Keynote address at *IFIP Third International Conference on Advances in Production Management Systems*, Winnipeg, 1987.

A New Science of Manufacturing

Brian R. Gaines

Department of Computer Science
University of Calgary
Calgary, Alberta, Canada T2N 1N4

The total integration of the manufacturing process, both within itself, and within the overall operation of the organization is now technically feasible in terms of communications, control and information technology. However, the integration of integrated manufacturing systems within the management structure of the organization, and the management of the complexities, new opportunities and new problems, of such systems present major difficulties that are impeding use of new technologies. It has been suggested that a new science of manufacturing is required integrating technology, management and economics. This paper has analyses the requirements for such a new science and develops a theoretical model for integrated systems that shows promise of satisfying them. It presents a study of the information technologies underlying computer-integrated systems, their relation to the structure and culture of the organization, the potential and problems in their integration, and the theoretical developments necessary to overcome these problems.

1. Introduction

Francis and Akeel have posed the challenge of generating a new *science of manufacturing*, noting that "to restore America's 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). Figure 1 is based on Francis' paper and shows the diverse range of topics that he considers to be key issues in modern manufacturing. It is certainly a challenge to propose a "science" that will encompass them all in some integrated framework, but it is becoming increasingly necessary to do so.

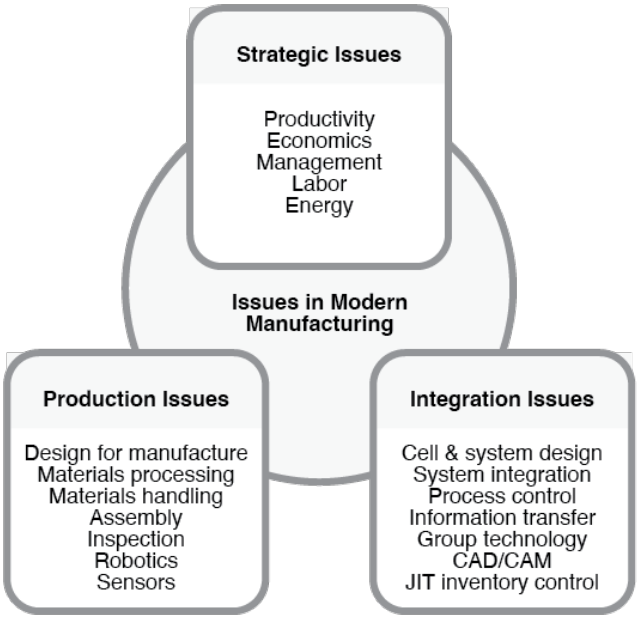

Fig.1 Issues in modern manufacturing (Francis 1986)

It is interesting to note that Uenohara (1986), in the Japanese keynote address complementing that by Akeel, was also concerned with new conceptual frameworks for manufacturing, defining it 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 emphasizing total manufacturing systems with customers involved as much as employees. He used the concept of a "virtual plant" as a worldwide distributed manufacturing process. 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 2.

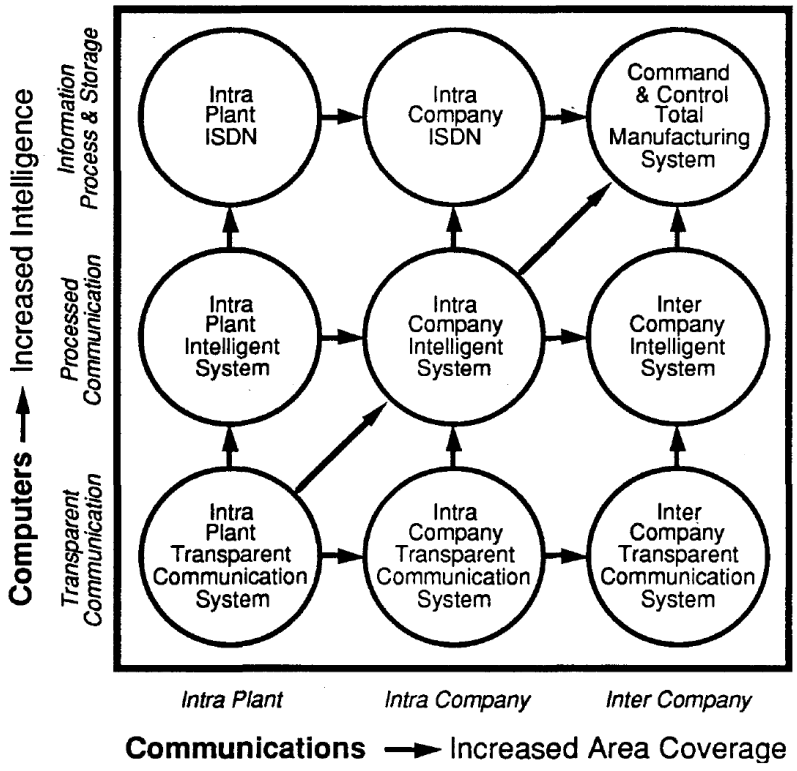

Fig.2 Virtual plants (Uenohara 1986)

We are all aware that there have been major changes in the production process through the introduction of computer control, robotics and integrated communications. Computer integrated manufacturing and the introduction of artificial intelligence and expert systems throughout the manufacturing system are major themes at conferences. We seem on the brink of a new era of manufacturing, yet 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. Whereas the direct labour demands of the new manufacturing techniques are low, the indirect labour demands on those managing the new technology have greatly increased. Total integration, with the new systems increasingly managing themselves, seems the answer. Yet, it is not clear that we know enough, and have adequate knowledge-based technologies, to achieve that degree of integration.

This paper analyses the nature and problems of total integration in manufacturing, showing why the operations research approach that has served us so well is no longer adequate, establishing the preconditions for a new science of manufacturing that will subsume it, and sketching out the framework for such a science in terms of communications, control and computing concepts.

2. Integration

We have entered an era of *system integration* where 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 ad hoc activities of such divisions have grown to become major cost centres, 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 is 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 Lotus Synphony and Ashton-Tate Framework, or through utilities such as IBM Topview and Microsoft 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);
- For network technology it is the integration of diverse services on a single 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 1986) and MIB (Leopold 1986);
- For frontiers materials research it is the integration of the information processing architectures of digital computers with the high-density, high-speed capabilities of bio-chips (Jarvis 1985) and optical processing (Miller 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 (Gaines 1986b).

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.

This paper analyses the problems of developing totally integrated systems in which modern information systems technology is used throughout the operations of major organizations.

3. Information systems in integrated manufacturing

An instance of the application of integrated networks to support the total operations of large organizations is the development of integrated manufacturing systems. Figure 3 shows the information systems in a modern production unit using computer integrated manufacturing techniques.

