When Knowledge is the Critical Resource, Knowledge Management is the Critical Task

By

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Abstract—**This paper argues that the increasing centrality of technology and other forms of knowledge to competitiveness induces long-run changes in both operations management and engineering management. Those emergent trends in practice are paralleled by changes in academia, in both teaching and research. In several domains of management practice, the "public good" nature of knowledge undermines the effectiveness of both market and planning models of organization, reinforcing the role of cooperation as a third mode of coordination. Researching the essential issues posed by such a change requires a paradigm shift from management science and operations research formulations to more qualitative, less analytical, and more inductive approaches.**

I. Introduction

THE THESIS of this essay is that the growing role of technology and other forms of knowledge in competitiveness is driving parallel changes in management practice and in management theory and teaching.

Put in the broadest terms, one might schematically propose that when cultivated land was the scarce factor of production, the physiocrats' theory of natural resources as the source of wealth appeared almost self-evident. Later, when labor came to be seen as the scarce factor of production, Ricardo's theory of value as embodied labor overtook the physiocrats'. When savings and capital subsequently supplanted labor as the scarce factor, all resources appeared as forms of capital (physical capital, money capital, human capital, etc.), and the neoclassical marginalist theory emerged. Today, as knowledge and, in particular, technology move to center stage as the critical resource, we are groping for a new understanding of the wealth of nations.

This paper seeks to show that the reason the growing role of technology poses a paradigm problem can be stated succinctly: technology, as a domain of knowledge, has the peculiar quality of not being used up by being used—indeed, the more it is used, the more there is, since new insights and new knowledge are likely to accumulate. The notion of scarcity is turned inside out, and the central task of those who seek to augment wealth is not only the efficient use of scarce resources but also the encouragement of active cooperation across multiple boundaries for the generation of new knowledge resources.

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This paper takes as its initial focus a specific management and engineering domain—manufacturing—and seeks to show how accelerating technological change is obsoleting many presuppositions in operations management and in manufacturing engineering in both the academic and the business worlds (Sections II and III). I then suggest that the reason for this obsolescence is the public good character of technology (Section IV) and I briefly sketch the resultant impact on other areas of management (Section V). In conclusion, I shall argue that in studying knowledge management issues, researchers will find it necessary to abandon formal analytic modeling as their primary norm of rigor (Section VI).

II. Trends in Production Operations Management

A. Trends in Teaching

Two trends in management education are particularly striking: the growing interest in the production operations management (POM) area and the simultaneous "crisis of confidence" as regards the reliance on traditional approaches in that area.

The decline in U.S. international competitiveness has been attributed to a wide variety of factors: amongst them, poor operations management has attracted considerable attention [20]. Interest in POM research and enrollment in POM courses have increased correspondingly.

At the same time, however, the focus of these courses has begun to shift. The traditional POM course had as its centerpiece the tool kit provided by decades of creative research into the formal modeling of scheduling, production planning, inventory control, etc. The discipline base was that of applied management science (MS) and operations research (OR).

The heightened significance of operations management in competitiveness and thus in business strategy has led researchers and educators to relativize the role of these traditional tools. The applied MS/OR methods have a "tactical" scope when compared to the strategic dimension of the issues that have come to the fore. New strategic concepts are making their way into the POM curriculum, base on the work of Skinner [45], [46], Hayes and Wheelwright [21], and Buffa [9]. Courses in POM increasingly highlight the strategic dimension: coursework in quality statistics is supplemented by concepts of quality strategy; classes on scheduling algorithms are supplemented by material on just-in-time as a continual

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improvement strategy; stand-alone courses in manufacturing strategy multiply.

B. Trends in Operations Management Practice

These efforts to address operations management from a strategic point of view reflect the growing concern with operations as a competitive asset—or liability—in senior management circles. The growth in articles on this subject in journals like *Harvard Business Review* is striking.

This challenge "from above," is, moreover, complemented by a lesser known challenge to the traditional MS/OR approach coming "from below." The very nature of productive techniques is changing in a manner that limits the usefulness of the traditional methods and indeed the centrality of the traditional questions. The degree of automation of leading-edge manufacturing or service operations, as embodied in the objective of computer-integrated manufacturing or in the reality of large-scale on-line integrated computer systems emerging in financial services, is now such that even at a tactical level, the old techniques are insufficient. Whether it is in the evaluation or the scheduling of a flexible manufacturing system (FMS), in problems of quality control in a CAD/CAM environment, or in determining work standards for robot operators, to name but a few issues, the inherited MS/OR toolbox is under increasing strain.

