

Computer Support for Cooperative Work in Advanced Manufacturing

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Abstract. In order to prevail in the emerging turbulent business environment, the work organization of advanced manufacturing must be able to adapt diligently and dynamically to the vicissitudes of a volatile market. Meeting this demand requires horizontal exchange of information within a self-organizing cooperative ensemble of decision makers with a high degree of autonomy in their strategies and conceptualizations. Advanced manufacturing therefore poses new demands on the information system of the enterprise that are not addressed in the prevailing approach to Computer Integrated Manufacturing.

The Transformation of Manufacturing

The world of manufacturing is teeming with change. Comprehensive changes in the general societal environment pervade individual manufacturing enterprises with a whole new regime of demands and constraints. Simultaneously, the technology of manufacturing is subjected to radical, sweeping, and interlaced changes. The combined effect of these onslaughts is a profound transformation of the work organization.

The Transformation of the Business Environment

The business environment of modern manufacturing enterprises is becoming rigorously demanding. In this process, some global developments in the political economy of industrial society play a key role:

First, the pace of technological change is accelerating in all branches of production, spurred by the exponential growth of scientific research activities and the

tighter coupling between research and production (Albrecht, 1982). This development is enhanced by the shortening of the incubation period of product design due to the introduction of computer-aided design and engineering technologies.

Because of this, product life cycles are being reduced dramatically. For example, in the production of automobiles and trucks major redesigns of engines, cars, axles, and brakes used to occur every six or seven years. Today, however, product life cycles have been cut in half, that is, to about three or four years. In an industry such as the production of engineering workstations, which used to have a product life cycle of three years, it now has been reduced to less than six months (Gunn, 1987). In response to these dynamic conditions of competition, manufacturing enterprises are reducing batch sizes as well as the overall lead time of their operations so as to be able to penetrate markets and recoup investments while the product is still competitive.

Second, driven by the development of the means of transportation and communication and the creation of an increasingly integrated world market, global competition is becoming increasingly fierce (Ohmae, 1985; Gunn, 1987). In response to this development, companies are paying more attention to customers' needs and propensities; they treat their markets as 'fashion markets.' In order to indulge customers, the shortest possible elapse time from order to delivery is becoming a competitive advantage in its own right, and product life cycles are being cut short as yesterday's models are superseded by tomorrow's. This reinforces the demand on the flexibility and versatility of manufacturing enterprises. Also in order to humor customers, companies are expanding the list of models and variants in their sales catalogues. As a result, manufacturing has become beset by rampant product diversification. For example, as reported by Aoki (1988), a Japanese automobile factory that had produced 500 varieties of cars (combinations of engine, transmission, color, body type, options etc.) in the mid 1960's, produced 32,100 varieties by 1978. The average number of cars per variety was 11 in a three month period. Even more spectacularly, the number of variants handled by Volvo, the Swedish automobile manufacturer, is on the order of 460,000 (Boisen, 1985). Needless to say, a manufacturing operation of this magnitude of complexity cannot be conducted in a mode of coordination based on the production of parts and subassemblies for inventories. And in fact, in order to cope with product diversification, manufacturing organizations are converting to an order-driven mode of coordination, e.g., by applying just-in-time principles. Thus, the ongoing diversification not only deepens the complexity of day-to-day operations but enhances further the requirement of versatility and flexibility that work organizations in manufacturing must meet.

And third, as a result of the sweeping introduction of new advanced manufacturing technologies, industries like automobiles, electronics, etc., that were labor-intensive as recently as a decade ago, are being transformed into capital-intensive industries. As observed by Ohmae (1985), this shift "demands deep and immediate market penetration" so as to "defray heavy initial investment and to sustain the heavy outlays necessary for continued production process innovation". To meet this challenge, the work organization must be able to slash lead time and work-in-pro-

cess to barest minimum. To be a "world-class manufacturer," according to Gunn (1987), a company needs inventory turnovers in raw materials and work-in-process on the order of 25 to 100 turns per year as opposed to the 1 to 4 turnovers that used to be the standard. Likewise, while the ratio of value-added lead time to cumulative manufacturing lead time in traditional batch manufacturing has been on the order of 5 %, the rate now required in global competition is greater than 50 %. Thus, the requirement of increasing manufacturing versatility and flexibility engendered by the dynamic character of the business environment is reinforced by an effort to speed up capital turnover.

That is, in the emerging business environment, manufacturing enterprises have to cope with shorter product life cycles, roaring product diversification, minimal inventories and buffer stocks, extremely short lead times, shrinking batch sizes, concurrent processing of multiple different products and orders, etc. To prevail, then, the work organization of advanced manufacturing must be able to adapt diligently and dynamically to the vicissitudes of a volatile market.

The Transformation of Work

The strategic measures employed to meet this challenge include, first and foremost, advanced manufacturing technologies such as Computer Aided Design, Computer Aided Engineering, Computer Aided Manufacturing, Flexible Manufacturing Systems, and Computer Integrated Manufacturing. However, far from alleviating the demands on the work organization, the introduction of these technologies adds new dimensions to the current change of manufacturing work.