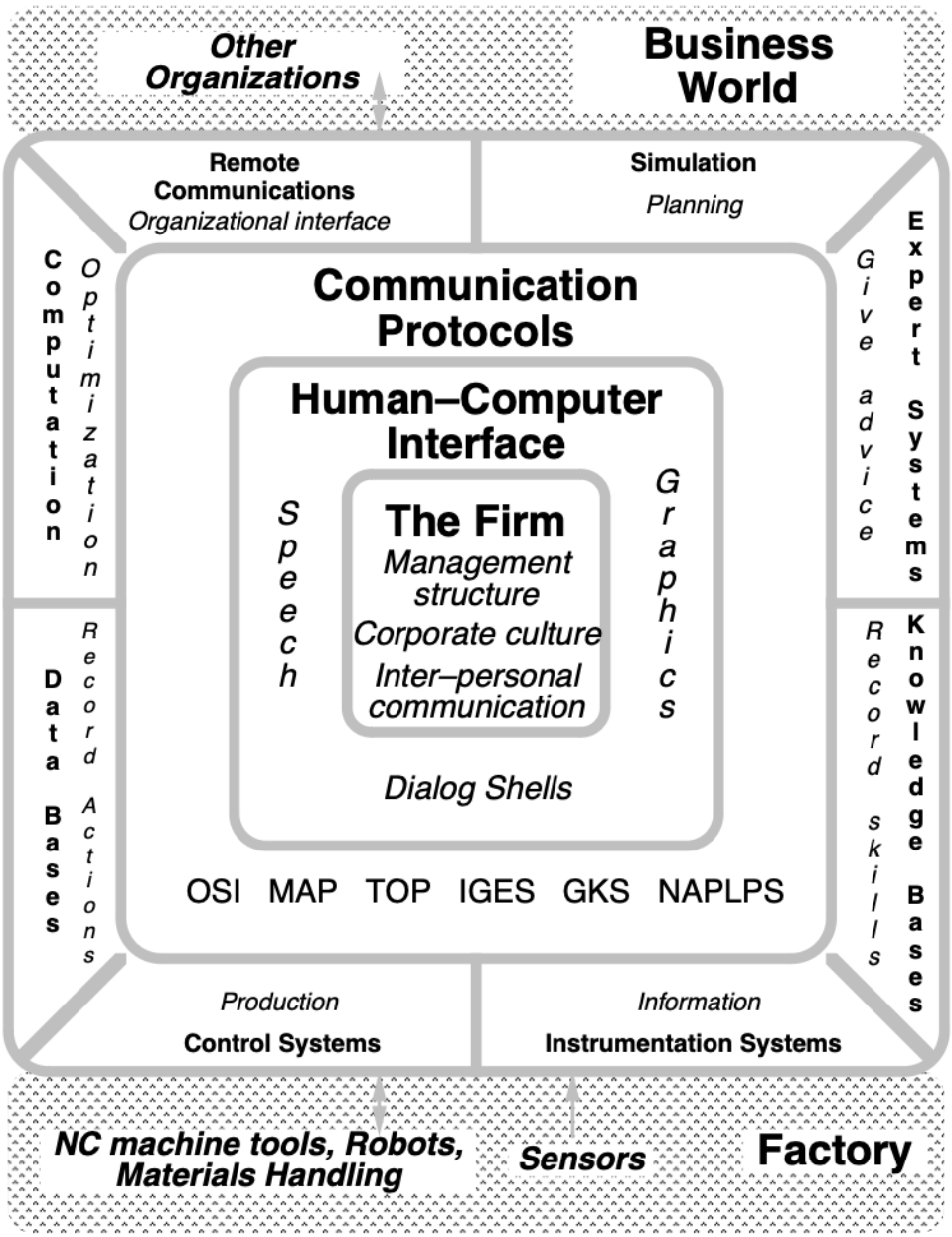

Fig.3 Information systems in a modern production unit

The outer ring comprises eight basic information technologies that together support the manufacturing system and its interface to the factory and business world. The centre 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.

3.1 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 & 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 & Shaw 1986c). In particular, in order to be successful the technical systems must be consistent with the organizational structures and processes. 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.

3.2 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 & Ammons 1984, Mills 1986, Majchrzak, Chang, Barfield, Eberts & 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 & Shaw 1986a,b). 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.

3.3 Communication protocols

The days of single-vendor, special-purpose systems designed against a static, well-defined specification are long gone. Integrated manufacturing systems integrate 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 & Zimmerman 1983), 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.

The *manufacturing automation protocol* (MAP) 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).

3.4 The applications ring: Basic technologies

The outer ring in Figure 3 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 co-ordinated 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 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.

3.5 The applications ring: Decision technologies

Three technologies in the outer ring of Figure 3 are particularly relevant to decision aids for planning integrated manufacturing systems.

Knowledge Bases are distinguished from databases by containing inference rules rather than 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 & Suh 1985), FMS justification (Sullivan & LeClair 1985), job-shop scheduling (Fox 1985), simulation (Bruno, Elia & Laface 1985), on-line process control (Brown, Alexander, Jagannathan & Kirchner 1985) and robot control (Kirschbrown & 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 (Gaines 1986a, Shannon, Mayer & Adelsberger 1985).

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 & 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 & Velanzano 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 1986d, Wichmann & Lenz 1986).

4. Higher level protocols in integrated manufacturing

The diagram of Figure 3 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 3 are the network protocols, and it is useful to examine these in more detail because they involve concepts that are useful in formalizing more of topics encompassed in Figure 3.

Figure 4 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 is the level with which MAP and TOP are primarily concerned. 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.

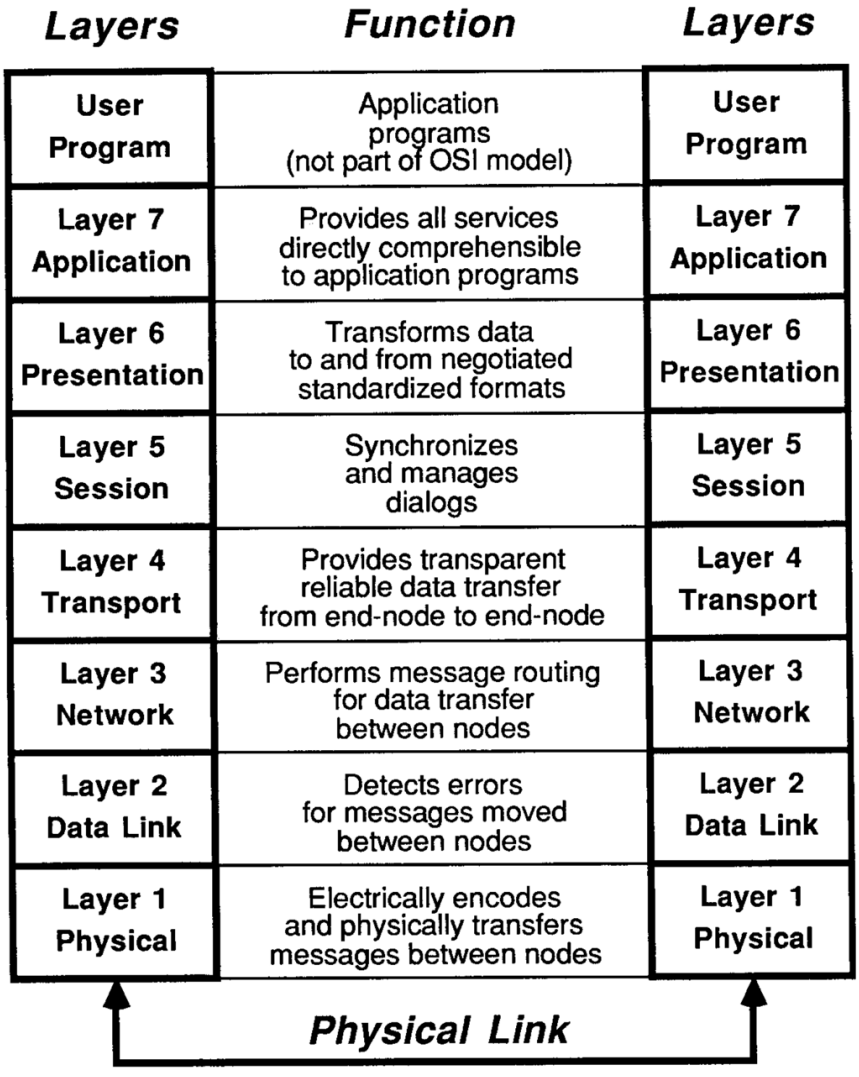

Fig.4 The Open Systems Interconnection reference model

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.

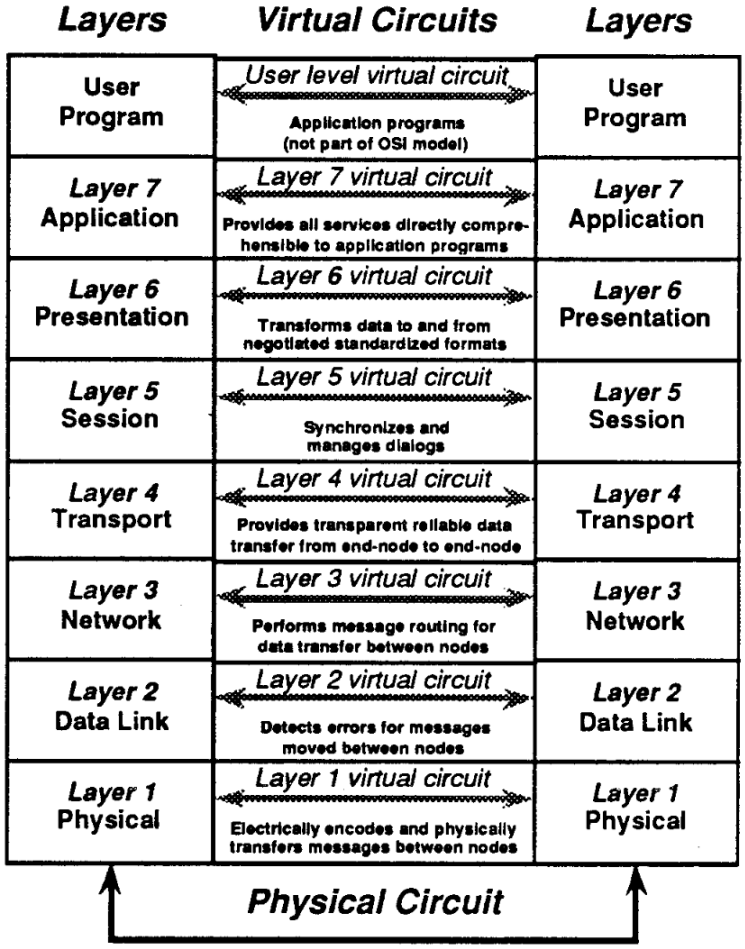

Fig.5 Virtual circuits in an extended OSI framework

The concept of *virtuality* is fundamental to computing systems—programming replaces hardware with "virtual" hardware created by software (Gaines 1975, 1979, Weegenaar 1978). 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 3 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 3, 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.