It is important to understand the two main sources of this strain. The first source of strain is the integrative capacities of increasingly ubiquitous electronic technologies. The higher level and greater span of the new automation technologies mean that process change projects became so large, installation and debug periods become so long, interdependencies between suppliers and users become so critical, and utilization procedures so difficult to define before implementation, that apparently tactical problems become strategic. Most importantly, it would seem that this fusion of the tactical and the strategic is not merely a one-time start-up problem that will be resolved when today's leading-edge processes become, with time, more conventional. Certainly, some problems which today escalate to a strategic level will eventually be routinized and pushed back down to a tactical level. But it can reasonably be predicted that the greater number of them will permanently change our idea of the tactical/strategic distinction.

Two illustrations may help. FMS installations typically cost upwards of $10 million and take upwards of three years to realize their flexibility potential, since it takes about that long to train in-house people to develop and debug the range of programs needed. It is highly unlikely that this delay can be brought down to less than about two years, no matter how many vendors nor how many experienced programmers and operators are available. Under these circumstances, a commitment to installing an FMS is a tactical decision with direct and multiple strategic implications. Indeed, the FMS decision could be described just as accurately as a strategic one with tactical consequences [19]: five years from now, what range of products will the plant be producing? What lead times will be required? What software capabilities will the firm need? What personnel practices will be most effective, and will they be compatible with those in the rest of the plant?

A second example is the difficulty of evaluating computer-integrated production systems. As a National Research Council report [35] expressed it: "In the integration of computer-aided technologies, however, both costs and benefits span multiple functions and are difficult to capture by traditional accounting procedures. The best measures, these [surveyed] companies say, are responsiveness, productivity, quality, lead time, design excellence, flexibility, and work-in-process inventory. Progress is also measured in terms of its consistency with corporate objectives." Many such variables are, of course, implicit in the traditional valuation procedures; the difference is that now they must be explicit. And they must be explicit because the variables that were taken to be fixed parameters for the purposes of tactical analysis (acceptable quality level, suppliers' delivery lags, set-up times, product variety, new product introduction frequency, etc.) have become critical levers for competitiveness that the new investments are designed to help activate.

These examples indicate how increasing levels and spans of automation obsolete inherited approaches to the management of technological change. When change was slower in pace and more limited in scope, it only marginally violated the assumptions required for the traditional analytic tools to retain their usefulness. Today's automation projects, however, are increasingly liable to be multiyear, multiorganization, and multilevel. They are less and less "marginal" or tactical in nature.

C. Trends in Research

Bohn and Jaikumar [8] have outlined the resultant crisis of the traditional POM research agenda. The traditional applied MS/OR approach illuminates an important range of issues under the following general conditions: the technologies are known, the environment is stationary and known, labor's task is to follow well-defined procedures, inputs are available in complete markets, and goals are well defined. These assumptions permit rigorous model building and deductive analysis; their restrictive character allows tractability. The hope of the advocates of the traditional paradigm has been that a research program which generates increasingly sophisticated models will be able to progressively relax these restrictions and thus throw light on an ever-expanding subset of the issues faced by managers in the real world.

Nothing guarantees, however, that by following this route we shall ever get within striking distance of the central issues created by the new competitive role of technology. Today, it seems urgent to tackle head-on the analysis of production under more realistic assumptions: when the precise capabilities of technologies are not known in advance, when labor's task is problem solving, when intangible inputs like tacit knowledge and worker motivation are central, and when organizations have to continually redefine new goals.

This suggests that the challenge to the centrality of the traditional POM research agenda coming "from below" lies not only, and perhaps not most critically, in the blurring of the line between tactical and strategic concerns. A second key source of strain undermining the salience of the MS/OR approach lies in the transformation of the very nature of the tactical/operational aspects of the new technologies. The central issue here is, I believe, one that has not received enough attention: it is the "knowledge intensity" of the new operations systems. The intricate meshing of state-of-the-art capabilities from disparate technological fields in these large systems requires a high level of technical and technology management expertise on the part of those who manage, design, implement, and operate them. Knowledge intensity—measured roughly as the average educational and training level of the total workforce—tends to rise.

This increase in knowledge intensity imposes on operations management a task of learning which is no longer the prelude to a return to a stable normalcy and passive optimization. Not only has the level of automation changed, but, since automation tends to feed on its own accomplishments, the rate of change of technology draws automation levels upward on an accelerating curve. Knowledge intensity increases mean that operator skill requirements change in nature, emphasizing task interdependence, cognitive problem solving, and responsibility for results rather than mere work effort [2], [3], [22], [40]. Learning, and above all learning how to learn, become increasingly central management concerns. Developing a theoretical framework for understanding the behavioral and managerial determinants of the learning process becomes a high-priority research issue.

Not only, therefore, are operations issues pushed upward in the corporate hierarchy of priorities, but the increasing knowledge intensity transforms the content of those operations issues. The challenge facing practitioners and researchers alike is to find a conceptual framework that can come to grips with the new problems.

