows the science of manufacturing to be extended to encompass corporate, market and socio-economic issues within a unified framework. It also leads to an analysis of the significance for manufacturing of the knowledge level in software engineering and, in particular, of the impact of the conceptual control of information, its communication and processing through object oriented methodologies. Finally, in terms of future perspectives, the impact and importance of adopting a manufacturing ethos in the overall development of the knowledge sector, and general human knowledge processes, are highlighted.

1 Introduction

This paper sets the scene for analyzing the foundations of object oriented technologies and their roles in computer-integrated manufacturing. The primary significance of object oriented software engineering, user interfaces, system communications and knowledge representation, is analyzed to be in allowing *conceptual models*, natural to people, to be used directly to design, integrate, apply and manage manufacturing technology. The need for powerful and flexible control that simply and directly implements human ideas at a high level is itself analyzed to arise from social trends in a post-modern, post-industrial economy. As large-scale usage of people as manufacturing system components declines, the need to emulate the skills of those people through information technology increases. As the sourcing of manufactures is increasingly treated as a global enterprise, any particular manufacturing unit has not only to compete on a world-wide basis but also to be able respond flexibly to new market opportunities and to the loss of competitive advantage in particular product lines.

There has been no ‘revolution’ in the nature of manufacturing—the basics remain the same—but the long-term *evolution* towards lowered costs, improved quality and increased flexibility through total automation has entered a new phase. The gap between concept and market has narrowed to an extent that the pressures on design, engineering, manufacturing and distribution are now immense. There is no margin for error and no time for experiments. Decisions have to be taken rapidly with high information input and the minimal intrinsic uncertainties. They have to be implemented rapidly and effectively with the minimal necessary risk. These are not new considerations in manufacturing, but they are now dominant and inescapable.

We are all aware that there have been major changes in the production process through the introduction of computer control, robotics and integrated communications (Goldhar and Schlie, 1991a, 1991b). Computer integrated manufacturing and the introduction of knowledge-based systems throughout the manufacturing system are major themes at many conferences. However, the way ahead is by no means clear. Many companies have had poor returns from robotics, both as users and as suppliers. The introduction of flexible manufacturing techniques has created the potential for cost-effectiveness in short run manufacturing, but also generated major problems of management (Kim, 1991a). Whereas the direct labor demands of the new manufacturing techniques are low, the indirect labor demands on those managing the new technology have greatly increased. Total integration, with the new systems increasingly managing themselves, seems the answer (Editorial, 1990a, 1990b). Yet, it is not clear that we know enough, and have adequate knowledge-based technologies, to achieve that degree of integration.

In response to these problems, Francis and Akeel have posed the challenge of generating a new *science of manufacturing*, noting that for “competitiveness in manufacturing, fundamental and interrelated issues of strategy, integration, and production must be addressed” (Francis, 1986), and “what is wanted is a new science of manufacturing that integrates technology, management and economics” (Akeel, 1986). Information technology in general, and object oriented technologies in particular, provide only part of the basis for such a science. However, it is a necessary and vital part that has itself to satisfy the requirements for quality, flexibility, low cost and ease of understanding placed upon manufacturing as a whole. It is also a complex part since the roles of object oriented conceptual design range from software engineering for the control of equipment to knowledge modeling for the total enterprise. The management of this complexity, its partitioning to achieve effective control, and its integration to avoid inefficiencies, involves significant new skills that we are now acquiring, and to which this conference contributes.

This overall objective of this paper is to present trends in manufacturing as a major instance of the development of a post-modern *knowledge science* in which presuppositions, models and techniques are made completely overt and thus become *operational* through information technology. A “new” science of manufacturing will not be radically different in content, but it will be radically different in representation and completeness of overt detail. It will close the gap between concept and market because operational concepts can be translated automatically into physical reality. It will extend to all processes of fabrication and production including biotechnology, software and knowledge manufacturing. It will be “new” because it is an integral part of a new phase of development of our society, but it will also be “old” as a logical continuation of the long-term evolution of manufacturing.

The next section gives a brief overview of some of the post-modern, post-industrial socio-economic trends influencing manufacturing. The following section examines the infrastructure of information technology and its role in manufacturing. The next section analyzes the role of information technology at every level of a manufacturing enterprise. The following sections restructure this analysis in terms of protocols and models, and analyze the roles of different types of object oriented technology in this structure. The final section discusses the role of manufacturing science in developing information industries of biotechnology, software and knowledge itself.

2 Post-Modern, Post-Industrial Society

It is now commonplace to talk in terms of a *new era* of manufacturing (Compton, 1988) associated with automation, flexibility, information technology and the need to compete in a global economy. However, historically, every period of manufacturing has been a “new era” (Kogane, 1985), generating innovative technology in response to social needs and continually changing the infrastructure of manufacturing, at both the physical and knowledge levels. It is the essence of our civilization’s increasing needs for, and increasing capabilities to exert control over our physical environment (Beninger, 1986) that technology is in a constant state of change. Innovation and the inexorable growing obsolescence of all that we have and know have been the essence of all manufacturing environments throughout the ages. The cost-benefit trade-offs of substituting new materials and processes, under uncertainties of market demand and competitive pressures, have formed the context in which manufacturing skills have been situated, developed and tested throughout the history of our civilization.

However, we are now in a time of social change in general that is far more profound than any technological attributes through which we may distinguish modern manufacturing. The so-called *modern* era (Habermas, 1985; Heller, 1990) commenced with the European enlightenment of the seventeenth century, and is characterized by its emphasis on the untrammeled freedom of inquiry of the human mind, giving rise to the growth in science and technology of the past three hundred years. This growth has now achieved one fundamental objective for a significant proportion of the human population in the developed world—that of having an adequate supply of the basic necessities of life for that population without involving them in the labor of generating that supply. The basic needs of human life for food, shelter, energy and security, the two lowest levels of Maslow's "hierarchy" (Lederer, 1980), are fundamental to existence, and their satisfaction on a robust and cost-effective basis has been a major objective of research in science and technology (Bijker, Hughes and Pinch, 1989). The automation of food production was a first phase, and the automation of manufacturing is a second phase, in the achievement of this objective.

The socio-economic system is truly a "system" in that it evolves as a whole (Nelson and Winter, 1982), and it only when we pull it apart from different perspectives that "causes" and "effects" appear. From one perspective, human labor has priced itself out of manufacturing—people are too expensive to use as manual operators when processes can be automated. If we see industrial employment as a way of redistributing resources this has negative social consequences—unemployment "caused by" technological advance. If we look at this from the more fundamental perspective of the preceding paragraph, the same phenomenon is evidence that we are achieving basic social objectives. Our society has to readjust its mechanisms for redistributing resources (Erikson and Vallas, 1990), and not attempt to propagate a system that unnecessarily forces people into the service of machines.

Thus, what is fundamentally different about the current era of manufacturing commencing in the 1970s is the detachment of "manufacturing" as a process of fabrication from "industry" as the basis of "employment" in our society (Gershuny, 1978). The economic phenomena involved are fundamentally simple. Manufacturing industry has become associated with three distinct socio-economic processes:

1 The satisfaction of needs for manufactured goods.
2 The accumulation of wealth through the sale of these goods.
3 The distribution of resources through employment in the manufacturing sector.

It is this third process that most of all characterizes what is often termed "industrial society" as documented by such writers as Toffler (1980)—that is, a society in which the demands for human labor in manufacturing industry dominate the overall socio-economic infrastructure.

However, as we move into the post-industrial, post-modern era, it is only the third process that is changing radically. Employment in the manufacturing sector is declining and the skills required are changing dramatically. The first process, of satisfying needs, clearly remains and no-one would expect it to decline—we are no more in a 'post-manufacturing' era than we are in a 'post-food production' era (Cohen and Zysman, 1987). The second process, of accumulating wealth, is also significant if the manufacturing sector is to remain entrepreneurial and innovative as part of the free-market economy, and not become a *public good* requiring governmental control and funding through a general levy based on taxation.