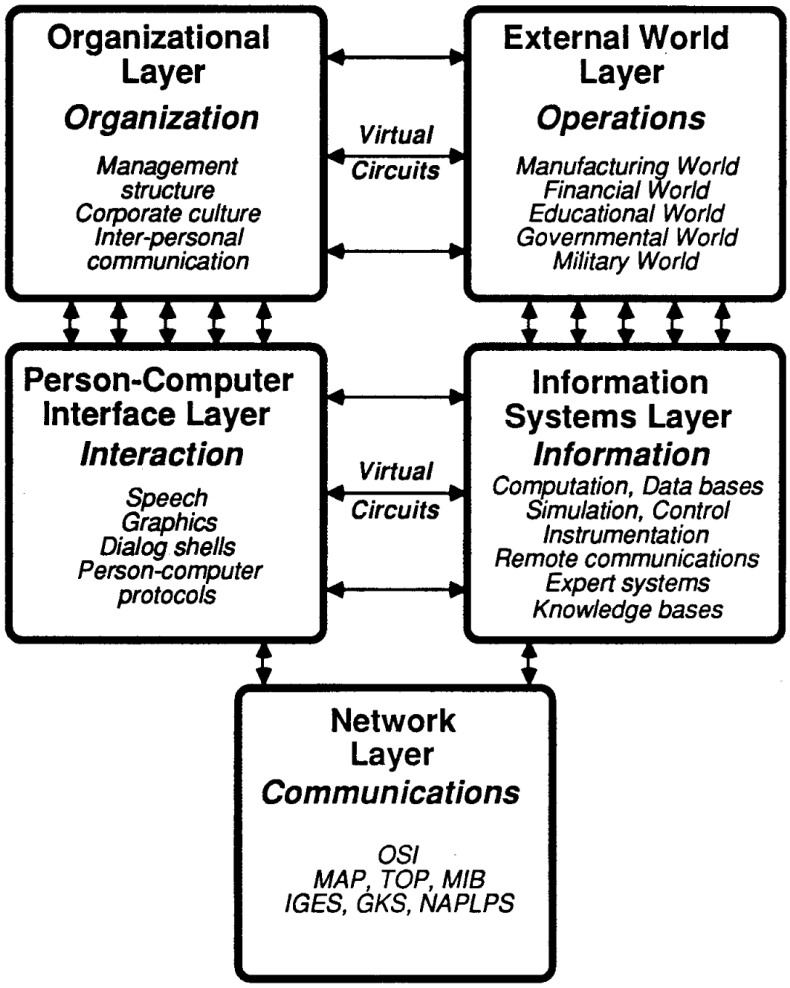

Fig.6 Virtual circuits in an organizational structure

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 himself as interacting with a complex administrative and productive 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 himself 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 1986c). The next Section briefly outlines such a model and the following Section uses it to begin to analyse and model the top level of Figure 6 in a way that provides an integrated theory for the whole structure in Figures 3 and 6.

5. Knowledge engineering for integrated manufacturing

New technologies create new problems but they also often provide new means to solve them. The development of knowledge-based systems has focused attention on techniques for *knowledge engineering*, the acquisition of knowledge from human experts and its transfer to expert systems. Effective techniques for knowledge engineering are based on the observation that there are common patterns in the way in which we model the world, explain phenomena, anticipate events and communicate knowledge. These patterns are part of the process of human understanding and may be termed general systems principles. Their significance is that, since they underlie physical laws and social conventions, their identification in particular modelling schema enables us to analyse those schema in a universal framework. The extraction of these systemic principles is straightforward if we examine the systems of *distinctions* being used in the evaluation and protocol methodologies. As Brown (1969) has noted, by analysing the distinctions made in any discipline, "we can begin to reconstruct, with an accuracy and coverage that appear almost uncanny, the basic forms underlying linguistic, mathematical, physical and biological science, and can begin to see how the familiar laws of our own experience follow inexorably from the original act of severance."

The basic systemic distinctions underlying the physical processes, management activities, and information technologies, shown in Figures 3 and 6 can be analysed in terms of Popper's (1968) *3 worlds theory*. Figure 7 shows the existential hypotheses underlying Popper's 3 worlds as very general distinctions made about distinctions:

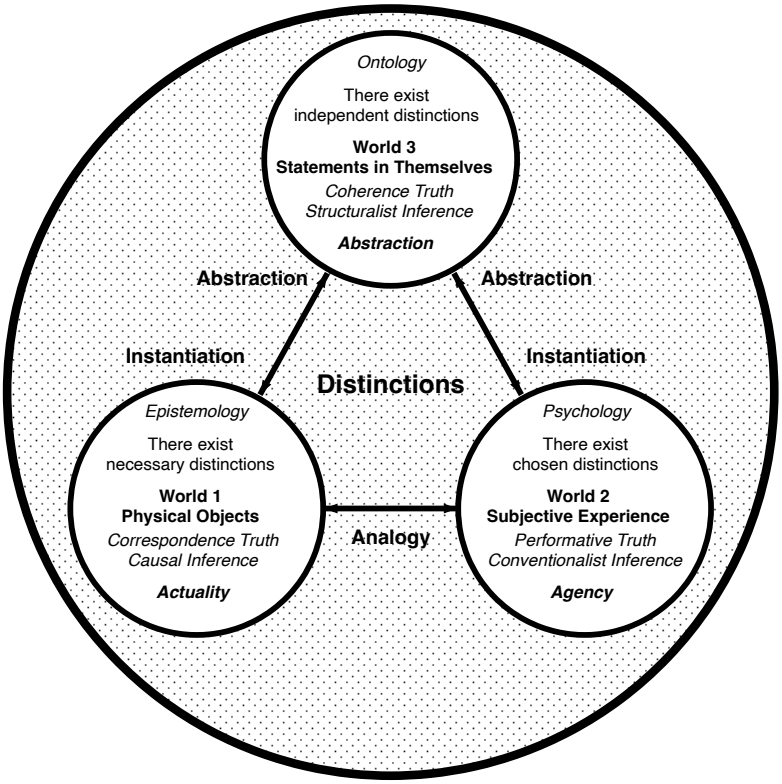

Fig.7 Three worlds (Popper 1968)

- World 1 arises from the hypothesis that there exist *necessary* distinctions
  - —the conceptual framework involved is that of *epistemology*, and a key concept is that of *actuality*
  - —truth in this world relates to *correspondence* between distinctions made and the properties of physical objects, and hence inference is *causal*.
- World 2 arises from the hypothesis that there exist *chosen* distinctions
  - —the conceptual framework involved is that of *psychology*, and a key concept is that of *agency*
  - —truth in this world relates to the ongoing consistency of subjective choices of distinctions to make and is *performative* in nature, and hence inference is *conventionalist*.
- World 3 arises from the hypothesis that there exist distinctions *independent* of their source in actuality or agency
  - —the conceptual framework involved is that of *ontology*, and a key concept is that of *abstraction*
  - —truth in this world relates to the internal *coherence* of the systems of distinctions made, and hence inference is *structuralist*.

These basic distinctions give rise to the notions of *abstraction* and *instantiation* as relations between world 3 and worlds 1 and 2 as shown, and also to that of *analogy* between worlds 1 and 2 when we attribute to agency to the causal dynamics of physical objects or necessity to the social conventions of human activity. In terms of Figures 3 and 6, the physical processes of manufacturing below to world 1, the management processes to world 2, and the information technologies to world 3.