First, the role of the worker in the process of production is transformed radically by the introduction of a control mechanism between the human agent and the transformation process, thus liberating the worker from the first order feedback loop of controlling the drawing, milling, grinding, drilling, handling, etc., processes. By delegating the execution of the automatic sensori-motor routines of skill-based work to the machine system, workers are left in charge of higher-order cognitive functions like planning, supervision, and fault diagnosis. Relieved of the regime of the first-order feedback loop, the individual worker is able to attend to a wider segment of the total transformation process; that is, the required domain knowledge becomes more extensive and more complex.

Second, the control functions of the various production processes (milling, grinding, drilling, handling, washing, painting, etc.) are being integrated by means of complexes of computers and data communication facilities (CAD/CAM, FMS, CIM, etc.). Thus, advanced manufacturing systems are being developed into tightly coupled megasystems, not unlike modern chemical plants where multiple chemical processes are combined into one continuous production process without intermediate storage which might have served to decouple the subsystems. In such settings, workers must cope with complex systems where disturbances and accidents are not linear courses of events released by only one cause and where the potential ramifi-

cations of any incident or intervention are immense. In other words, with the evolving integration, the size of the problem space of any agent in charge of control and maintenance grows exponentially. Thus, the functions of diagnosing possible disturbances and predicting relevant accidental courses of events are becoming increasingly demanding (Rasmussen, 1987; Hirschhorn, 1984).

In sum, the work organization of advanced manufacturing must be able to cope with very complex and dynamic decision making situations. However crucial advanced manufacturing technologies may be for the competitive capability of companies, in so far as the demands posed on the work organization are concerned, the technological development is just another factor adding to the complex and dynamic character of the situation. Thus, as demonstrated by a number of studies (e.g., Child, 1987; Blumberg and Gerwin, 1984; Savage, 1987), the competitive potentials of advanced manufacturing technologies cannot be realized without concomitant changes in the organization of work .

The Transformation of the Work Organization

The crucial point in understanding the characteristics of the work organization of advanced manufacturing is to conceive the work organization as an emerging formation of cooperative relations, adapting dynamically to the demands and constraints of the environment and the technical resources available. (See Schmidt, 1990, for an elaboration of this conception).

An 'Open Systems' Approach

Historically, manufacturing and administrative organizations have of course been highly successful in reducing the complex and dynamic character of their environments. By severely limiting the range of products and services offered and by imposing strict schedules and procedures on their customers and clientele, organizations in areas of mass production and mass-transactions processing were able to create artificial work settings where actions, for all practical purposes, could be assumed to be subsumed under preconceived plans. In fact, however, these work settings were always the exception. By far, most of the work in industrial societies is performed in other kinds of settings (e.g., batch or job production, office work). And in view of the fundamental trends in the political economy of modern industrial society, they will probably remain an exception, a transient form in the history of work.

Anyway, in the dynamic environments characteristic of modern work settings, work coordination by means of preestablished schemes of task allocation, procedures, plans, and schedules is no longer adequate. In flexible work organizations, patterns of cooperative work relations are in a state of perennial change and renegotiation, loosely and indefinitely controlled by communication and propagation of

decisional criteria within the cooperating ensemble (cf. Kaplan, 1989). Thus, in view of the dynamic nature of the environment of manufacturing operations, patterns of cooperative work relations should be conceived as being essentially ephemeral.

To the analyst and designer, the radical transformation of manufacturing calls for an 'open systems' perspective on work organization. In the words of Gerson and Star (1986):

"Every real-world system is an open system: It is impossible, both in practice and in theory, to anticipate and provide for every contingency which might arise in carrying out a series of tasks. No formal description of a system (or plan for its work) can thus be complete. Moreover, there is no way of guaranteeing that some contingency arising in the world will not be inconsistent with a formal description or plan for the system. [...] *Every real-world system thus requires articulation* to deal with the unanticipated contingencies that arise. Articulation resolves these inconsistencies by packaging a compromise that 'gets the job done,' that is, closes the system locally and temporarily so that work can go on."

Of course, a work organization in a highly routinized and stable setting, e.g., a chemical plant producing one product for a placid and predictable market, is an open system in the sense that it exchanges energy, materials, information etc. with the environment. But in the analysis of conventional mass-production organizations a cautious and guarded abstraction from the 'open' nature of the system is legitimate and provides valuable insight. The current transformation of manufacturing, however, makes a complete inversion of perspective mandatory. Instead of conceiving of the work organization as a closed and stable system, subject to local and temporary disturbances, a work organization in charge of manufacturing under contemporary competitive conditions should be conceived of as an open system that reduces complexity and uncertainty by local and temporary closures.

Because of the high demand on flexibility and the high degree of interdependency, advanced manufacturing acquires a distinct quality of self-organization. As pointed out by Susman and Chase (1986), "many decision or actions will be handled by whoever is first exposed to the information related to them, rather than by someone assigned the authority to take such actions." Thus, the pattern of communication and flow of information within the cooperating ensemble is in principle, unpredictable: "Predicting when and where such exchanges must occur will be difficult, and lower-level personnel will be as likely to initiate such exchanges with those at upper levels as they are to receive them, and the horizontal flow of information across functions and manufacturing cells will also be reciprocal." (Susman and Chase, 1986)

Cooperative Work and its Coordination

The general implications of these changes in the organization of manufacturing work are fairly well understood (cf., e.g., Mintzberg, 1979; Hirschhorn, 1984; Blumberg and Gerwin, 1984; Kern and Schumann, 1984; Susman and Chase, 1986; Savage, 1987; Child, 1987; Cummings and Blumberg, 1987; Aoki, 1988).