The move towards a *knowledge economy* (Machlup, 1980) is a natural stage in the evolution of post-industrial society. As people come to play less of a direct role in supplying the fundamental needs of society, their physical labor may be replaced with physical machinery, but their sensory and cognitive capabilities also need emulation. As information technology is developed to support this substitution it necessarily moves from providing basic data processing to the emulation of the higher processes that we associate with human knowledge. The infrastructure of resources, education, research, development, and software and knowledge manufacturing necessary to provide a basis for this substitution itself involves large-scale socio-economic change that we associate with the knowledge economy.

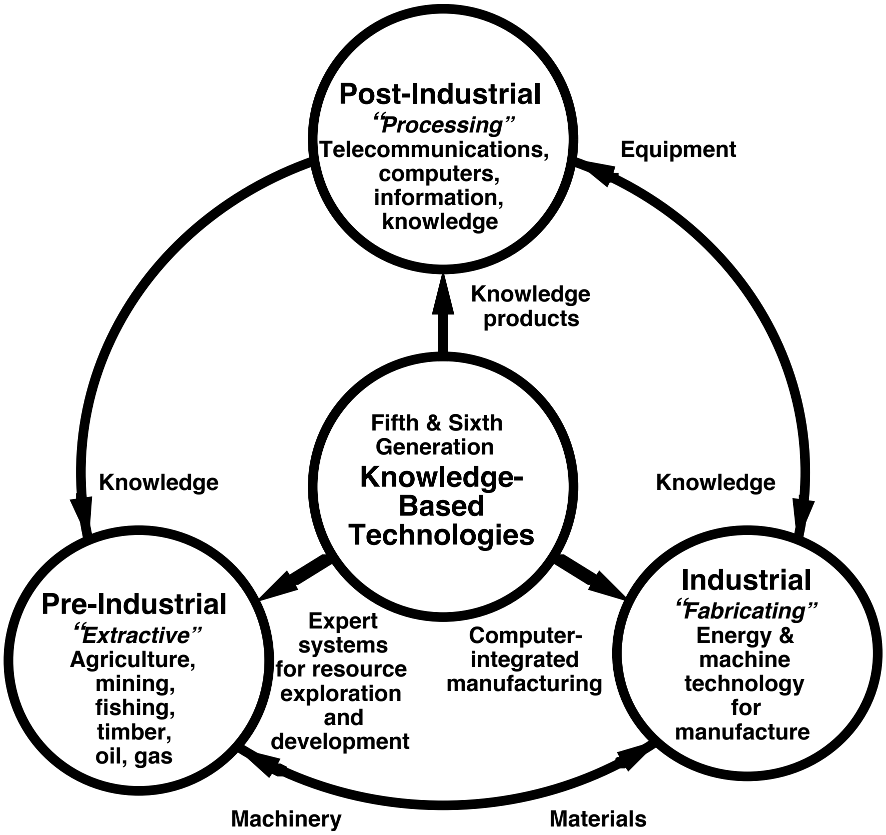


Figure 1 Relations between pre-industrial, industrial and post-industrial sectors

Figure 1 shows Bell's (1973) three sectors model of the structure of our economy drawn in such a way as to show the mutual support between sectors and the overall significance of knowledge-based technologies. The automation of the pre-industrial, extractive sector was made possible by machinery from the industrial, fabricating sector, and in turn supplies material to the industrial sector. The automation of the industrial sector was made possible by information technology from the post-industrial, processing sector, and in turn supplies equipment to the post-industrial sector. Knowledge-based information technologies are already supporting improved efficiency and quality in every sector. For example, genetic engineering which is itself very much an information technology (Gaines and Shaw, 1986c) is making major changes in agriculture, and agricultural research continues to grow as direct employment in that sector continues to fall (Dinar, 1991; Parayil, 1991). Obviously, the exchange relations between sectors do not tell the whole story. The industrial sector provides products that are highly significant and do not relate to the other sectors. The post-industrial sector provides products that are part of new knowledge markets not involving physical goods.

These socio-economic fundamentals may seem far removed from the technical issues of object oriented approaches to computer-integrated manufacturing that are the theme of this conference. However, it is important to remember that what we see as major technical changes in information technology in manufacturing are not occurring in isolation and are not autonomous. They reflect deeper changes in information technology in general that themselves derive from even deeper processes of social and economic change. In evaluating the new technology we may do much within the framework of the cost-benefit structure of particular manufacturing processes and requirements.

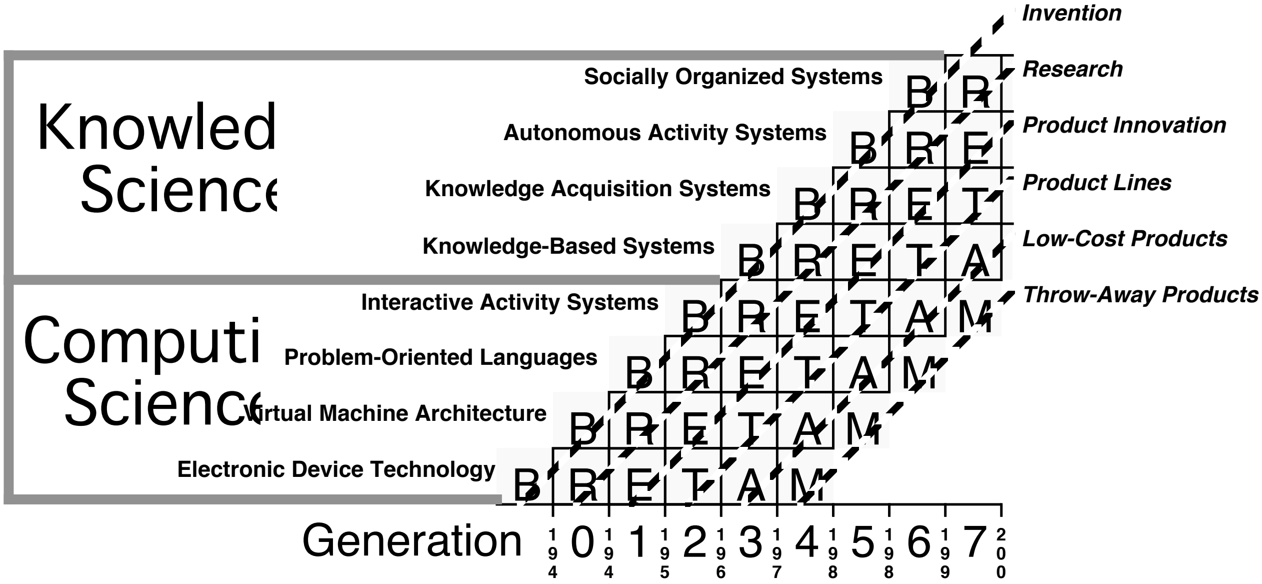
When we examine some aspects of the new technology, however, such as the capabilities for on-line enterprise modeling and integration by electronic data interchange (EDI) between customer and supplier (Baker, 1989), the need to understand much wider issues rapidly becomes apparent. It is organizations who can use the new information and manufacturing technologies to long-term competitive advantage in a rapidly changing, new and unfamiliar post-industrial and post-modern world who will continue to survive (Strassman, 1985; Meyer and Boone, 1989; Porter, 1990; Morton, 1991) and, more importantly, continue to serve the basic needs of humanity.

3 Trends in Information Technology

A foundational perspective on trends in information technology may be gained by examining the *learning curves* that characterize innovation and diffusion in all technologies and determine the dynamics of technological substitution (Ayres, 1968; Marchetti, 1980). Logistic curves have been found to be a useful model of the introduction of new knowledge, technology or product in which growth takes off slowly, begins to climb rapidly and then slows down as whatever was introduced has been assimilated. Such curves arise in many different disciplines such as education, ecology, economics, marketing and technological forecasting (Dujin, 1983; Stoneman, 1983). From the learning curves for information technology it should be possible to determine the state of the technology in relation to manufacturing requirements during the present and coming generations of the technology.

It has also been noted in many disciplines that the qualitative phenomena during the growth of the logistic curve vary from stage to stage (Crane, 1972; De Mey, 1982; Gaines and Shaw, 1986c). The era before the learning curve takes off, when too little is known for planned progress, is that of the inventor having very little chance of success. When an inventor makes a *breakthrough*, very rapidly his or her work is *replicated* at research institutions world-wide. The experience gained in this way leads to *empirical* design rules with very little foundation except previous successes and failures. However, as enough empirical experience is gained it becomes possible to inductively model the basis of success and failure and develop *theories*. This transition from empiricism to theory corresponds to the maximum slope of the logistic learning curve. The theoretical models make it possible to *automate* the scientific data gathering and analysis and associated manufacturing processes. Once automation has been put in place effort can focus on cost reduction and quality improvements in what has become a *mature* technology.