In the analysis of system dynamics a fundamental distinction is that between the activity and the origins of a system, between its behaviour and its structure. In abstract terms the behaviour of a system provides a description of what the system does, and the structure of a system provides a description of what the system is. One of the most important problems of system theory is the analysis of the relations between behaviour and structure—in one direction, given the structure of a system, to derive its behaviour—in the other direction, given the behaviour of a system, to derive its structure. In the study of physical systems, mathematical techniques have been developed for moving in both directions with causal models (Klir 1985), that is interrelating the necessities of world 1 behaviour and structure. However, integrated manufacturing systems are not purely physical systems since they involve the choice behaviour of people (Tack, Bolc & Slagmolen 1986) and hence show phenomena of the life-world (Schutz & Luckman 1973) which are essentially different from those of the physical world and cannot be encompassed by causal models (Ulrich 1983).

The dynamics of human behaviour are best modelled as those of an *anticipatory system* (Rosen 1985), enhancing its survival by modelling the world, both passively and actively, in order to better anticipate the future. This corresponds to the choice component of world 2 phenomena, that agents are not bound by rigid necessity but can plan and chose certain aspects of their behaviour. Figure 8 shows an analysis of the relations between a system, its origins and its activities, when the *actuality—agency* distinction of Figure 7 is also taken into account. The origins of a system have two components: its *causal structure* relating to how it was created; and its *anticipatory structure* relating to why it was created. The activities of a

system also have two components: its *causal behaviour* relating to how it carries out its activity; and its *anticipatory behaviour* relating to why it carries out its activity.

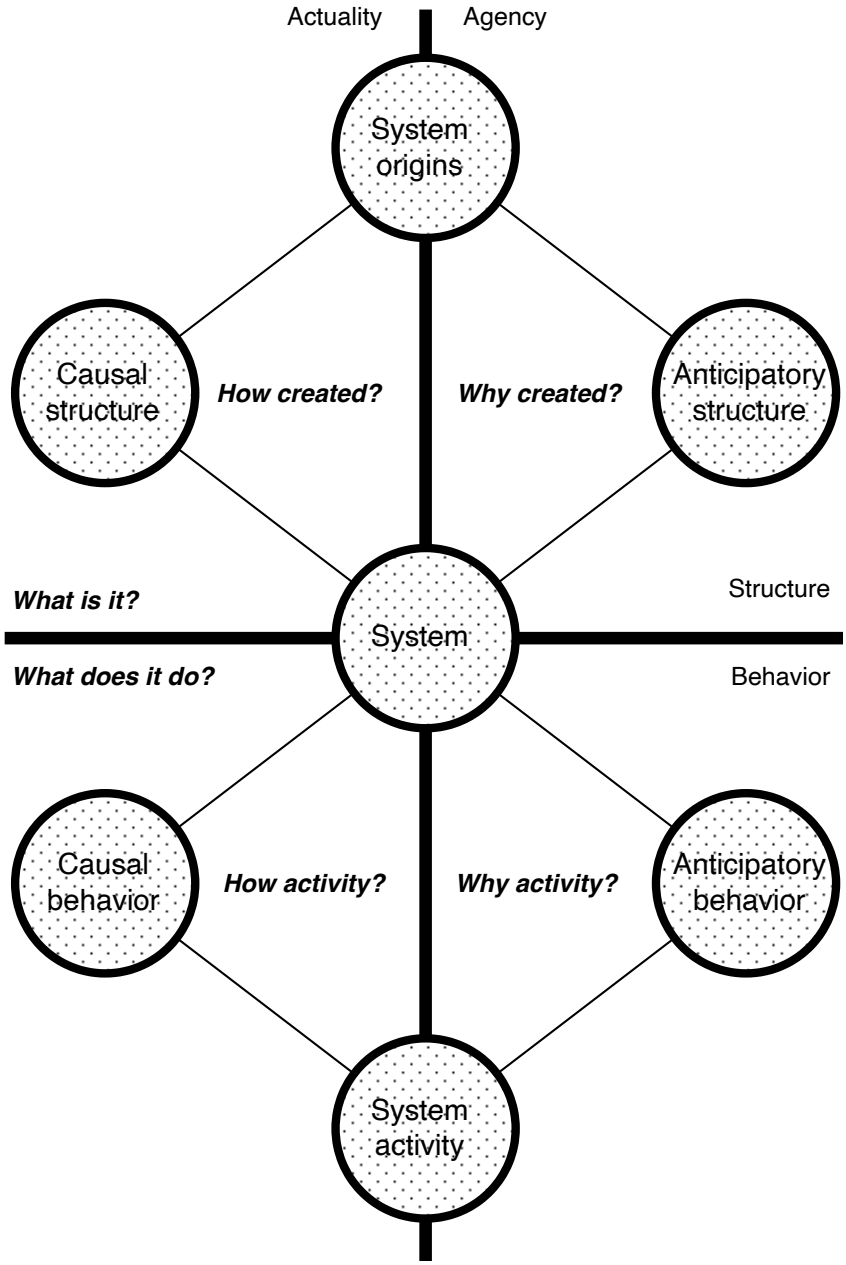

Fig.8 Relations between a system, its origins and its activities

The basic distinctions of *actuality—agency* and *structure—behaviour* are sufficient to define the virtual machine hierarchy fundamental to computing, and to account for its technical and human components and their relations. Figure 9 fills in Figure 8 to show how the levels of virtual machine arise from the basic distinctions. The origins of any computer-based service are that a *virtual machine*, a computing system, has been programmed by agents, the *implementors*, to create an actuality, the *implementation*. This results in a second virtual machine, the programmed computing system. The activities of the computer-based service are that a *virtual machine*, a programmed computing system, is being operated by agents, the *operators*, to create an actuality, the *operations*. This results in a third virtual machine, the service itself. The relations between the central virtual machine and its structural and behavioural components represent fundamental concepts in system implementation and operation (Edwards and Mason 1987):

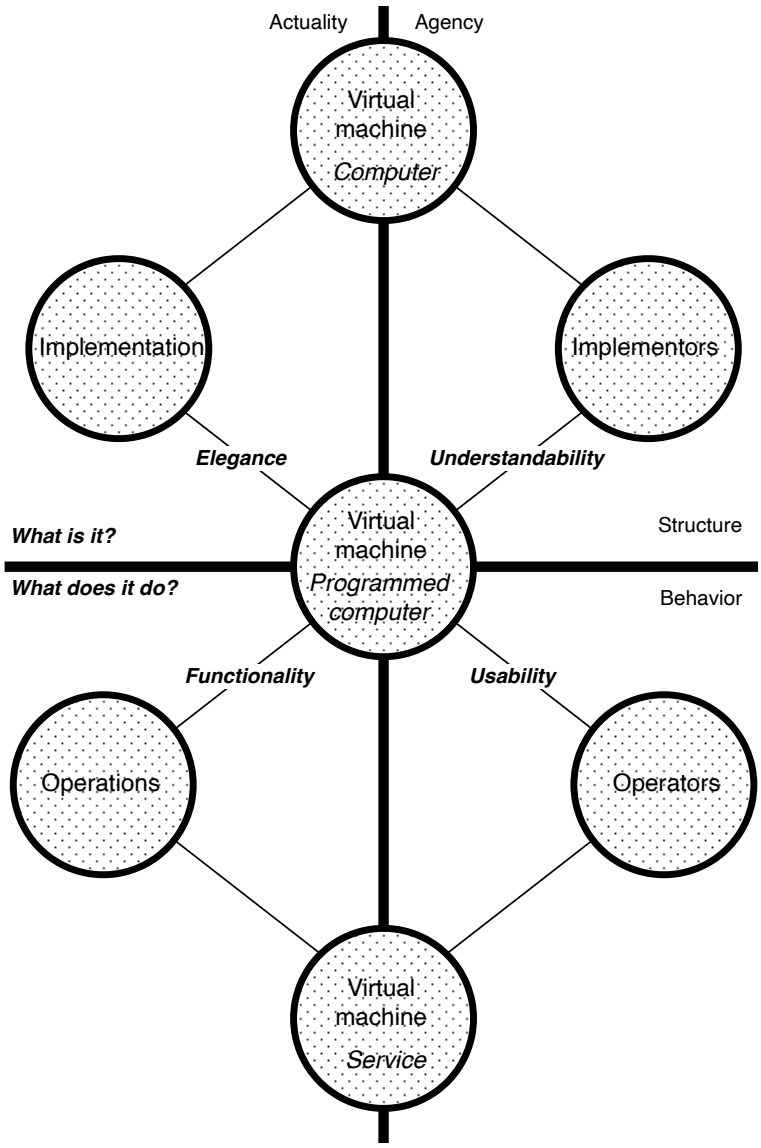

Fig.9 Levels of virtual machines

- *elegance* considerations, capturing the notion of efficiency in design, concern the relation between the system virtual machine and the underlying resource with which it is implemented—this is another virtual machine capturing the characteristics of the high-level language, operating system, and so on, used in implementation;
- *understandability* considerations, capturing the notion of comprehensibility in design, concern the relation between the system virtual machine and the implementors responsible for creating it;
- *functionality* considerations, capturing the notion of capabilities provided, concern the relation between the system virtual machine and the tasks for with which it is being implemented.
- *usability* considerations, capturing the notion of capabilities suitably interfaced, concern the relation between the system virtual machine and the operators who use it.