A feature of the emerging work organization that has been figured prominently in the debate is the 'self-regulating work group' of 'multi-functional workers.' For example, having observed that advanced manufacturing systems are tightly coupled to vendors and customers and that this may place severe demands on the adaptive capacity of the system, Cummings and Blumberg (1987) conclude that for advanced manufacturing systems the "appropriate work designs should be oriented to groups of employees rather than individual jobs, and to employee self-control rather than external forms of control, such as supervision. This calls for self-regulating work groups." These observations are quite pertinent and a number of socio-technical experiments in recent years have demonstrated the competitive advantages accruing from work redesign in this direction.

However, cooperative work relations in advanced manufacturing enterprises are not limited to the group or team responsible for, e.g., a particular shop. Cooperative work relations embrace operations of the entire enterprise, from Marketing to Shipping, from Design to Final Assembly. Cooperative work relations may even embrace subcontractors supplying parts and subassemblies and may thus transcend the confines of companies as formal entities.

Since manufacturing involves multitudes of discrete parts and processes that may interact in unpredictable ways, the reciprocal dependency of the different functions of advanced manufacturing is actually very high. In the words of Harrington (1984), manufacturing should be conceived as "an indivisible, monolithic activity, incredibly diverse and complex in its fine detail. The many parts are inextricably interdependent and interconnected." Thus, as observed by Susman and Chase (1986), the various categories of workers - product designers, process planners, programmers, supervisors, operators, etc. - "will be highly interdependent with one another because of the need to exchange information to keep the factory operating." Accordingly, for a manufacturing enterprise to be able to adapt diligently and dynamically to changing conditions, the entire enterprise must react "simultaneously and cooperatively" (Harrington, 1973). Rapid and concerted adaptation of all the specialized functions, from Marketing to Shipping, of a diversified manufacturing operation to the vicissitudes of a volatile and complex environment is indeed the very essence of advanced manufacturing.

In conventional manufacturing, i.e., manufacturing of standardized products in large quantities for fairly stable markets, the basic coordination mechanism of the diversified manufacturing operation - "the vital control center for the company's manufacturing planning and control system" (Gunn, 1981) - is a "master production schedule" based on forecasts and standard lead times for the various parts. In so far as the underlying forecasts are accurate, coordination across functions and departments can be mediated by plans and other organizational procedures. Direct cooperative interaction across functions only takes place to handle exceptional contingencies such as shortages or to expedite a high priority order.

In advanced manufacturing, however, exceptional contingencies are the norm. The 'feed-forward' oriented mode of coordination is superceded by a 'feedback' oriented mode or, rather, the role of the central plan is transformed from an opera-

tional coordination mechanism to a procedure for ensuring and providing an adequate resource envelope for short term feedback oriented scheduling tasks. (Rindom, 1990; Kaavé, 1990). Thus, in an interesting discussion of the work organization of advanced manufacturing, Aoki (1988) conceives of the *kanban* or just-in-time system as a "semi-horizontal operational coordination mechanism" and argues that this mode of coordination is an effective way to adapt to changing market circumstances quickly without accumulating costly buffer inventories when many varieties comprising a large number of parts are involved. Aoki does not conceive the *kanban* mechanism as a panacea, however. Relating the mode of coordination on a company-wide scale with the concomitant demands on local work organization and job design, he observes that the semi-horizontal mode of coordination "crucially depends on the skills, judgment, and cooperation of [a] versatile and autonomous work force on the shop floor", and "a certain degree of blurring of job territoriality between workers on the one hand and foremen, engineers, programmers, etc., on the other".

However, the *kanban* system is not adequate for coordination of manufacturing operations faced with severe demands on flexibility and very small batch sizes. In a *kanban* system, information only propagates 'up-stream' as parts are used down the line. The speed and pattern of propagation of information is severely restricted and the information ultimately conveyed has been filtered and distorted by the successive translations along the line up-stream. The *kanban* system does not provide facilities allowing decision makers to anticipate disturbances and to obtain an overview of the situation. They are enveloped by an overwhelming and inscrutable automatic coordination mechanism. Accordingly, in manufacturing operations that must cope with the demands of a turbulent market, the indirect, dumb, and formal *kanban* mechanism is often subsumed under a very direct, intelligent, and informal cooperative coordination. In two manufacturing enterprises investigated by Rindom (1990) and Kaavé (1990), informal networks of clerks, planners, operators, and foremen in various functions such as purchasing, sales, production, shipping etc. were cooperating directly in controlling the flow of parts. A decision maker in this network would explore the state of affairs 'up-stream' so as to be able to anticipate contingencies and, in case of disturbances that might have repercussions 'downstream,' issue warnings. Such an informal network may even 'appropriate' the *kanban* system in order to increase its flexibility. To adjust the number of cards to the needs of the situation, cards may be held back temporarily, handed over directly, etc. In so doing, they exploit their detailed knowledge of lead times and inventories to control production far more closely and effectively than warranted by the *kanban* system.