The fast, sustained, learning curve for electronic devices, and the scope for positive feedback in the information sciences, together result in a tiered infrastructure for the information sciences and technologies which is fundamental to their nature (Gaines, 1990a, 1991). It involves a succession of learning curves as rapid advances in one level of technology trigger off invention in others as shown in Figure 2. Advances in digital *electronic device technology* in the 1930s allowed the *virtual machine architecture* that detached computing from electronics to be developed in the late 1940s. This in turn triggered off developments in *problem orientated languages* in the 1950s, and the increasing reliability of computers enabled *interactive activity systems* to be developed in the 1960s. It is this last development that supports digital communications, interactive systems and networking and is most critical to the integration aspects of computer-integrated manufacturing. The development of the manufacturing automation protocol (MAP) as a standard during this period illustrates the direct impact on manufacturing (Jones, 1988).



- **Breakthrough: creative advance made**
- **Replication period: experience gained by mimicing breakthrough**
- **Empirical period: design rules formulated from experience**
- **Theoretical period: underlying theories formulated and tested**
- **Automation period: theories predict experience & generate rules**
- **Maturity: theories become assimilated and used routinely**

Figure 2 Learning curves in the infrastructure of the information technology

A major transition from information technology to knowledge technology took place in the 1970s with the advent of *knowledge-based systems*, and this in its turn has stimulated research in *knowledge acquisition systems*, *autonomous activity systems*, and *socially organized systems*. This research on the computer processing of knowledge, as contrasted with its digitization, communication and delivery, is not critical to the basic engineering of computer-integrated manufacturing systems. However, it may be expected to have a major impact on the evolving role of computers in emulating high-level human skills, and in further integration of manufacturing with other corporate activities through enterprise modeling. Such developments belong to the new era of knowledge science that focuses more on the purpose of computer-based activities than on the underlying technologies of hardware, software, communications and human-computer interfaces.

One important factor in the application of information technology in manufacturing that is apparent in Figure 2 is that there is a significant time interval between inventions and product innovation based on them. This seems to be remarkably constant at about sixteen to seventeen years across diverse areas of technology (Mensch, 1975). In terms of the learning curves this interval corresponds to the *replication/empirical* periods when the technology is first being investigated. There is a corresponding interval during the *theory/automation* periods before products become mature, and automated mass-production at low cost is feasible. The resultant trajectories of *invention*, *research*, *product innovation*, *product lines*, *low-cost products* and *throw-away products* where replacement is cheaper than maintenance are shown superimposed on Figure 2. It becomes reasonable for pioneering applications to experiment with the new technology during the product innovation era, but it is not until low-cost products become available that widespread use will become common, and it is the mature technology of throw-away products that becomes used routinely as the expected mode of operation.

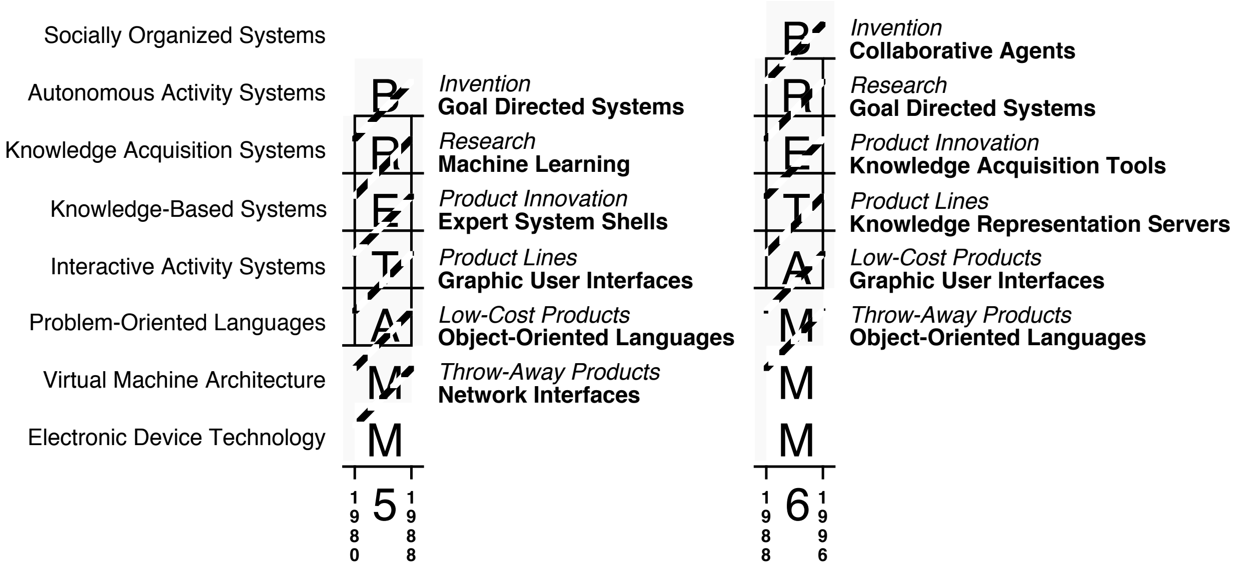


Figure 3 Significant technologies in the fifth and sixth generations

Figure 3 left shows the cross section of Figure 2 that is relevant to the state of the art in information technologies during the previous, fifth generation of computers. The top three levels on the right of invention, research and innovation show why the fifth generation is generally recognized for its innovations in artificial intelligence (Moto-oka, 1982; Gaines, 1984). It was during this period that knowledge-based system products such as expert system shells first became available. However, in terms of reliance upon proven technology, it is the lower levels of product lines and below that are significant. The fifth generation was that in which human-computer interaction was dramatically improved through *graphic users interfaces*, *object oriented languages* brought control of complex system development in software engineering, and *networking* became ubiquitous. All these innovations took for granted advances in the underlying device technology that offered very fast powerful and reliable processors and large high-speed memories at low-cost.

Figure 3 right shows the equivalent picture of what is happening now as we progress through the sixth generation of computers. Hardware and networking have become almost negligible in cost and almost indefinitely powerful. Large-scale distributed systems are becoming readily available in terms of equipment and hardware architectures. Object oriented languages, and their associated application programming support environments (APSEs) and class libraries, are becoming routinely available at very low-cost. Graphic user interfaces (GUIs) are become standardized and portable across platforms as a routinely available technology. By the end of this generation the lowest level of knowledge-based system technology will have become available as well-supported product lines. These will support large-scale conceptual modeling at the enterprise level, the integration of heterogeneous information and processes at lower levels, and the emulation of many aspects of human skilled behavior. Whether they are called "object oriented deductive databases," "second generation expert system shells," or "knowledge representation servers," or something completely different, is a matter for fashion, chaos theory, linguistics and marketing, to determine—we can already define their functionality and exhibit their application and that is enough.

4 Integrated Information Systems

As the base level computer technologies all approach maturity in the infrastructure of Figure 2, we have entered an era of *system integration* in which the dominant theme in information systems development is the integration of diverse technologies into unified systems. In the late 1960s suppliers of computer-based information systems found it necessary to form separate system integration divisions to cope with the complexities of hardware and software interaction and integration. The informal activities of such divisions have grown to become major cost centers, and it is no longer possible to treat system integration as a fairly informal customization stage in system production. This has focused developmental effort on system integration as a major technology in its own right. In the 1980s integration became the primary developmental thrust in all areas, and at all levels, of information systems:

- For personal computer applications it is the integration of spread-sheets, word processors, databases and telecommunications in packages such as *Works* and *Jazz*, or through environments such as that of the Macintosh and *Windows* (Gordon, 1984).
- For data processing it is the integration of all records within an organization into a uniformly structured database at the core of all applications (Nolan, 1983; Sagawa, 1990).
- For network technology it is the integration of diverse services on a broad-band carrier, such as a fibre-optic link, to provide integrated service digital networks (Bartee, 1986).
- For network applications it is the integration of diverse multiple sub-systems within a single networking framework through protocols such as MAP (General Motors, 1984), TOP (Boeing, 1985) and MIB (Leopold, 1986).
- For frontiers computer research it is the integration of the fourth generation technologies of databases, distributed systems and supercomputers, together with the fifth generation technologies of pattern recognition, artificial intelligence and expert systems, to provide a new generation of knowledge-based systems (Moto-oka, 1982; Gaines, 1984).