The logic underlying Figures 8 and 9 may be iterated to interpolate as much detail as required between the upper and lower levels—what is "activity" at one level becomes "structure" for the lower level. Figure 10 shows an analysis of the key features of an intelligent integrated system in terms of six layers:-

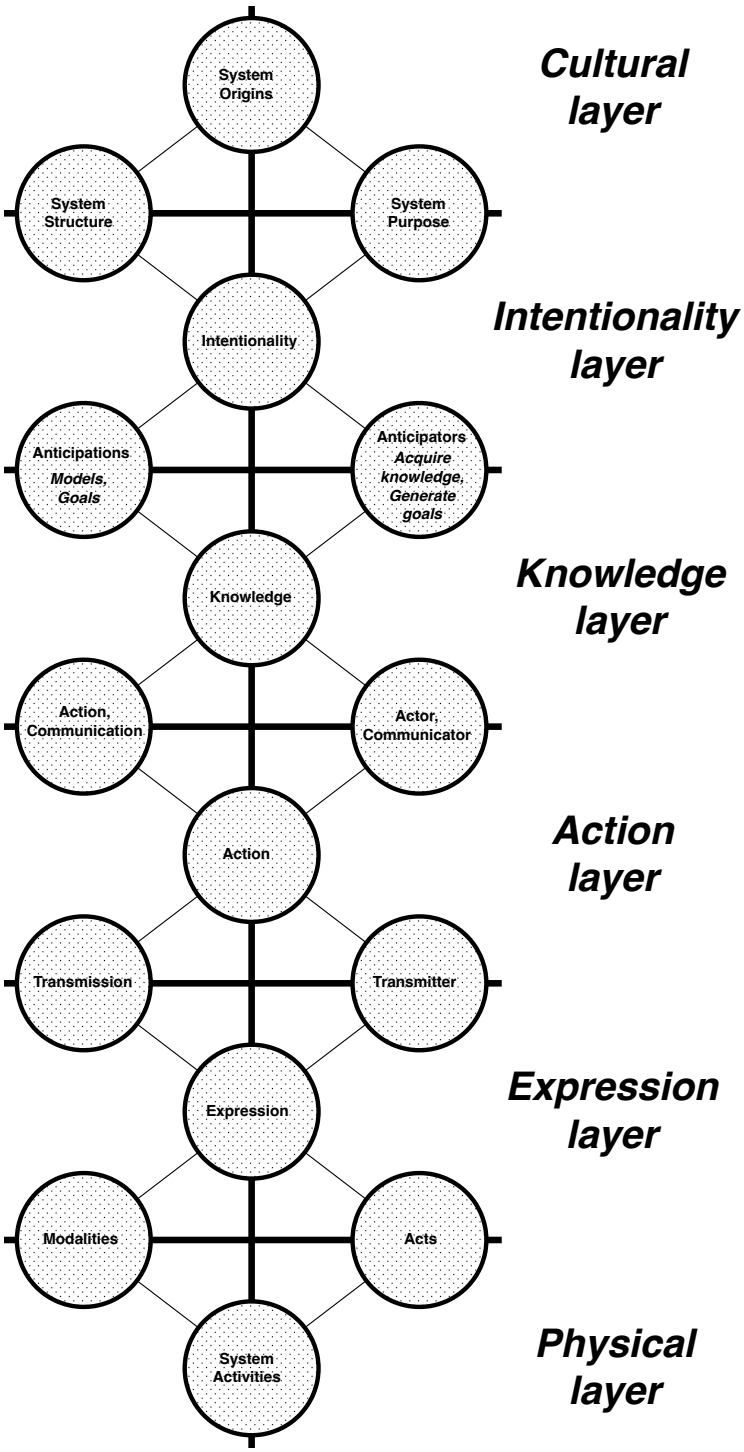

Fig.10 Layers of of an intelligent integrated system

- At the top level the overall intelligent integrated system originates in terms of purpose and structure as part of the culture within which it embedded. This *cultural layer* captures the milieu within which the system has been generated and can itself be subject to detailed analysis.
- At the next level the activities generated through this structure and purpose lead to a system of intentionality in which anticipatory activity leads to the acquisition of knowledge, or models of the world, and the generation of goals. This *intentionality* layer captures the anticipatory nature of an intelligent system in supporting its survival through prediction and action.

- At the next level the activities generated through anticipation lead to actions and communications—a linguistic distinction between activities directed to World 1 effects and World 2 effects, respectively. This *knowledge* layer captures the internal processes supporting the modeling and control activities of an anticipatory system.
- At the next level the activities generated through action and communication have to be transmitted to some external medium. This *action* layer captures the internal processes supporting the interfacing of an anticipatory system to the world.
- At the next level the activities generated through transmission have to be expressed in such a way as to have the desired effect in the world. This *expression* layer captures the internal processes supporting the encoding of actions and communications.
- At the lowest level the activities generated through expression exist physically in the external world. This *physical* layer captures the external effects of the activities of an anticipatory system.

Figure 11 shows the virtual circuits in, and between, two organizations using intelligent integrated systems with the structure shown in Figure 10.