In advanced manufacturing, production planning and control thus requires horizontal and direct cooperation across functions and professional boundaries within the company or within a network of companies. Quality control in advanced manufacturing has similar implications.

With reduced product life cycles and batch sizes and increased competitive emphasis on product quality, there is increased pressure to design products with re-

spect to manufacturability and to manufacture products right the first time. Consequently, as observed by Susman and Chase (1986), manufacturing functions such as product design, quality assurance, industrial engineering, production, etc. will become increasingly interdependent. For instance, the objective of the concept of Company Wide Quality Control (CWQC) is to make the 'voice of the customer' audible throughout the company so as to ensure that distributed decision making (e.g., local action to handle local disturbances) is guided by pertinent knowledge of customers' needs and requirements (Kogure and Akao, 1983; Sullivan, 1986a, 1986b).

In sum then, the work organization of advanced manufacturing may be conceived of as an ensemble of semi-autonomous groups of multi-functional workers cooperating on a wide scale spanning the entire company and perhaps even a network of companies. For manufacturing enterprises to prevail under the rigorous regime of the emerging global markets, requires concurrent and interactive horizontal coordination of the diversified activities of the manufacturing operation as a whole. This requirement, in turn, poses new demands on the information and communication infrastructure of the enterprise.

The Dialectics of Cooperative Work

As noted above, rapid, simultaneous, and concerted adaptation of the various specialized functions of a diversified manufacturing operation to the demands of a dynamic and complex environment is the very essence of advanced manufacturing. The ambition of the efforts in the Computer Integrated Manufacturing (CIM) field is thus to link and fuse the diverse information processing activities of the various manufacturing functions such as design and process engineering, production planning and control, process planning and control, purchasing, sales, distribution, accounting, etc. by means of a unitary and comprehensive information system so that the different functions are performed concurrently and interactively (Harrington, 1979; Harrington, 1984; Gunn, 1987). In order to facilitate this, the CIM concept envisages a comprehensive database system that 'integrates' the information processing pertaining to all functions of manufacturing.

In this concept, a number of important questions are still open, however. First of all, the central concept of computer-mediated 'integration' raises the question of the role and characteristics of cooperative work in advanced manufacturing since the various manufacturing functions are actually integrated through the agency of cooperative work. The comprehensive database system envisaged in the CIM concept thus can be conceived as a computer system that mediates horizontal cooperation among a large number of distributed decision makers throughout all functions of manufacturing. Some of the key issues in CIM systems design are therefore identical to the issues addressed by the new R&D area of Computer-Supported Cooperative Work or CSCW (for an overview of this field and its issues, see

Bannon and Schmidt, 1991). Of course, CIM encompasses process control systems (CNC, CAM, FMS, etc.) that do not have any relation to cooperative work. But so far as the very *integrative* facility of CIM systems is concerned, CIM is essentially computer-supported cooperative work. In so far, CIM is faced with some tough and challenging problems.

In fact, the very notion of computer-mediated integration is problematic in view of phenomena such as discrepancies of global and local goals, discordant decisional criteria, incommensurate conceptualizations, incongruent problem solving strategies, etc., all of which can be attributed to the distributed nature of cooperative work.

The core of the matter is that cooperative work is, in principle, distributed in the sense that decision making agents are semi-autonomous in their work. This distributed nature of cooperative work is constituted by different features of cooperative work:

Situated action

Reality is inexhaustible. As pointed out by Suchman (1987), "the relation of the intent to accomplish some goal to the actual course of situated action is enormously contingent." Plans may of course be conceived by actors prior to action but they are not simply executed in the actions. Action is infinitely rich compared to the plan and cannot be exhausted by a plan. Action is 'situated' - to use Suchman's term - in the sense that circumstances encountered invariably defeat the very best plans and designs. Accordingly, each individual encounters contingencies that may not have been predicted by his or her colleagues and that, perhaps, will remain unknown to them. Each participant in the cooperative effort is faced with a - to some extent - unique local situation that is, in principle, 'opaque' to the others and have to deal with this local situation individually. For example: shortage of materials, delays, faulty parts, variations in component properties, design ambiguities and inconsistencies, design changes, changes in orders, cancellation of orders, rush orders, defective tools, software incompatibility and bugs, machinery breakdown, changes in personnel, illness, etc.

No goal or criterion applies to all contingencies. In order to handle local contingencies effectively, actors may have to apply criteria that violate even putatively global criteria such as corporate policy. In fact, on closer examination the putative global goals and criteria are also local in the sense that they are formulated in specific contexts as answers to specific questions.