- For frontiers information science research it is the integration of the multiple disciplines of knowledge processing—philosophy, neurology, psychology, linguistics, anthropology and sociology—to provide new foundations for knowledge science (STA, 1985; Gaines, 1986c).

As usual in the development of new technologies, however, the thrust towards integrated systems, while solving old problems also creates new ones:

- First, the overall complexity of the total system after integration can be very high. This is, of course, the objective—to design, develop and implement complex systems by integrating a number of simpler ones. Success in such an approach to system design is critically dependent on decoupling the system layers—only the functionality of the lower levels must be relevant to the upper levels—consideration of their implementation and operation should be irrelevant to the system design. However, this decoupling is not easily achieved—it becomes the major, and most problematic, design objective.
- Second, the problems of designing complex systems are exacerbated if the components include not only hardware and software but also people. The liveware component may be designed in part by selection and training but there remains a massive residual uncertainty about its functionality and performance that conventionally requires human "management." The integration of people and the associated management processes into large-scale integrated systems presents major new problems. In particular, the management structures already in place are unlikely to be appropriate to the overall integrated system. Major changes in organizational structure and corporate culture will generally be necessary to the effective implementation and operation of large-scale integrated systems.
- Third, the classic approach to the design of complex systems is based on homogeneous system concepts—that the overall system is designed as a set of related components developed with mutual interaction in mind. Heterogeneity may be introduced in the design of such systems, but its introduction is a design decision made in the light of overall system functioning, not a result of the fairly anarchical evolution of systems not originally intended to be integrated. However, we have to face the problem in large-scale heterogeneous systems that they have not been 'designed', and that large parts of the systems created by our attempts at integration are anarchical. We cannot 'homogenize' such systems but we still need some overall conceptual model that is sufficiently homogeneous, at least in the facilities the model offers us, for us to manage them.

Fortunately, the advances in technology that have created these problems also bring with them the means of solution. Object oriented languages and associated systems provide a technology suited to modeling the diversity and complexity of integrated heterogeneous systems (Gaines, 1990b; Dilts and Wu, 1991). The model can encompass as much detail as required to capture the important features of the system. The operational form of the model makes it possible to simulate system behavior at various levels of detail. The high-level representation makes it possible to use the model to aid designers and advise users. There are major problems in keeping the model up-to-date which place important constraints on the implementation and application of such knowledge-based systems. However, these constraints are intrinsic to the operation of heterogeneous systems, and the modeling approach throws light on the fundamental problems.

5 Enterprise Information Systems

Integrated manufacturing systems are an instance of the application of large-scale integrated systems to support the total operations of large organizations. Figure 4 shows the information systems in a modern production unit using computer integrated manufacturing techniques. The outer ring comprises eight basic information technologies that together support the manufacturing system and its interface to the factory and business world. The center shows the firm itself with its corporate structure, and the rings surrounding it show the human interfaces and communication protocols necessary for the systems' management and integrated operation. The figure has been simplified to the minimum structure necessary to support an effective integrated manufacturing system, and the residual complexity shows the need to consider the total context of the information technology involved. Such a system will not necessarily succeed if any one component, or even several, are advanced state-of-the-art technologies. However, it will probably fail if one component is inadequate or the total system is not well-integrated.

The Firm

The central core is the non-technology part of the system, the people that manage and operate the plant, their organization and value systems. The overt operation of the integrated manufacturing system is part of the *technical culture* of the firm in Hall's (1959) terms. It can be communicated, documented and partially programmed. It can also be changed fairly readily in response to new requirements, techniques and technologies. The management structure of the firm is part of its *formal culture*. Only part of it is overt and documented and it is resistant to change. What has come to be called the "corporate culture" (Deal and Kennedy, 1982) is in Hall's terms the *informal culture* of the firm. It pervades the organization, is communicated by example, rarely documented, and changes only slowly or under pressures of survival.

The managerial structures and social processes of the firm are not normally treated as part of its information technology. However, it is possible to develop socio-cognitive models of organizations that encompass both the people and the information technology supporting them (Gaines and Shaw, 1986c). In particular, in order to be successful the technical systems must be consistent with the organizational structures and processes (Wall, Clegg and Kemp, 1987; Majchrzak, 1988; Bolwijn, Boorsma, Breukelen, Brinkman and Kumpe, 1989; Corbett, Rasmussen and Rauner, 1991). This applies particularly to inter-personal communications where computer networks will not be used if they violate the managerial and social norms of the firm, and to decision and control paths which have to conform to existing authority and procedures that are not necessarily those of the organization chart.

Human-Computer Interface

Recognition that the managerial and social structure of the firm dominates its style of operation draws attention to human-computer interaction as a critical technology. Advances in graphics, voice input/output and intelligent terminals have improved the technical repertoire for interaction. Widespread contact with low-cost personal computers has increased computer literacy and user acceptance of the technology. The human factors of flexible manufacturing systems and computer-aided design are being studied (Mitchell, Govindaraj and Ammons, 1984; Mills, 1986; Majchrzak, Chang, Barfield, Eberts and Salvendy, 1987). However, much remains to be done to bring the human engineering of computer-based systems to the same level of professionalism as hardware and software engineering (Gaines and Shaw, 1986b, 1986a). For decision and control systems involving expert systems and simulation, information presentation and ease of communication are of prime importance. A technically powerful system will be wasted unless it is comprehensible and accessible to its users, and gives them confidence in the basis of its operations.