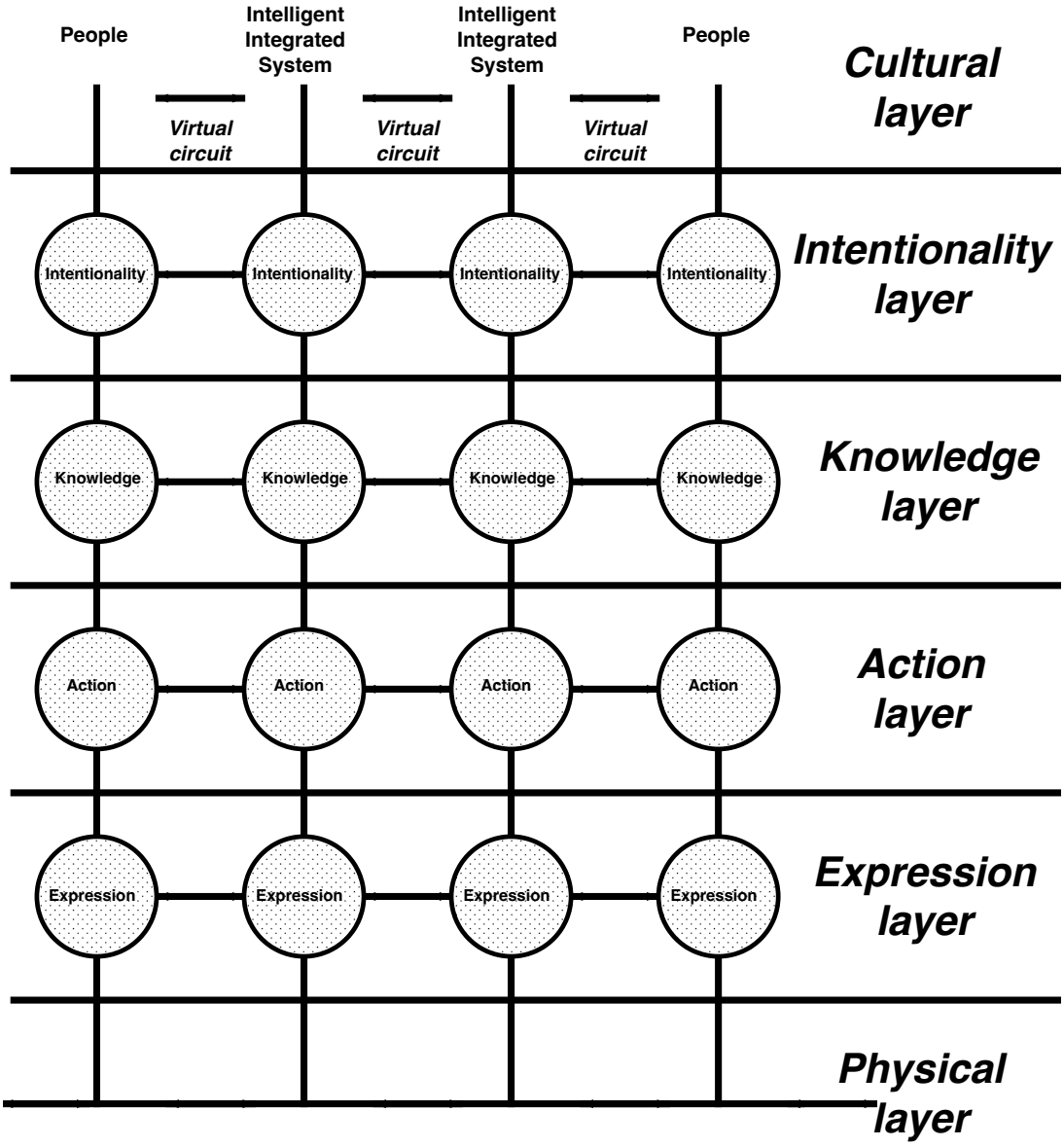

Fig.11 Virtual circuits in, and between, two organizations

Integrated systems have evolved as it has become possible to incorporate higher and higher layers within the system. Before automation all human activities involved direct interaction. The early stages of automation involved information systems as intermediaries in the expression of data through electronic instrumentation and control systems. At the next stage of numeric control complete actions could be specified that resulted in the machining of a piece part. The current generation of knowledge-based systems enables complete models of the manufacturing process to be incorporated that allow the overall process to be optimized and adapted to changing circumstances. The next generation of intentional systems will include models of the business objectives of the manufacturing system that will aid its reconfiguration to automatically take into account changing requirements and opportunities.

Figure 11 can be developed in much detail as necessary to model the roles of each person, each physical process and each of information processing activity within an organization. What is most interesting about this diagram, however, is that the same distinctions, terminology and model are being applied to the people, their interactions with each other, their interface to the information technology, its interface to other information technology, and the interfaces between organizations. The same systems principles apply to the psychology, sociology, human-computer interaction, computer-computer interaction, and business organization. This is the foundation on which a new science of manufacturing can be based that encompasses technology, management and economics.

6. Agency, actuality, accountability and impact analysis

If one compares the analysis above with a classical operations research approach to the analysis of manufacturing, the significant addition is the distinction made between actuality and agency, and the incorporation of the intentional processes of human agents within the overall model. Habermas (1981) has emphasized the essential differences between the dynamics of society and that of physical systems. The “laws” that govern human behaviour are largely conventions embedded in our society and propagated through our culture. They do not have the necessity of the laws underlying physical systems and their analysis differs in many ways from those of physical systems. Human beings create their future through acts of choice that are constrained by their forward-looking intentions. Physical systems unroll their future through acts of necessity that are determined by their previous states.

These differences, and the interactions between them, show up very clearly in the systemic analysis of the causes and responsibility for significant effects, such as a major commercial success or disaster. Figure 12 shows a significant effect on the far right with the chain of physical causation leading up to it on the left. The critical point in this physical analysis is precisely that at which the chain of causation breaks—that is, where human intervention is indicated because a choice was made. A second chain can then be traced as shown in the vertical direction, that of the *accountability* of the human agents responsible for that choice. The critical point in this social analysis is again precisely at that point where the chain breaks—this time, where human choice was made without adequate authority or justification. This defines the *accountability nexus*, the link from an agent to the responsibility for the significant effect.

Real-life situations usually involve many interlinked chains of the form shown in Figure 12, and the ‘breaks’ are rarely clear-cut. A combination of interdependent causes and interdependent accountabilities are generally involved and both the apportionment of responsibility and the generation, or prevention, of similar situations are complex problems. However, this is not to say that the situation is so vague as to be unanalysable. Quite the contrary, careful tracing of the chains of causality and accountability is just what is needed to maximize the chance of success or control the possibility of disaster.

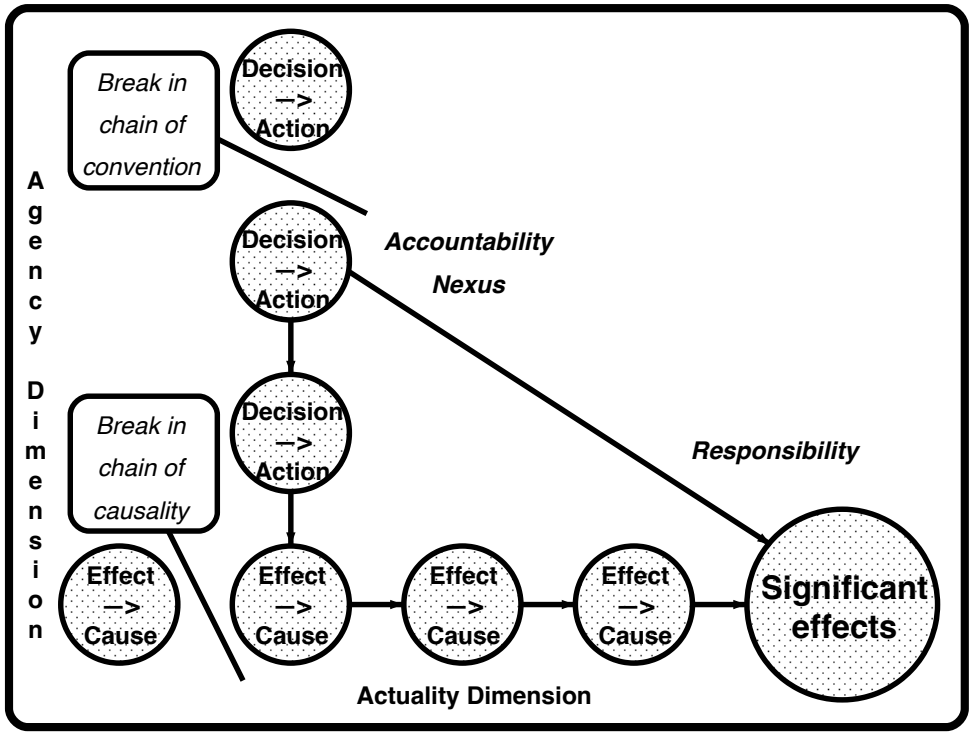

Fig.12 Interlinked chains of accountability and causality

At the top level of the operation of intentionality within an organization, the anticipatory processes may be seen as concerned with the potential impact of the choices available in any decision to be made. Figure 13 shows the logic of Figure 12 extended to show the dimensions of *impact analysis* of any human choice or decision.

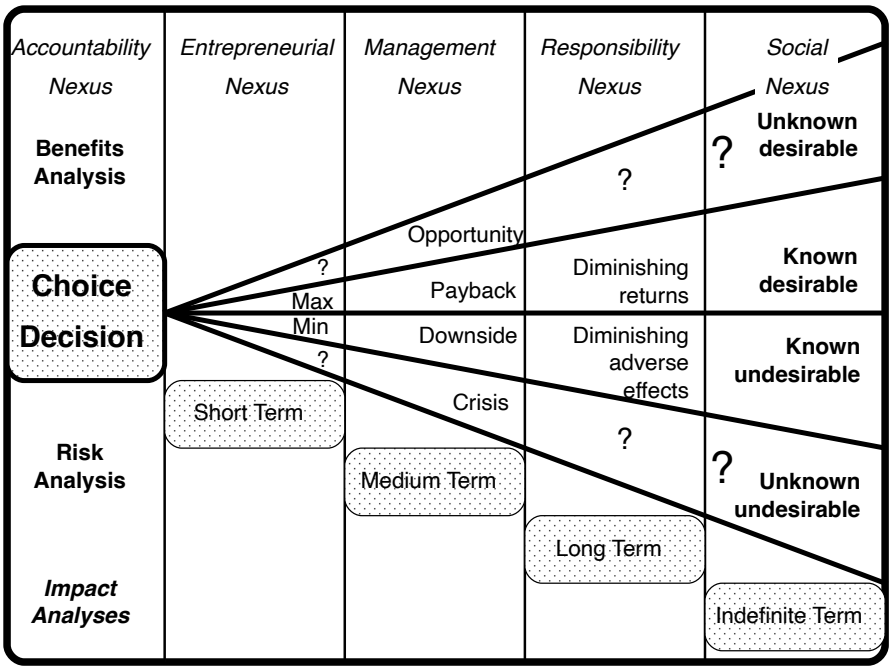

Fig.13 Impact analysis of human choice or decision

There are three basic logics underlying Figure 13:

• first, a system of *values* whereby certain consequences of the decision are regarded as desirable and others as undesirable—these arise from the cultural layer in Figure 10 and generate the intentional layer;

- second, a system of *knowledge* whereby certain consequences of the decision are known in advance and others are not—these are part of the knowledge layer in Figure 10;
- third, a logic of *impact* in which certain consequences of the decision are in some regions of impact and others are in different regions—these are incorporated in the action, expression and physical layers of Figure 10.