III. Trends in Manufacturing Engineering

When technological change and new competitive conditions highlight the strategic significance of operations capability, important changes are generated in the engineering profession and in engineering schools. The challenge is complex: on the one hand, no one can deny the importance of science in providing new sources of technological capability; but on the other hand, most economically useful technological change has resulted from, and continues to derive from, the application of old knowledge, not from the creation of new knowledge [41]. This middle zone between science and routinized production, the area of technology *per se*, generates the bulk of the economically relevant growth of knowledge. But the evidence is strong that U.S. industry is not doing well enough in this area and that the U.S. lags behind its international competitors in the application of new technologies to manufacturing [48]. How should the engineering profession respond to this challenge?

A. Trends in Engineering Practice

Increases in automation levels and in the knowledge intensity of operations challenge both manufacturing engineers and design engineers.

There is firstly a change in the duties of manufacturing engineers. Traditionally, they have been primarily preoccupied with tooling. But as a study of Batelle [6, p. 6] explained:

> The job responsibilities of manufacturing engineers have increased in scope and responsibility. Manufacturing engineers are being assigned increasing responsibility for planning, designing, and justifying the overall system for design and production of product. Use of the team approach in industry is growing, and is breaking down the distinction between engineering disciplines. Closer collaboration among technical personnel performing related functions is taking place. The manufacturing engineer has become more heavily involved in the decision process for purchasing new equipment, and must be able to justify that a new process, machine, or tool is cost beneficial.

This change, however, is not without problems. The same report explains that in 60 percent of the large companies surveyed (over 2500 employees), the manager of the manufacturing engineering function was four or more levels below the president. Even in smaller companies (250–2500 employees), 55 percent of the manufacturing engineering managers report three or more levels below the president.

Second, expectations for design engineers are also evolving. Experience in and understanding of manufacturing is becoming more important for engineers destined for product design departments. A report on the training of entry-level engineers [10] stated the problem baldly: "When an entry-level engineer is hired out of college, she/he is not prepared to begin designing hardware because she/he lacks knowledge of manufacturing processes and procedures." Automation in manufacturing and the accelerating rate of change of manufacturing technology make the product design engineer's task increasingly challenging in this dimension. It is usually only through extensive and expensive supervision by and apprenticeship with senior design engineers that entry-level product design engineers acquire the manufacturing knowledge not imparted by schools. The increasingly attractive alternative is a rotational training program which would imitate the European and Japanese models by taking new design engineers into manufacturing for at least several months.

As a result of these trends, firms find that they are recruiting manufacturing and product design engineers from increasingly similar pools, and that to attract high quality engineers into manufacturing, pay and status conditions have to be equalized. In many companies, manufacturing engineers have traditionally been on a lower pay curve than design engineers. Change in the organizational status of manufacturing engineers is inevitable as firms upgrade the skills and responsibilities of manufacturing.

B. Trends in Engineering Education

Not only do such shifts in organizational prestige encounter significant resistance in many companies, but our educational system is not well adapted to the new needs of industry. Until recently, there were only three bachelor of science programs in manufacturing engineering offered in the U.S.

The difficulty is partly the same as that found in management programs: the more inductive and qualitative methods needed for the analysis of the messy problems of manufacturing and implementation are not accorded as much respect as the more elegant, formal, and deductive accomplishments permitted by the rarified atmosphere closer to science. In the same way that applied MS/OR is closer to traditional norms of "rigor" than mathematically less-sophisticated qualitative research in strategic operations management, so too the engineer is encouraged to stay closer to the scientific sources of his/her work.

Recently however, engineering schools and industry have begun to respond to these challenges. One promising development was the announcement by IBM in 1982 of a $50 million grant program to help universities develop and update master's-level curricula in manufacturing engineering. The principal beneficiaries were Stanford, Georgia Institute of Technology, RPI, University of Wisconsin, and Lehigh. Twenty other schools benefited with a total of $40 million in CAD/CAM equipment. (The Sloan Foundation has also financed, on a somewhat more modest scale, the development of manufacturing sequences.)

The IBM announcement provoked some 150 universities to submit proposals. According to IBM [24], "Nearly all proposed curricula contain business courses such as marketing, economics, integrated information management, production planning and control, production planning, organizational behavior, and industrial management. The proposed curricula emphasize systems integration, engineering, science and business to create multidisciplined engineers." This orientation corresponds to the Batelle study's findings regarding the skill areas for future training most frequently mentioned by their manufacturing engineer survey respondents; the top five areas were manufacturing management, numerical and computer control, administration, CIM, and manufacturing planning [6].