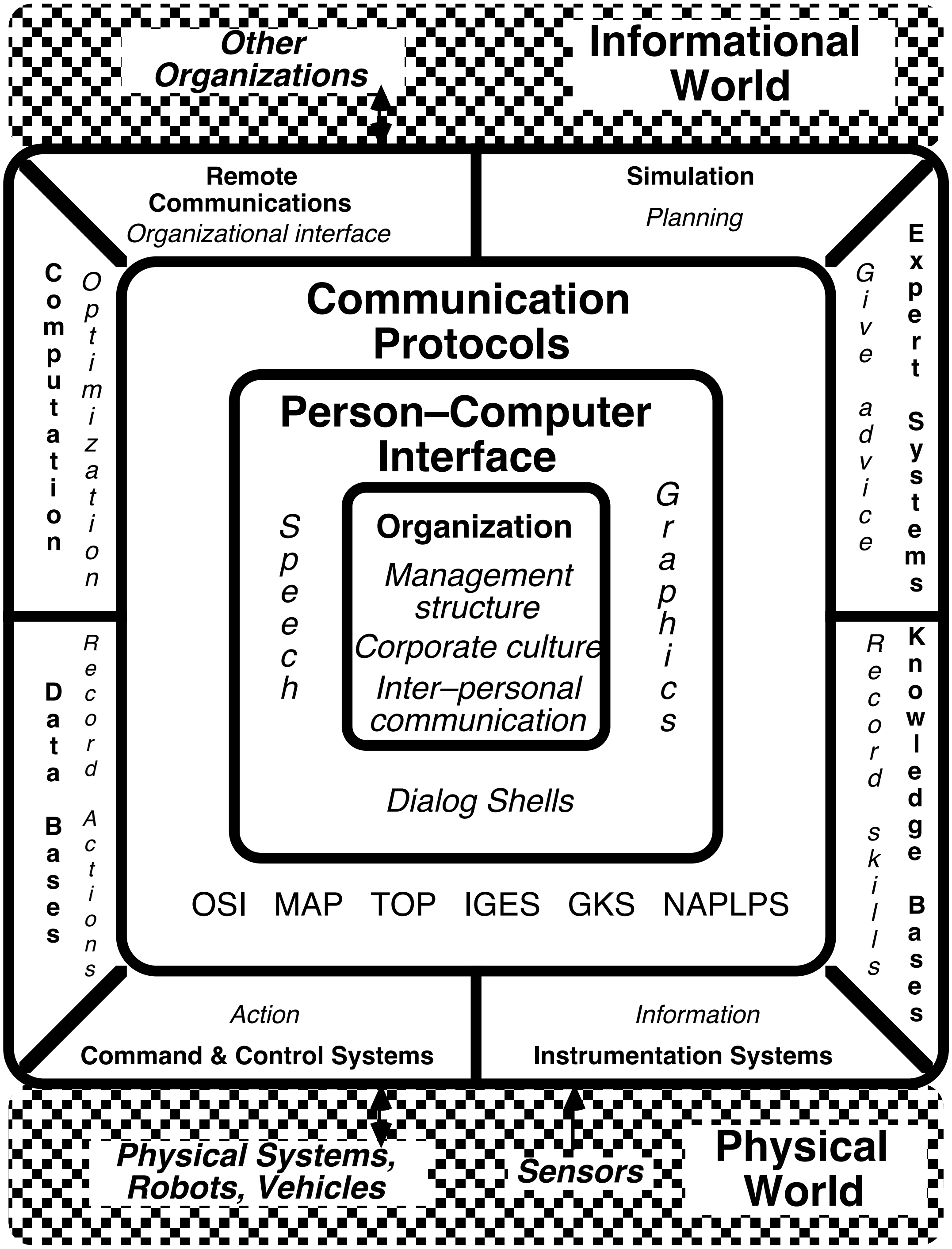


Figure 4 Enterprise information technology as an integrated heterogeneous system

Communication Protocols

The days of single-vendor, special-purpose systems designed against a static, well-defined specification are long gone. Integrated manufacturing systems encompass all aspects of the operation of a firm, from its financial planning and accounting, through its inventory control, customer, order, delivery and payment records, production planning, scheduling, control and monitoring, to its liaison with other organizations concerned with distribution, marketing, environmental control, and so on. Equipment from many vendors, purchased at different times, for different purposes, by different parts of the organization, has to operate together. In this lies the major practical obstacles to the creation of effective integrated systems at present.

The technical problems are beginning to be resolved at the lower levels by the adoption of industry standards in communication protocols such as the open systems interconnection (OSI) standard (Day and Zimmerman, 1983; Modiri, 1991), the provision in data-processing and database packages for the import and export of data from “foreign” systems, and the provision of data-communications for parameter-setting and data-collection in control and instrumentation systems. These alone are necessary but not sufficient to allow the widespread creation of integrated manufacturing systems. They provide a syntactic framework for system integration but no coherent semantics in which to express it.

MAP, the manufacturing automation protocol, has been developed to give application-level semantics to the OSI standard by General Motors (1984) as a major corporation heavily affected by integrated manufacturing system developments. It was sponsored by the GM Engineering and Manufacturing Computer Coordination activity in late 1979, placed in the public domain as a cooperative effort across computing, manufacturing equipment and manufacturing industries, and, at least initially, attracted widespread industry support. MAP defines an application-layer protocol for OSI specific to manufacturing requirements. It is particularly significant in system design in offering the capability to collect operational and performance data on a scale, and with a richness of context, impracticable currently (McCarthy, 1985).

The Applications Ring: Basic Technologies

The outer ring in Figure 4 shows the main information technologies in integrated manufacturing systems and their typical applications. Moving counter-clockwise around the ring:

Remote Communications are necessary to interface the factory with its suppliers and consumers. A particular firm is part of an industrial infrastructure each part of which is trying to optimize its productivity, profitability and stability. This can best be achieved if suppliers are aware of consumers’ needs and projected needs and consumers are aware of the production and delivery schedules of suppliers.

Computation Systems perform the classical number-crunching tasks under the control of algorithms that with modern software engineering have a high degree of accuracy, conformity to specification and reliability.

Database Systems have become the classic core of a firm’s information system, recording all its activities in a coordinated fashion and making the information available on a controlled basis to those systems and people with a legitimate need to know.

Control Systems began to be integrated with information systems (Dilts, Boyd and Whorms, 1991) as numerically-controlled machine tools came into use and with the development of industrial robots capable of part-handling, tool-changing and materials movement, total automation of production has come into widespread use.

Instrumentation Systems have had to increase in capability to compensate for the fewer people observing the manufacturing process and the increased need for timely information on the state of the plant, tool wear, and so on, to enable the manufacturing system to optimize overall operation.

The Applications Ring: Decision Technologies

Three technologies in the outer ring of Figure 4 are particularly relevant to decision aids for planning integrated manufacturing systems.

Knowledge Bases are distinguished from databases by containing inference rules in addition to facts. The rules may necessarily be heuristic in nature, generating plausible advice rather than hard facts. If databases may be said to record a firm's activities then knowledge bases may be said to record its skills, particularly its management skills.

Expert Systems are the means to apply a knowledge base to the solution of a particular problem. They stand in relation to the knowledge base as does conventional computation to the data base. They differ in that their role as advisors and dependence on heuristics makes *accountability* and *comprehensibility* of major importance. An expert system has to be able to justify and explain the basis of its advice.

Expert system technology can be applied at a number of levels in computer integrated manufacturing including product design (Kim and Suh, 1985), FMS justification (Sullivan and LeClair, 1985), job-shop scheduling (Fox, 1985), simulation (Bruno, Elia and Laface, 1985), on-line process control (Brown, Alexander, Jagannathan and Kirchner, 1985) and robot control (Kirschbrown and Dorf, 1985). However, the problem of major concern is the design stage at which the integrated manufacturing system has to be specified in terms of its performance and a range of diverse machine tools have to be brought together in an integrated system design. This stage presents a number of major conceptual difficulties currently that are impeding the rapid diffusion of computer integrated manufacturing technology into appropriate industries. It is typical of the problems that because of their complexity and diffuseness they have to be "managed" and are very susceptible to support through expert systems (Hayes-Roth, 1984).

Simulation has been separated from other forms of computation because it is computation based on a model of some other system and it is the relation of the simulated model results to that of the system modeled that is of paramount importance. The models used in simulation to infer the behavior of a system are generally deeper than the models used in expert systems to infer the proper advice about a system, even though both may be concerned with the same system (Shannon, Mayer and Adelsberger, 1985; Gaines, 1986a).

Simulation technology can be applied at a number of different levels in integrated manufacturing (Smith, 1985). However, the planning stage for flexible manufacturing is one of the most significant (Wortman and Miner, 1985). A flexible manufacturing system involves the integration of a number of different tools, probably from different manufacturers and possibly in a way not previously encountered by the manufacturers. There is a variety of semi-standard flexible manufacturing configurations recommended or used to demonstrate possibilities but the permutations required in practice go far beyond these. A flexible manufacturing system usually involves the integration of new technologies with older ones. The newer technologies are particularly in materials handling (Mangold, 1981; Edson, 1984) and in computer-based communication and software support for the overall system (Bruno, Demartini and Valenzano, 1984). These are not well-understood and problems of matching flow-rates between machines, and data-rates and formats between equipment controllers, are severe. Simulation provides a manager with a way of experimenting with configurations and coming to understand the potentials of different tools (Gaines, 1986b; Wichmann, 1986), and it can be used as a basis for adaptive control (Bilberg and Alting, 1991).