These regions are, in general, temporal, spatial, social, cultural, economic, anywhere where boundaries may be drawn. Figure 13 shows the temporal dimension divided into short, medium, long, and indefinite term effects:

- the short term is one of the initiating, entrepreneurial activity to implement the decision;
- the medium term is one of the management activity to follow through the consequences of the decision activation, maximizing the desired effects and containing the undesired effects;
- the long term is one of responsibility for the roll-on consequences of the preceding activity when management has moved to other activities;
- the indefinite term is one of society picking up the unexpected consequences of the decision beyond any reasonable responsibility horizons.

Thus, the distinctions and models already derived may be used as a basis for a detailed analysis of business phenomena involving a mix of physical and human processes. There are strong analogies between the actuality and agency dimensions as Figure 12 shows. However, there are also fundamental differences between backward-looking causal processes and forward-looking intentional processes. Operations research has been primarily concerned with the mathematical foundations of causal processes in the past, and this is still an essential component in the analysis of manufacturing systems. We have to extend the models to incorporate the intentional processes of people. The relevant foundations are being generated currently by work on knowledge acquisition for expert systems where a new paradigm is being used in information systems design—modelling expert activity in decision and control rather than the dynamics of the system about which decisions are being made (Gaines 1986a). The switch from a physical paradigm, not to a psychological paradigm, but rather to a balanced paradigm that incorporates models of both physical and human systems, is precisely that required for a new science of manufacturing.

7. Summary and conclusions

The total integration of the manufacturing process, both within itself, and within the overall operation of the organization is now technically feasible in terms of communications, control and information technology. However, the integration of integrated manufacturing systems within the management structure of the organization, and the management of the complexities, new opportunities and new problems, of such systems present major difficulties that are impeding use of new technologies. It has been suggested that a new science of manufacturing is required integrating technology, management and economics, and this paper has analysed the requirements for such a new science and developed a theoretical model for integrated systems that shows promise of satisfying these requirements.

Figure 14 summarizes the features of the theoretical model. It extends the layered communications model of computer communications to incorporate the interactions between people and information systems, and between the organization and the business world. It distinguishes the physical world of material flows from the psycho-social world of knowledge and intentionality flows, and the logical world of information and control flows. Provided these basic distinctions are made, however, it is possible to model the complete

structure and activities encompassed in Figure 14 within a unified framework. It is the detailed development of this unified framework that will constitute a new science of manufacturing. The empirical data, theoretical concepts, mathematical tools, and computational techniques necessary for this development are available now. The challenge is to bridge the gap between them and the commercial needs of modern manufacturing.

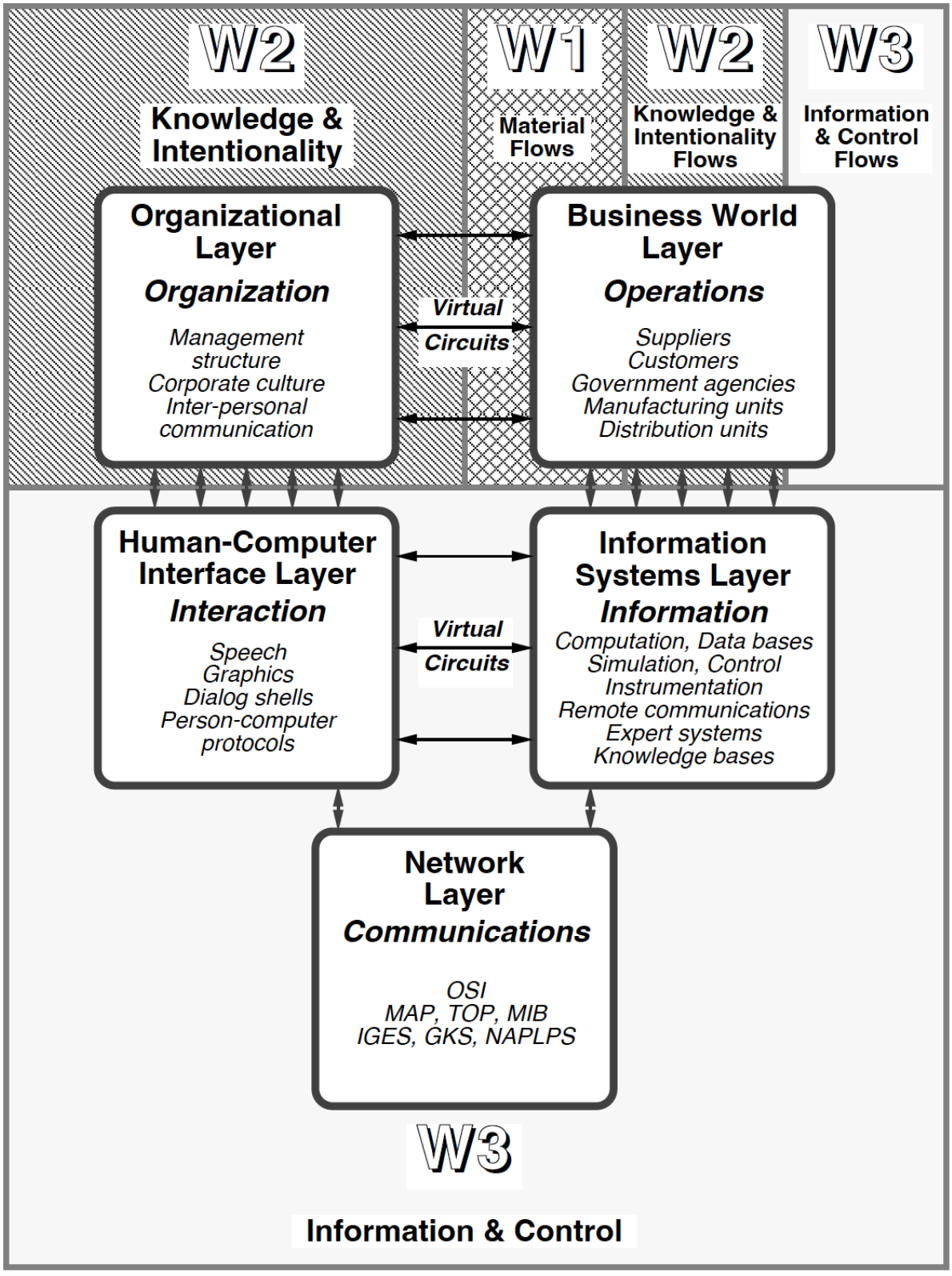

Fig.14 A unified framework for a new science of manufacturing

8. Acknowledgements

Financial assistance for this work has been made available by the National Sciences and Engineering Research Council of Canada.

9. References

Akeel, H.A. (1986). Role of robotics in flexible automation—an American perspective. **Proceedings of Japan-USA Symposium on Flexible Automation**. 3-4. Osaka (July).

Bartee, T.C., Ed. (1986). **Digital Communications**. Indianapolis: Sams.

Boeing (1985). **TOP: Technical and Office Protocols**. Seattle: Boeing Computer Services.

Brown, G.S. (1969). **Laws of Form**. London: George Allen & Unwin.

Brown, T., Alexander, S.M., Jagannathan, V. & Kirchner, R. (1985). Demonstration of an expert system for manufacturing process control. Birtwistle, G., Ed. **AI, Graphics and Simulation**, 110-113 (January). La Jolla, California: Society for Computer Simulation.

Bruno, G., Demartini, C. & Valenzano, A. (1984). Communication and programming issues in robotic manufacturing cells. **International Conference on Robotics**, **84CH2008-1**, 361-367. Silver Spring, Maryland: IEEE Computer Society Press.