For example, in a particular enterprise that manufactures specialized technical equipment the individual products are quite voluminous. This often gives rise to a plethora of local problems in the shipping department and conflicts of decisional criteria (Kaavé, 1990). The machines are shipped in containers with room for 26 machines. To reduce transportation costs, it is desirable to cram in all 26 machines. Now, customers do not issue orders in neat batches of 26. Usually, however, the

different customers have filed several orders at any one time so that it may be possible to collect 26 machines from different orders to fill a container. At the same time, the floor space in Shipping is insufficient. Machines are piled from floor to roof, from wall to wall. Accordingly, the foreman in charge of Shipping will strive to get rid of machines whenever possible. So, when the first machines for F arrive in Shipping, they will be attributed low priority, and the foreman will try to persuade Assembly and Quality Control to delay machines for F. But when the next machines for F eventually start arriving and are piling up, the machines for F get a higher priority in Shipping and the foreman will now try to persuade Assembly and Quality Control to expedite machines for F. When the container is finally dispatched, it may contain machines on order to be delivered now, one or a few machines from an earlier order that have been delayed for some reason, and perhaps - if the sum of these machines does not amount to 26 - one or more machines from an order with a later delivery date. In sum, the foreman in Shipping is faced with conflicting goals and criteria. He has to take his local problem of limited floor space into consideration while at the same time trying to reduce the cost of transportation and dispatch orders according to the different priorities attributed to the different orders. There is no way that he can satisfy all goals. He muddles through as best he can, which is usually quite proficient.

In sum, due to the 'situated' nature of human action cooperative work arrangements take on an indelible distributed character. No agent in the cooperative ensemble is omniscient.

Incommensurate Perspectives

Reality is inexhaustible in another - more systematic - sense too. The world defies unitary and monolithic conceptualizations. As pointed out by Gerson and Star (1986), "no representation of the world is either complete or permanent." A representation is a "local and temporary closure." Accordingly, a multiplicity of distinct perspectives is required to match the multiplicity of the field of work. A perspective, in this context, is a particular - local and temporary - conceptualization of the field of work, that is, a conceptual reproduction of a limited set of salient structural and functional properties of the object, such as, for instance, generative mechanisms, causal laws, and taxonomies, and a concomitant body of representations, e.g., models, notations, etc. Thus, to grasp of the diverse and contradictory aspects of the field of work as a whole, the multifarious ontological structure of the field of work must be matched by a concomitant multiplicity of perspectives on the part of the decision-making ensemble (Schmidt, 1990). Accordingly, the cooperative ensemble reproduces the multiplicity of its environment in the form of the multiplicity of 'small worlds' of professions and specialities.

There are two aspects to the multiplicity of perspectives.

First, as demonstrated by Rasmussen in a number of studies (e.g., 1979, 1985), a stratified structure of conceptualizations is characteristic of a number of work do-

mains. In technical domains, for example, Rasmussen (1985) has identified five levels of abstraction in a *means-end hierarchy* (see figure 1):

"When moving from one level of abstraction to the next higher level, the change in system properties represented is not merely the removal of the various functions or element at the lower level. In man-made systems these higher level principles are naturally derived from the purpose of the system, i.e. from the reasons for the configurations at the level considered. Change of level of abstraction involves a shift in concepts and structure for representation as well as a change in the information suitable to characterize the state of the function or operation at the various levels of abstraction. [...] In other words, models at low levels of abstraction are related to a specific physical world that can serve several purposes. Models at higher levels of abstraction are closely related to the specific purpose that can be met by several physical arrangements."

<i>Means-End Levels</i>	<i>Properties of the System Selected for Representation</i>
<i>Purpose, Constraints</i>	Properties necessary and sufficient for relating the performance of the system with the reasons for design, with requirements of environment. Categorization in terms referring to properties of the environment.
<i>Abstract Function</i>	Properties necessary and sufficient to establish relationships according to design or intention; energy, value, information, truth, etc. Relationship to underlying causal structure and function is depending on convention and design choice. Categorization in abstract terms, referring neither to system nor to the environment.
<i>Generalized Function</i>	Properties necessary and sufficient to establish "black box" input-output models of functions irrespective of underlying implementation; this level is necessary for coordination of different physical processes to serve joint higher purposes. Categorization according to recurrent, familiar input-output relationships.
<i>Physical Function</i>	Properties necessary and sufficient for use of object; for adjustment of object for use, to adjust to limits of use, to predict whether objects will serve particular use to select part to move for control of physical process. Categorization according to underlying physical process.
<i>Physical Form</i>	Properties necessary and sufficient for classification and recognition of material objects.

Figure 1. The means-end representation of technical systems (Rasmussen, 1988).

Second, perspectives are not always related to conceptual *levels* in the sense of a stratified order, however. In addition to conceptualizations as different levels of generative mechanisms or means-end relationships, conceptualizations may reflect *different functional requirements* that are contradictory in the sense that efforts directed at solving one functional problem interfere with efforts directed toward the others. That is, contradictory ends divides the field of work into distinct object domains, orthogonal to the levels of abstraction of the means-end hierarchy (see figure 2).