6 Higher Level Protocols

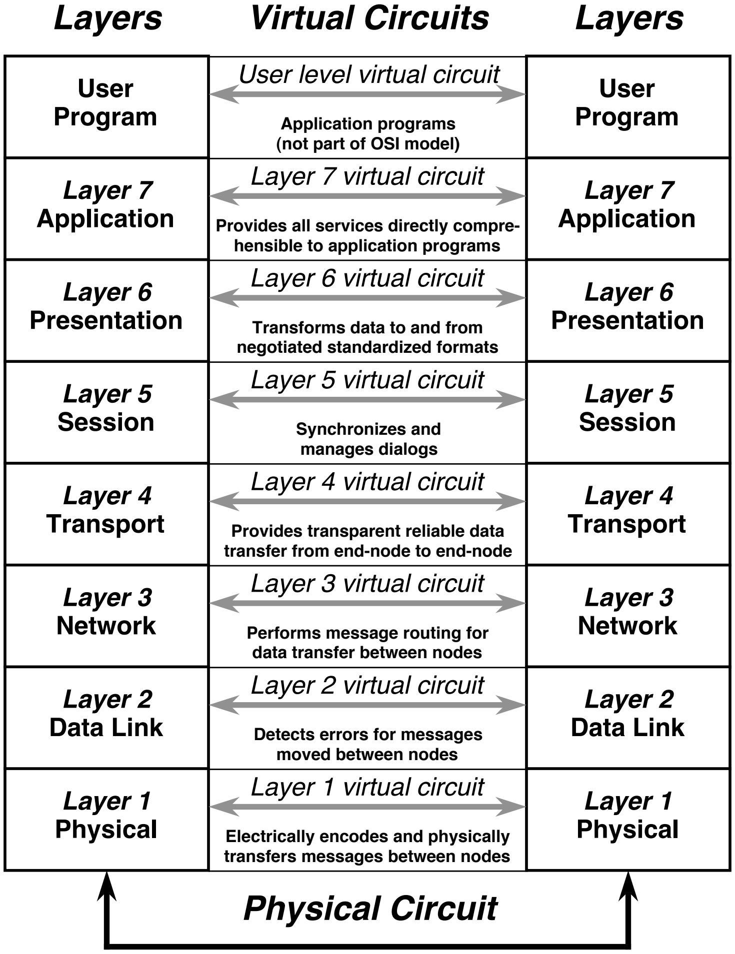
The diagram of Figure 4 captures the key problem areas for computer integrated manufacturing in a neat picture, but it gives no basis for treating them in an integrated way. How do the corporate culture, human-computer interface and network protocols relate, and how does this affect operations? The only strongly formalized and standardized structures within Figure 4 are the network protocols, and it is useful to examine these in more detail because they involve concepts that are useful in formalizing the other subsystems shown.

Figure 5 shows the Open Systems Interconnection Reference Model. It models communications as a protocol with seven layers each having a distinct function that can be defined fairly independently of the other layers. Within each layer the system can be viewed as providing services to the layer immediately above using the capabilities of the layer immediately below. The first level defines standards for the physical transfer of messages—electrical levels, timings, connectors, and so on. The seventh level defines standards for the content of messages in relation to applications programs—this and the previous level are those which are specialized in MAP and TOP. Intermediate levels are concerned with intra-message validity, network addresses, end-to-end message transfer checking, correct sequencing, and standard data formats for very general data structures such as graphics.

The most important concept underlying the OSI model is shown in Figure 5, that of *virtual circuits*. The designer of a particular level is concerned primarily with its relation with the equivalent level in the system with which it is communicating. He need have little concern with the levels above or below it. Hence he thinks in terms of messages passing directly between equivalent levels, through a "virtual circuit," rather than through the multiple levels of the actual system.

The concept of *virtuality* is fundamental to computing systems—programming replaces hardware with "virtual" hardware created by software (Gaines, 1975; Weegenaar, 1978; Gaines, 1979). Nelson (1980) has proposed virtuality as an analytic principle, noting that we project to the user a virtual world from within the computer. The capabilities of the computer are used to create a model world that mimics the characteristics of some real world. Classic examples are the Xerox Star and, more recently, the Apple Macintosh simulating a desk on which are folders containing documents, in- and out-trays, and a trash bin. As Smith (1983) notes, "if everything in a computer system is visible on a display screen, the display becomes reality."

The top level above the OSI defined layers in Figure 5 is the "user level virtual circuit," representing the interactions between user programs through the communications network, and hence the interactions between users themselves, and their activities, if the programs are interactive. This concept of virtual circuits between users, and user activities, is very powerful in enabling us to restructure Figure 4 to provide a more integrated framework for the other sections not directly included in the communications protocol. It can be redrawn in such a way that the relation of managerial and operations considerations to higher-level protocols in integrated communications networks is apparent. Figure 6 shows the same conceptual blocks as those in Figure 4, but now in hierarchical form with the human-computer interface, information systems, organizational structure and business worlds shown as higher level "layers" above the network layer. In OSI terms these upper layers may be seen as subsuming and extending the presentation and application layers of the protocol, and give substance to the user level virtual circuit.



Layers	*Virtual Circuits*	*Layers*
User Program	*User level virtual circuit* Application programs (not part of OSI model)	**User Program**
Layer 7 **Application**	*Layer 7 virtual circuit* Provides all services directly comprehensible to application programs	***Layer 7*** **Application**
Layer 6 **Presentation**	*Layer 6 virtual circuit* Transforms data to and from negotiated standardized formats	***Layer 6*** **Presentation**
Layer 5 **Session**	*Layer 5 virtual circuit* Synchronizes and manages dialogs	***Layer 5*** **Session**
Layer 4 **Transport**	*Layer 4 virtual circuit* Provides transparent reliable data transfer from end-node to end-node	***Layer 4*** **Transport**
Layer 3 **Network**	*Layer 3 virtual circuit* Performs message routing for data transfer between nodes	***Layer 3*** **Network**
Layer 2 **Data Link**	*Layer 2 virtual circuit* Detects errors for messages moved between nodes	***Layer 2*** **Data Link**
Layer 1 **Physical**	*Layer 1 virtual circuit* Electrically encodes and physically transfers messages between nodes	***Layer 1*** **Physical**

Figure 5 The Open Systems Interconnection model

The virtual circuits between the human-computer interface layer and the information systems layer in Figure 6 are easy to understand. The user of a computer terminal does not think of himself as communicating through a network but rather as directly interacting with some data-processing sub-system. This layer may go beyond the OSI specification but it seems a natural extension of it to the technical aspects of the interaction between people and computing systems. However, the "virtual circuits" at the level above, between the organizational layer, and the the business world layer, may seem rather less credible. It is a reasonable metaphor that the sales manager does not see him or her self as interacting with a complex administrative and production system, but rather as communicating directly with a customer organization by supplying it with goods. It is a reasonable metaphor that the chief executive does not see him or her self as concerned with that level of communication but rather as communicating directly with the board and shareholders through a flow of profits and dividends. However, can these metaphors be given technical substance through extension of the layered hierarchical model of virtual communication paths?

The main problem in extending the model to the management level is that people are directly and necessarily involved, and they have different dynamics from technical systems. However, this is also true for the level below where human-computer interaction is involved, and models have been developed at this level that integrate the human and technical components with a hierarchical layered communication model (Gaines, 1988; Hoorde, 1990).