Bruno, G., Elia, A. & Laface, P. (1985). A rule-based system for production scheduling. **Proceedings COMPINT'85**, **IEEE 85CH2136-O**, 35-39 (September). Montreal.

Day, J.D. & Zimmerman, H. (1983). The OSI reference model. **Proceedings IEEE**, **71**(12), 1334-1340 (December).

Deal, T.E. & Kennedy, A.A. (1982). **Corporate Cultures: The Rites and Rituals of Corporate Life**. Reading, Massachusetts: Addison-Wesley.

Edson, D. (1984). Bin-picking robots punch in. **High Technology**, **4**(6), 57-61 (June).

Edwards, J.L. & Mason, J.A. (1987). Evaluating the intelligence in dialogue systems. **International Journal of Man-Machine Studies**, **27**(1), to appear.

Fox, M.S. (1985). Knowledge representation for decision support. Methlie, L.B. & Sprague, R.H., Eds. **Knowledge Representation for Decision Support Systems**. pp. 3-26. Amsterdam: North-Holland.

Francis, P.H. (1986). Toward a science of manufacturing. **Mechanical Engineering 108**(5), 32-37 (May).

Gaines, B.R. (1975). Analogy categories, virtual machines and structured programming. Goos, G. & Hartmanis, J., Eds. **GI—5.Jahrestagung**. **Lecture Notes in Computer Science**, **34**, 691-699. Berlin: Springer Verlag.

Gaines, B.R. (1979). The role of the behavioural sciences in programming. **Structured Software Development Vol.2**. pp. 57-68. Maidenhead, UK: Infotech International.

Gaines, B.R. (1984). Perspectives on fifth generation computing. **Oxford Surveys in Information Technology**, **1**, 1-53.

Gaines, B.R. (1986a). Expert systems and simulation in industrial applications. Luker, P.A. & Adelsberger, H.H., Eds. **Intelligent Simulation Environments**, **17**(1), 144-149 (January). La Jolla, California: Society for Computer Simulation.

Gaines, B.R. (1986b). Sixth generation computing: a conspectus of the Japanese proposals. **ACM SIGART Newsletter** (95), 39-44 (January).

Gaines, B.R. (1986c). Foundations of knowledge engineering. Bramer, M.A., Ed. **Research and Development in Expert Systems III**. pp.13-24. Cambridge: University Press.

Gaines, B.R. (1986d). Expert systems and simulation in the design of an FMS advisory system. Hurrion, R.D., Ed. **Simulation in Manufacturing**. pp.311-324. Bedford, UK: IFS Conferences.

Gaines, B.R. & Shaw, M.L.G. (1986a). From timesharing to the sixth generation: the development of human-computer interaction part I. **International Journal of Man-Machine Studies**, *1*(1), 1-27 (January).

Gaines, B.R. & Shaw, M.L.G. (1986b). Foundations of dialog engineering: the development of human-computer interaction part II. **International Journal of Man-Machine Studies**, **1**(2), 101-123 (February).

Gaines, B.R. & Shaw, M.L.G. (1986c). A learning model for forecasting the future of information technology. **Future Computing Systems, 1**(1), 31-69.

General Motors (1984). General Motors Manufacturing Automation Protocol. Warren, Michigan: General Motors Corporation.

Gordon, P. (1984). What is integrated software?. **PC World**, **2**(11), 72-77 (October).

Habermas, J. (1981). **The Theory of Communicative Action: Reason and the Rationalization of Society**. Boston: Beacon Press.

Hall, E.T. (1959). **The Silent Language**. New York: Doubleday.

Hayes-Roth, F. (1984). The industrialization of knowledge engineering. Reitman, W., Ed. **Artificial Intelligence Applications for Business**. pp. 159-177. Norwood, New Jersey: Ablex.

Jarvis, M.T. (1985). **Molecular Electronics: Beyond the Silicon Chip**. Fort Lee, New Jersey: Technical Insights.

Kim, S.H. & Suh, N.P. (1985). On an expert system for design and manufacturing. **Proceedings COMPINT'85**, **IEEE 85CH2136-O**, 89-95 (September). Montreal.

Kirschbrown, R.H. & Dorf, R.C. (1985). KARMA—a knowledge-based robot manipulation system. **Robotics**, **1**(1), 3-12 (May).

Klir, G.J. (1985). **Architecture of Systems Problem Solving**, New York: Plenum Press.

Leopold, G. (1986). Bus standard for hospitals is next. **Electronics**, **59**(11), 17-18 (March).

Majchrzak, A., Chang, T.-C., Barfield, W., Eberts, R. & Salvendy, G. (1987). **Human Aspects of Computer-Aided Design**. Philadelphia: Taylor & Francis.

Mangold, V. (1981). The industrial robot as a transfer device. **Robotics Age**, **3**(4) (July).

McCarthy, J.J. (1985). MAP's impact on process plants. **Control Engineering**, **32**(11), 67-69 (October).

Miller, R.K. (1986). **Optical Computers: The Next Frontier in Computing**. Madison, Georgia: SEAI.

Mills, J.B. (1986). The spectrum of human factors in CIM. **Proceedings of 3rd International Conference on Human Factors in Manufacturing**. pp. 23-34. Bedford, UK: IFS Conferences. (November).

Mitchell, C.M., Govindaraj, T. & Ammons, J.C. (1984). Human-machine interface in the control of flexible manufacturing systems. **Proceedings of IEEE International**

Conference on Systems, Man and Cybernetics, **84CH2063-6**, 59-62 (October). Halifax, Nova Scotia.

Moto-oka, T., Ed. (1982). **Fifth Generation Computer Systems**. Amsterdam: North-Holland.

Nelson, T. (1980). Interactive systems and the design of virtuality. **Creative Computing**, **6**(11), 56-62 (November).

Nolan, R.L. (1983). Computer data bases: the future is now. Salerno, L.M., Ed. **Catching Up With the Computer Revolution**, 225-248. New York: Wiley.

Popper, K.R. (1968). Epistemology without a knowing subject. Van Rootselaar, B., Ed. **Logic, Methodology and Philosophy of Science III**. pp. 333-373. Amsterdam: North-Holland.

Rosen, R. (1985). **Anticipatory Systems**. Oxford: Pergamon.

Schutz, A. & Luckmann, T. (1973). **The Structures of the Life-World**. London: Heinemann.

Shannon, R.E., Mayer, R. & Adelsberger, H.H. (1985). Expert systems and simulation.
Smith, C.A. (1985). The role of simulation analysis in improving the manageability of integrated systems. **Proceedings of Autofact'85**, 11.1-11.10 (November). Detroit, Michigan: Society of manufacturing Engineers.

Smith, D.C. (1983). Visibility in the Star user interface. **Proceedings of Graphics Interface '83**, 181. Ottawa: National Research Council of Canada.

Smith, C.A. (1985). The role of simulation analysis in improving the manageability of integrated systems. **Proceedings of Autofact'85**, 11.1-11.10 (November). Detroit, Michigan: Society of manufacturing Engineers.

Sullivan, W.G. & LeClair, S.R. (1985). Justification of flexible manufacturing systems using expert system technology. **Proceedings of Autofact'85**, 7.1-7.13 (November). Detroit, Michigan: Society of Manufacturing Engineers.

Tack, P.J., Bolk, H. & Slagmolen, G. (1986). Decision making around flexible manufacturing systems (FMS): the problem of context and rationalities. **Proceedings of 3rd International Conference on Human Factors in Manufacturing**. pp. 199-206. Bedford, UK: IFS Conferences. (November).

Uenohara, M. (1986). Flexible automation in Japanese electronics industry. **Proceedings of Japan-USA Symposium on Flexible Automation**. 5-12. Osaka (July).

Ulrich, W. (1983). **Critical Heuristics of Social Planning**. Bern: Haupt.

Weegenaar, H.J. (1978). Virtuality and other things like that. **Proceedings of IEEE COMCON**, **CH1388-8/78**, 287-293.

Wichmann, K.E. (1986). An intelligent simulation environment for the design and operation of FMS. Lenz, J.E. (Ed.) **Proceedings of 2nd International Conference on Simulation in Manufacturing** 1-11 (June). Bedford, UK: IFS Conferences.

Wortman, D.B. & Miner, R.J. (1985). The role of simulation in designing manufacturing systems. **Proceedings of Autofact'85**, 11.11-11.20 (November). Detroit, Michigan: Society of manufacturing Engineers.