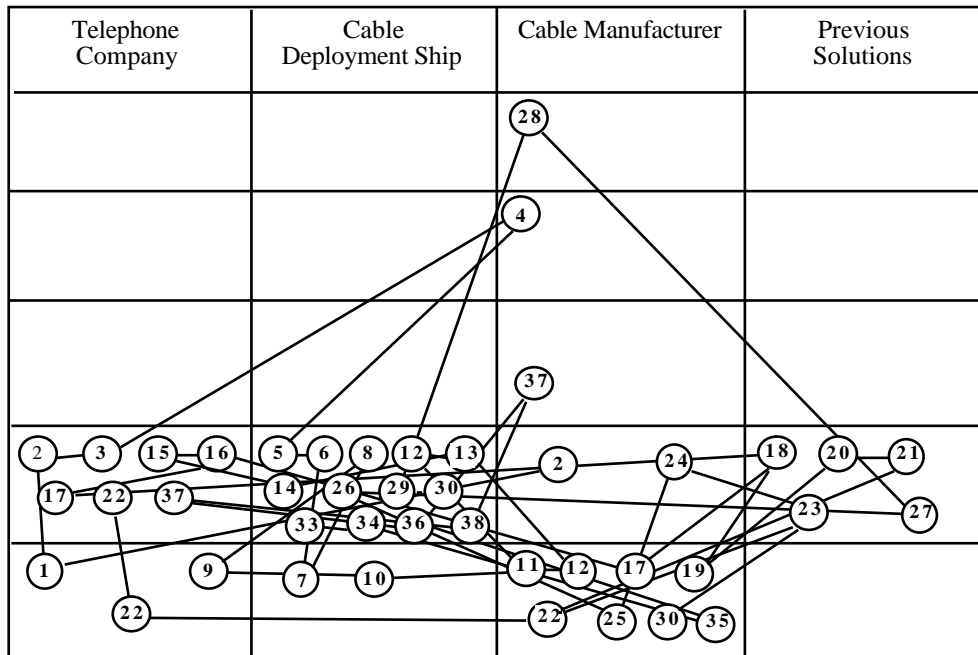


Figure 2. The figure shows the trajectory in the field of work of a design task: the design of a cable joint for optic fiber telephone cables. In this case, the object of design belongs to different object domains: it is a joint in a telephone cable, it is part of an assembly task under rough sea conditions, and, finally, it is an object to be manufactured by the equipment of the cable manufacturer (Rasmussen, 1990).

An omniscient and omnipotent agent to match the multifarious nature of the field of work in advanced manufacturing does not exist. The application of multiple perspectives - whether stratified conceptualizations such as means-end relationships or the orthogonal conceptualizations of distinct object domains - will typically require the joint effort of multiple agents, each attending to one particular perspective and therefore engulfed in a particular and parochial small world. So, in addition to the distributed character of cooperative work stemming from the contingent nature of work, cooperative work in complex settings is distributed in the profound sense that the cooperative ensemble is divided into myriads of small worlds with their own particular views of the world.

This dissolution must be overcome, however. The cooperative ensemble must interrelate and compile the partial and parochial perspectives by transforming and translating information from one level of conceptualization to another and from one object domain to another (Schmidt, 1990). There is no omniscient and omnipotent agent to perform these transformations and translations. Rather, the transformations and translations are performed in the context of specific situations, to solve particular problems. The generalizations by means of which the partial perspectives are integrated are not globally valid; they are merely satisfactory to solve the problem at hand. They are local and temporary closures.

Bucciarelli (1984) has provided an excellent example of this aspect of cooperative work. In a study of cooperative work in engineering design he observed that

"different participants in the design process have different perceptions of the design, the intended artefact, in process. What an engineer in the Systems Group calls an interconnection scheme, another in Production calls a junction box. To the former, unit cost and ease of interconnection weigh most heavily; to the latter, appearance and geometric compatibility with the module frame, as well as unit cost, are critical.

The task of design is then as much a matter of getting different people to share a common perspective, to agree on the most significant issues, and to shape consensus on what must be done next, as it is a matter for concept formation, evaluation of alternative, costing and sizing - all the things we teach."

This also applies to the the propagation of goals and criteria from one level of conceptualization to another. Propagation of goals and criteria within a cooperative ensemble is not a simple 'decomposition' or a syllogistic inheritance operation but involves a conceptual translation and a transformation of representation (Rasmussen, 1988). Again, there is no omniscient and omnipotent agent to perform these transformations and translations.

An interesting issue, raised by Charles Savage in a 'round table discussion' on Computer Integrated Manufacturing (Savage, 1986), illustrates this issue quite well:

"In the traditional manual manufacturing approach, human translation takes place at each step of the way. As information is passed from one function to the next, it is often changed and adapted. For example, Manufacturing Engineering takes engineering drawings and red-pencils them, knowing they can never be produced as drawn. The experience and collective wisdom of each functional group, usually undocumented, is an invisible yet extremely valuable company resource."

This fact is ignored by the prevailing approach to CIM, however:

"Part of the problem is that each functional department has its own set of meanings for key terms. It is not uncommon to find companies with four different parts lists and nine bills of material. Key terms such as *part*, *project*, *subassembly*, *tolerance* are understood differently in different parts of the company."

The problem is not merely terminological. It is the problem of multiple incommensurate perspectives. The effort to 'design for assembly,' for example, requires an 'iterative dialogue' involving guardians of incommensurate perspectives: Assembly, Subassembly, Parts Processing, Process Planning, Design, Marketing, etc. The issue raised by Savage (1986) is rooted in the multiplicity of the domain and the contradictory functional requirements. In Savage's words: "Most business challenges require the insights and experience of a multitude of resources which need to work together in both temporary and permanent teams to get the job done".