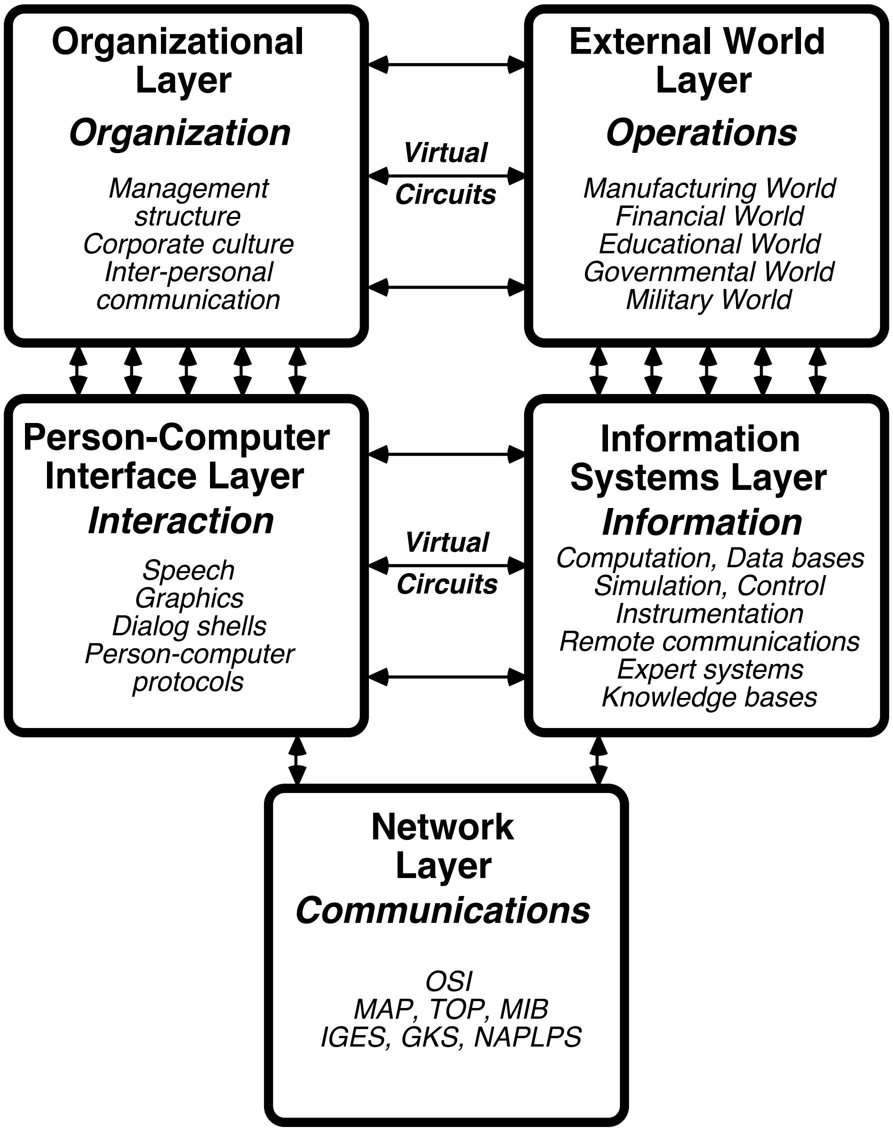


Figure 6 Knowledge structures for heterogeneous systems as a hierarchical protocol

The diagram of Figure 6 readily extends to encompass other dimensions of system structure significant in manufacturing such as the geographic partitioning of organizations requiring inter-plant and inter-company communications. Figure 7 shows this in the context of Uenohara's (1986) model of "virtual plants" as worldwide distributed manufacturing processes. His vision of the future was that increasing coverage of communications and increasing intelligence of computers would lead to "Command & Control" of the total manufacturing system through the increasing integration shown in Figure 7.

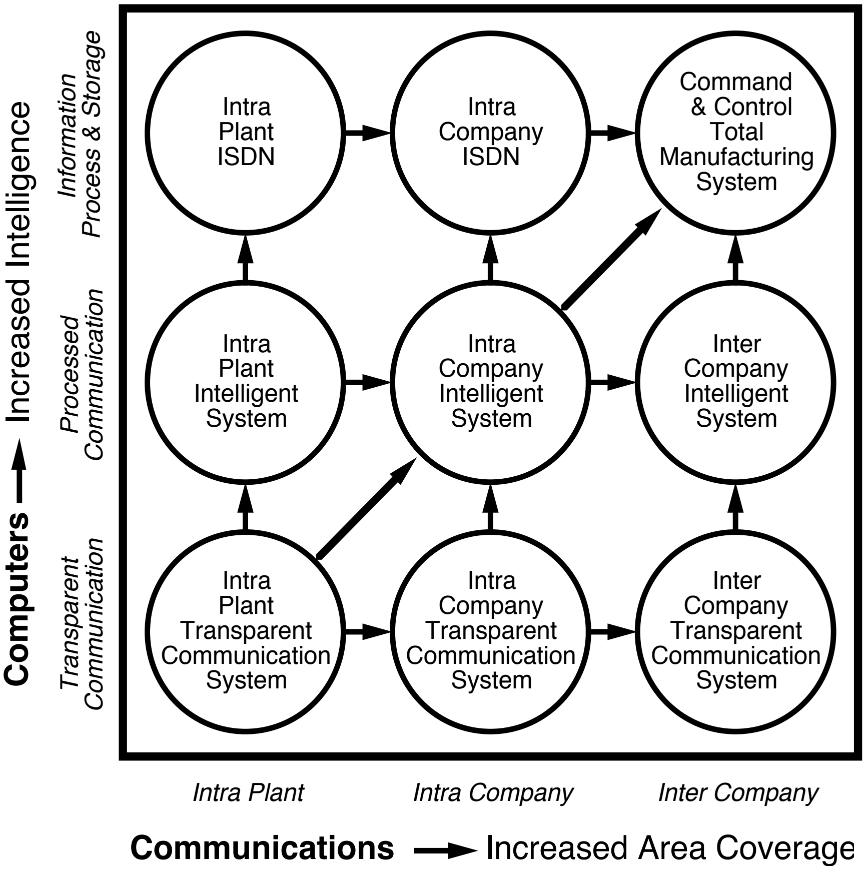


Figure 7 Uenohara's model of "virtual plants" based on the evolution of intelligent integrated systems

7 Object Oriented Technologies

Why are object oriented software technologies fundamental to the effective development of system architectures with the form shown in Figure 6? The answer is surprisingly simple—that the detailed development of each structure in Figure 6 is a *modeling* activity, and that the object oriented approach to software engineering is precisely characterized as the support, at all stages from conceptualization, through design, implementation, maintenance and evolution, of a system architecture based on operational models. In a very general sense all system development involves modeling, but in past software engineering these models have been largely conceptual, perhaps implicit in the code but usually invisible within the web of information structures necessary to make a computer perform a task. Object oriented software technologies allow a model to *be* the code. What is visible and accessible is the model without the encumbrance and confusion of the underlying layers of implementation.

All other aspects of object oriented software technologies derive from the overall emphasis on, and support of, the modeling approach. *Abstraction* and *aggregation* are the basic modeling operations whereby a system is decomposed into subsystems and these are classified as belonging to a hierarchy of generic types. *Modularity*, *encapsulation* and *information hiding* are the techniques necessary to allow the aspects of the implementation irrelevant to its specification as a model to be invisible. In a good object oriented development system, all these features are made available through textual and graphic languages that make the modeling process, and the model, as comprehensible as possible to those with domain knowledge, while requiring them to need to know as little as possible about the underlying information technology that makes the model operational (Shriver and Wegner, 1987; Bertino and Martino, 1991).

The type of object oriented software appropriate to different areas of modeling depends on the nature of the domain. There is a generic underlying compiler technology represented by languages such as C++ (Stroustrup, 1991) and Eiffel (Meyer, 1988) that provides the primitives for abstraction, aggregation, modularity, encapsulation and information hiding (Booch, 1991). This enables highly generic *class libraries* to be built for the usual data types and structures involved in data processing (Uhl and Schmid, 1990). These are then extended to be generic class libraries for particular types of major application. Figure 8 shows the relations between the basic technology and three major domains where class libraries are now assuming significant roles in relation to the blocks in Figure 6.

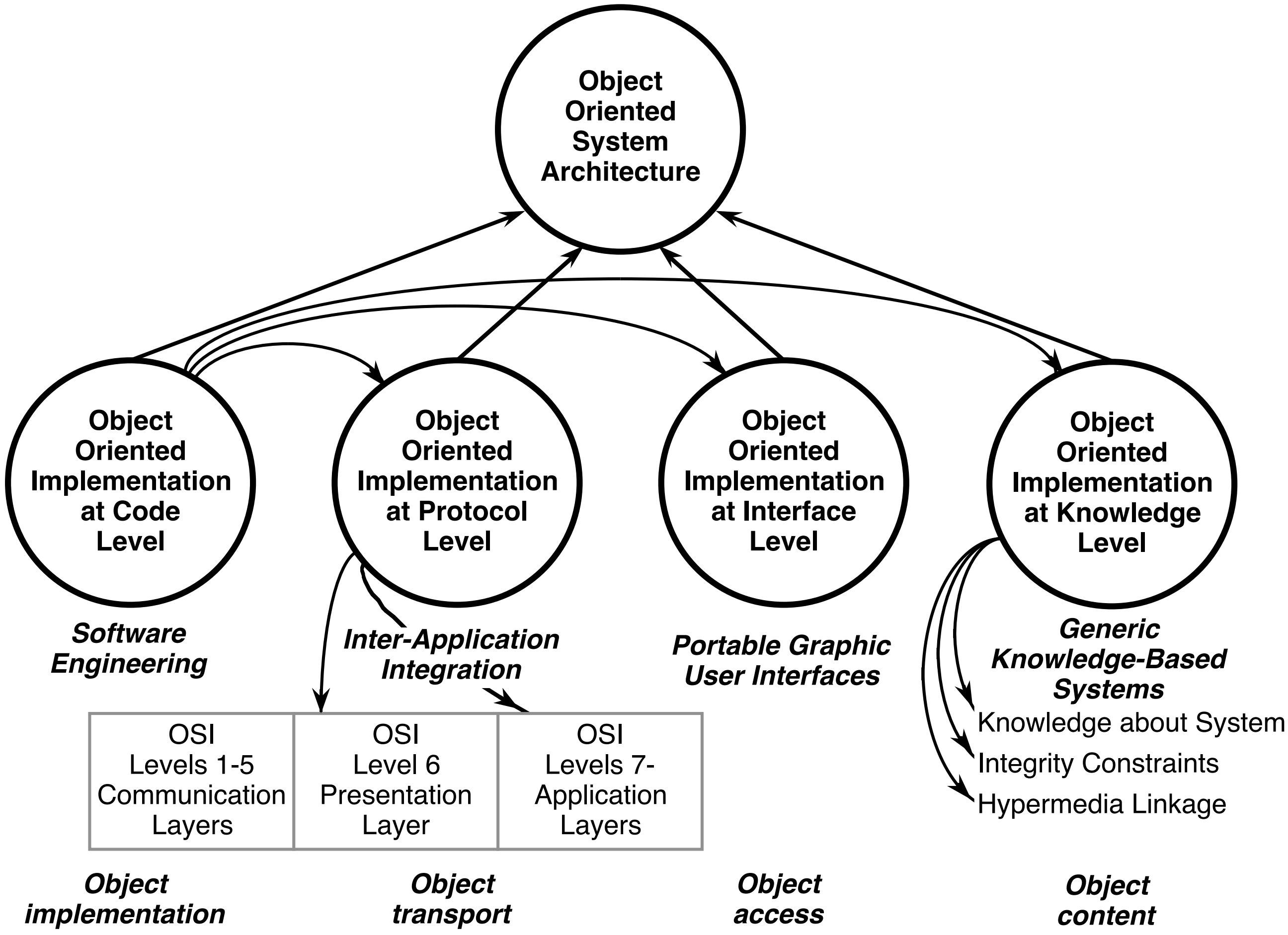


Figure 8 The major object oriented technologies

Reading Figure 8 from left to right, the technologies are:

- Object oriented implementation at the code level—typically C++ and highly generic class libraries.
- Object oriented implementation at the protocol level—class libraries for the presentation layer of the OSI protocol supporting data structures for the common items moved between applications such as structured document, diagrams, and spreadsheets.
- Object oriented implementation at the interface level—class libraries supporting platform-dependent graphic user interfaces.
- Object oriented implementation at the knowledge level—class libraries for the modeling of structures and organizations within the enterprise, such as employees, markets and manufacturing facilities.

What is shown are examples of currently significant object oriented technologies for very generic requirements occurring in nearly all information systems. There are large numbers of similar technologies being developed for more specific domains such as process control, publishing and accounting, and the provision of class libraries has already become a major software industry. All of these generic technologies are then further specialized to support particular products, market sectors, industries, corporations and divisions, projects and individuals within them. The advantages of basing information technology on a modeling system capable of system decomposition through abstraction and aggregation are: first, that our conceptual frameworks for any particular domain can be matched exactly through a model that needs no further human effort to become the operational code; and, second, that the basic building blocks of all our models can be standardized and reused by many different organization in many different applications.

The overt conceptual structures for all aspects of the manufacturing enterprise that are the basis of class libraries already exist in many publications on the principles of manufacturing and industrial operations. For example, Hubka and Eder (Hubka and Eder, 1984) provide a conceptual theory for engineering design; Kerr (1991) has developed a knowledge-based model of manufacturing management; the ESPRIT Consortium AMICE (1989) defines an open system architecture for CIM, one outcome of which is the development of detailed class library structures for the applications layer of MAP (Edmond and Hermans, 1988; Klittich, 1988; Moss, 1988; Klittich, 1989); the ESPRIT TODOS project defines a conceptual structure for office information systems (Pernici and Rolland, 1990); object-oriented databases are being used to support the representation of complex objects in CAD systems (Odawara, 1989; Gupta, 1991); knowledge structures are being used as a basis for simulation (Fishwick and Modjeski, 1991); and object oriented model of detailed manufacturing processes are being developed (Milacic, 1988a; Milacic, 1988b; Oliff, 1988; Norrie, Fauvel and Gaines, 1990).

The development of object oriented protocols for inter-application communication as an integral part of the operating system is now a major industry thrust by all major vendors. These protocols support industry standards not only for the actual content of the information communicated but also for its meta-content in terms of what type of information is present and potentially present. This meta-level communication allows systems to “negotiate” the most effective basis for interaction, doing this dynamically with no human intervention required. Developing protocols that conform with these standards for all equipment involved in manufacturing is essential to progress in computer-integrated manufacturing. In future, we can expect to see equipment specified as much through its communication protocol sub-class library as through its performance characteristics.

The development of knowledge bases representing the generic architectures of systems, processes, and problem-solving procedures across a wide range of activities is now also a rapidly growing area of research and development. Large numbers of knowledge-based systems have been developed on an *ad hoc* basis, and their models of the world differ widely in their ontologies making it difficult for such systems to be used together effectively. Research groups in industry and universities are collaborating internationally to investigate bases for standardized common ontologies (Neches, Fikes, Finin, Gruber, Patil, Senator and Swartout, 1991). Modeling the total infrastructure of manufacturing organizations is one of the high priority objectives of this collaboration, and, again, it is essential that this be done if class library structures in the manufacturing industry are not to grow in an undisciplined fashion such that many of the benefits of reusability and integration are lost.

Conclusions

The purpose of this paper has been to present manufacturing as a knowledge science by providing an overview of the socio-economic environment of modern manufacturing, trends in information technology supporting manufacturing, and, in particular, the fundamental role of object oriented technologies in enabling the new demands on manufacturing to be met.

It is appropriate in conclusion to remind ourselves of the role of manufacturing as a scientific and engineering discipline in the development of the new industries that are arising out of the knowledge economy but are not normally seen as “manufacturing industries.” These include: *genetic engineering* (Prentis, 1984; Kenney, 1986; Teitelman, 1989); *software engineering*, particularly the development of the “software factory” (Fernström, 1991); and *knowledge engineering* (Adeli, 1990).

At the 1986 Japan-USA Symposium on Flexible Automation, Akeel’s call for a “new science of manufacturing” was complemented by Uenohara’s Japanese keynote address that was also concerned with new conceptual frameworks for manufacturing. Uenohara defined manufacturing as the “activity of processing and converting intellectual and physical raw materials and elements into hardware and software products for ease of consumer’s use,” and emphasized total manufacturing systems with customers involved as much as employees.

It is the nature of the knowledge economy that the differences between “intellectual” and “physical” raw materials, and between “hardware” and “software,” are no longer seen as fundamental. The science, engineering and management of the processes of manufacture, and the social and economic origins of the purposes of manufacture, are fundamental, but the domains to which they apply are incidental. For example, one very significant recent conference was concerned solely with common factors in operations management in the manufacturing and service sectors (Macbeth and Southern, 1989).

It is time that we began to apply manufacturing disciplines to knowledge itself. A major objective of the Japanese “Human Frontier Program” proposals was the “systematic acceleration of scientific research” (CHFP, 1986). It is an appalling indictment of the scientific process that the main medium of distribution of new knowledge is the paper-based journal, largely unchanged since its inception in 1664 (Zuckerman and Merton, 1971). We have to begin to treat knowledge as a human manufacture whose production is subject to the same type of principles that apply to manufacturing in general. It is not by chance that technical papers on the nature of human creativity are appearing in manufacturing journals (Kim, 1991b).

We have too long treated knowledge production as a mystery of human existence rather than an essential technology for the survival of our civilization. The attention to human, social and knowledge factors now necessary in manufacturing, coupled with the professional disciplines of the science and engineering that have made manufacturing such an essential and reliable sector of our socio-economic infrastructure, now combine to make manufacturing a role model for our overall management of the knowledge economy.

Acknowledgements

Financial assistance for this work has been made available by the Natural Sciences and Engineering Research Council of Canada. I would like to acknowledge the influence of many discussions over the years with Doug Norrie that have influenced the ideas presented in this paper, and to thank him and Mildred Shaw for their comments on the first draft.

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