In sum, in complex work settings such as advanced manufacturing the multiplicity of the field of work is matched by multiple 'small worlds', each specialized in applying a particular perspective. There is no omniscient and omnipotent agent to match the multifarious environment or to integrate the specialized and local knowledge.

Different Heuristics

Finally, in complex environments decision making is performed under conditions of excessive complexity and incomplete, missing, erroneous, misrepresented, misunderstandable, incomprehensible, etc. information and will thus require decision makers to exercise discretion. In discretionary decision making, however, different individual decision makers will typically have preferences for different heuristics (approaches, strategies, stop rules, etc.). Phrased negatively, they will exhibit different characteristic 'biases'. By involving different individuals, cooperative work arrangements in complex environments are arenas for different decision making strategies and propensities (Schmidt, 1990, 1991). Thus, the decision making process of the cooperating ensemble as a whole is distributed in the sense that the agents involved are semi-autonomous in selecting their heuristics.

However, in order to ensure a satisfactory degree of consistency and objectivity in the performance of the ensemble as a whole and thus to meet the requirements of the environment in terms of product quality, reliability, safety etc., the different heuristics must be integrated. To ensure this integration of heuristics, the different decision makers subject the reliability and trustworthiness of the contributions of their colleagues to critical evaluation. This way they are able, as an ensemble, to arrive at more robust and balanced decisions (Schmidt, 1990).

For example, take the case of an "experienced and skeptical oncologist," cited by Strauss and associates (1985):

"I think you just learn to know who you can trust. Who overreads, who underreads. I have got X rays all over town, so I've the chance to do it. I know that when Schmidt at Palm Hospital says, 'There's a suspicion of a tumor in this chest,' it doesn't mean much because she, like I, sees tumors everywhere. She looks under her bed at night to make sure there's not some cancer there. When Jones at the same institution reads it and says, 'There's a suspicion of a tumor there,' I take it damn seriously because if he thinks it's there, by God it probably is. And you do this all over town. Who do you have confidence in and who none."

This process of mutual critical evaluation was described by Cyert and March (1963) who aptly dubbed it 'bias discount.' Even though dubious assessments and erroneous decisions due to characteristic biases are transmitted to other decision makers, this does not necessarily entail a diffusion or accumulation of mistakes, misrepresentations, and misconceptions within the decision-making ensemble. The cooperating ensemble establishes a negotiated order.

In sum, then, cooperative work in complex settings such as advanced manufacturing is, in principle, distributed in the sense that decision making agents are semi-autonomous in their work in terms of: goals, criteria, perspectives, and heuristics. There is no omniscient agent.

The design of information systems for advanced manufacturing is therefore faced with the challenging problem of supporting the exchange and integration of information within a self-organizing cooperative ensemble of decision makers that have a high degree of autonomy in their cognitive strategies and conceptualizations. These problems, encountered in the practical effort to develop information systems

for advanced manufacturing, are among the key issues being explored in Computer Supported Cooperative Work (see Bannon and Schmidt, 1991).

The Fallacy of the Automation Paradigm

A computer system always incorporates a model of another system in the 'real world', e.g., in the simple case of a payroll system, a model of the wage calculation system (tariffs etc.) and the staff of the company (names, positions, account numbers, etc.).

Models, however, are limited abstractions; they are valid only within a limited area of application. Thus, a computer system will inevitably encounter situations in which the underlying model of the world is no longer valid. With simple systems the user is normally able to know immediately if and when the system's world model does not apply and to take the necessary corrective measures. However, the more complex the system, the more obscure the validity of the system's performance. Thus, as pointed out by Roth and Woods (1989), a "critical element for effective intelligent systems is that they provide some mechanisms to facilitate the detection and resolution of cases that fall outside their bounds." This facility is rarely provided, however: "One of the major failure modes that we have observed in AI systems is to not provide support for the human problem-solver to handle cases where the AI system is beyond its bounds."

Like any other computer system, a computer system for cooperative work in advanced manufacturing is based on a model of a part of the world. The world models embodied in CIM systems are as varied in nature and scope as the manufacturing domain itself. For the purpose of our discussion, two categories may be distinguished:

- *Models of organizational structures* such as procedures and schemes of allocation of tasks and responsibilities, e.g., master production schedule, order release procedure, order schedule, kanban systems, etc.
- *Models of conceptual structures* such as inventories of materials, components, parts, subassemblies, and finished products; process catalogues; bills of materials; order backlogs, etc.

Like any other model, the world model incorporated in a CIM system has an application area within which it is a valid (abstract) representation of the world. The validity of the model is of a local and temporary nature. That is, there is a boundary beyond which the model is invalid. Thus a CIM system will inevitably be placed in situations beyond the bounds of the underlying model. The critical question is: what happens to the cooperating ensemble using this system when the underlying model is beyond its bounds? Unlike a typical expert system, a CIM system is not controlled by a single agent in a position to know if its performance is blatantly unsatisfactory and switch the thing off. A CIM system is part and parcel of the infrastructure of the enterprise. Thus, CIM systems designed on the conventional

'automation' paradigm, are disasters to come. (Martin et al., 1990, argues along the same line).

With no omniscient and omnipotent agent to ensure the integration of the special and local knowledge and heuristics of the different semi-autonomous agents, the company-wide database system as perceived by the CIM concept is problematic.

(1) The data incorporated by a CIM system will be incomplete. First, it may of course capture all data from the various numerically controlled processes but captured data pertaining to organizational issues (scheduling, task allocation, training, etc.) will be utterly inadequate for competent management. Second, even data pertaining to computer-controlled production functions may be insufficient for product design and process planning. The processing capabilities of existing equipment will for instance be represented as finite lists of recorded constraints. And, as a rule, constraints will not be recorded unless they are perceived relevant to design and planning. Thus, constraint that have been irrelevant heretofore but may be crucial for new design concepts may not have been recorded. And third, unforeseen contingencies will inevitably require local interventions that are not detected by or reported to the system, and due to the unpredictable nature of the local contingencies, no scheme for automatic acquisition of data pertaining to local interventions can be exhaustive.

By any standard, then, a CIM system will be a coarse representation of the diversified and multifarious reality of the manufacturing operation. The CIM system that allegedly will enable managers to have "complete information about production processes" (Kaplan, 1990) is a chimera. The pioneering ICAM project contended, of course, - in the authoritative words of Harrington (1984) - that "every one of the many acts of manufacture, and every bit of the managerial control of those acts, can be represented by data. [...] In the ultimate analysis, all of manufacturing may be seen as a continuum of data processing." This conception may be a valid and useful assumption in the *theoretical* analysis of manufacturing operations, but in *design* of CIM systems it is neither tenable nor conducive to assume that a complete data representation of a manufacturing operation is possible. As observed by Havn (1990),

"It has never been possible to produce a data representation of all aspects of manufacturing. The ICAM project is in fact based on a transfer by analogy of the nature of knowledge in engineering sciences to the organizational context."

(2) Data incorporated in the CIM system will not be indexed consistently. The system would of course provide a global classification scheme to support the distributed indexing of information items to be included in the database, for example, taxonomies of parts, materials, processes, etc. (cf. Group Technology). Such a classification scheme is itself an partial and temporary conceptualization, however. In order to include an information item in the database, an agent needs to interpret the conceptual structure of the classification scheme, relate it to the specialized conceptualizations of his or her particular perspective, and translate it to local circumstances. That is, the scheme will not be applied uniformly, and the database will over time become inconsistent.

(3) The conceptual structure of the CIM system, as embodied in the classification scheme, is itself of transient validity. The semantics of categories will change and new categories emerge. In order not to deteriorate, the scheme must evolve with the conceptual evolution of the social world it is a reflection of. That is, the conceptual structure of the CIM system is itself subject to the vicissitudes of distributed decision making and it will thus itself be incomplete and inconsistent.

What are the implication of the open systems conception of advanced manufacturing? Is CIM as such a futile endeavor? Not at all! We do not need to discard the CIM concept. Rather, the implication is that the allocation of function between man and machine is a crucial point in CIM systems design.

Computer Support for Distributed Integration

The problem with incorporating models of organizational structures or conceptual schemes in computer systems is not that these models are fetishes, mere phantoms of our imagination. Rather, models serve a heuristic function in work activities by identifying constraints, pitfalls and strategic positions in the field of work. As observed by Suchman (1987),

“plans are resources for situated action, but do not in any strong sense determine its course. While plans presuppose the embodied practices and changing circumstances of situated action, the efficiency of plans as representations comes precisely from the fact that they do not represent those practices and circumstances in all of their concrete detail.”

This observation applies to conceptual schemes in general (plans, procedures, taxonomies, etc.)

Therefore, instead of pursuing the elusive aim of devising models that are not limited abstractions and thus, in principle, brittle when confronted with the inexhaustible multiplicity of reality, models of the reality of manufacturing operations in CIM systems should be conceived as *resources for competent and responsible workers*. That is, computer systems for support of cooperative work in complex environments such as advanced manufacturing should be designed so that users are able to maintain control of their work when the system is beyond its bounds.

Accordingly, in the case of models of organizational structures, CIM systems could provide facilities allowing users to *explore* prescribed procedures and formal structures, and leave it to the users to abide by or deviate from norm and practice according to their professional judgment of the contingencies of the situation at hand, currently and locally. Likewise, in the case of models of conceptual structures, CIM systems could provide facilities supporting users in exploring and modifying - cooperatively and yet distributed - shared models of conceptual structures that are openly incomplete and inconsistent.

Users should be able - when need be - to appropriate the system creatively, circumvent it, modify it, etc. like an informal network of operators and foremen may ‘appropriate’ a *kanban* system. However, providing support for distributed coop-

erative appropriation, circumvention, modification of the system is, perhaps, the toughest challenge in designing computer systems for cooperative work in advanced manufacturing. For example, how should the underlying world model of the system be made visible to the user? Is it possible to support the user in anticipating the consequences of a circumvention or modification under consideration? Should a modification of the underlying model affect other users? How should it affect them? How should different users perceive changes to the underlying model? How should a circumvention of the model be presented to other users? And so forth. Questions such as these are still open issues in research and development of computer systems for cooperative work in complex and dynamic settings such as advanced manufacturing.

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