These programs respond to the need for a new type of manufacturing engineer, one capable of addressing higher levels of automation. But a survey of the curricula of these courses shows that their potential weak point remains the messy world of implementation. Robotics courses are still naturally drawn to the fundamentals of control theory, and courses in the other manufacturing technologies are likewise drawn toward their respective source disciplines. The complex interdependence of the myriad problems that are typically confounded in the technological upgrading of a manufacturing department—machines, maintenance, materials flow, people, organizations, accounting, etc.—does not easily lend itself to the conventional pedagogical approaches of engineering schools. And, just as in the traditional business school POM department, this pedagogy is held back because faculty do not see research into such problems as very opportune.

The importance of courses which familiarize the manufacturing engineer with a range of new technologies largely justifies the weight of the technology-specific courses in these programs. But I submit that the absence of integrative implementation courses will become even more disturbing in the new programs than it was in the traditional programs. At lower levels of automation, one could hope that post-school experience would permit a natural accumulation of that implementation know-how. But at higher levels of automation, characterized by greater knowledge intensity, the multiplicity of specialized domains of competence raises the synthesis problems to a new level of criticality. Longer internships and a greater integration of education and work experience such as that envisaged by M.I.T.'s Leaders for Manufacturing program appear in this light as essential to the future shape of engineering, and especially to manufacturing engineering education.

C. Trends in Engineering Management Research

The key challenge of engineering management (EM) research has been the low status accorded problem-centered, as opposed to discipline-centered, research in academia. As a result, EM research has been fragmented by discipline base: MS/OR and economics have been applied to issues of project selection and project scheduling; organization theory has been applied to issues in the management of engineers and scientists; social psychology has been applied to issues in R&D team performance. The effect of this fragmentation has been to encourage research that is either overly narrow or overly broad.

Much of the analytic project scheduling research, for example, has been overly narrow. The analytic approaches deal with the easier parts of the scheduling problem. From the practitioners' point of view, one of the most critical parts of scheduling is understanding and predicting the tasks involved in accomplishing the project, and that remains a matter of experience and insight. Other, more qualitative approaches derived perhaps from cognitive science, would be needed to research these issues.

On the other hand, much of the organizational and behavioral research has been too broad. Few researchers in these disciplines have been willing or have seen necessary to differentiate between different technology domains, with the result that we know very little about how differences in technology domains—beyond very generic differences like research versus development—should influence R&D team management approaches [18].

As technology becomes an increasingly central factor in competitiveness, there is a concomitant increase in pressures on and opportunities for academic researchers to focus on the real-world problems of engineering management.

IV. The Origins of the Traditional Paradigm's Breakdown

In this and the following sections, I shall argue that an important underlying cause for these shifts in operations and engineering management, in both industry and academe, is that technology as a productive asset is what economists call a "public good"—it does not get "used up" by being used. This feature of technology explains why new forms of coordination are becoming increasingly central to competitiveness. It is the nature of these new forms which creates the need for new paradigms in practice and theory.

Technology and other forms of knowledge are assets whose management poses a profound dilemma for the design of efficient economic systems. A purely decentralized, market system can only generate an optimal rate of growth in the production of knowledge if knowledge is made fully appropriable so as to provide adequate incentives to risky research investments. Apart from the fact that full protection via patents, etc., turns out to be, practically speaking, very difficult to achieve, to the extent that protection is effective, such protection blocks a socially optimal distribution of the fruits of research and slows the overall system's productivity growth. Conversely, however, a centrally planned system can mandate the right distribution of knowledge, but fails to provide enough incentives to guarantee a high rate of new knowledge production. It can be shown with perfect rigor that in a world with such public good assets as technology there can be no optimal incentive structure [5], [23].

In such a world, Ouchi's [37] rationale for the importance of culture in organizational effectiveness appears central. He argues that culture-intensive organizations in which shared values integrate individuals into the common enterprise ("clans") are more effective than either markets or planning bureaucracies when performance is ambiguous. If, as it seems reasonable to assume, accelerating technical change generalizes performance ambiguity, then cooperation—the clan form—is destined to grow in significance relative to market and bureaucratic mechanisms.

The recent popularity of the "corporate culture" theme may thus not be merely a passing fad. It has of course a faddish element, but it also expresses an underlying shift away from exclusive reliance on bureaucratic rules and/or purely economic incentives and towards increasing reliance on shared values.

V. Managing Knowledge

A. Impact Areas

These insights from economic theory can cast some light on real-world management problems. The growing importance of cooperation as a third mode of coordination alongside and in conjunction with market and bureaucratic mechanisms is visible in several domains of management. Indeed, I submit that the impact of the growing centrality of technology and knowledge management can be felt in all the major relationship's charted in Fig. 1, which maps the vertical and horizontal relations spanning the relationship between industry and public agencies (area 1) right down to the first level of supervision (area 7).

The increasing centrality of knowledge encourages transformation of the relation between private firms and public or nonprofit agencies (area 1). Public/private collaboration is an increasingly important element of national economic competitiveness [36]. As science comes to play an increasingly important role in stimulating technology, basic research grows relative to applied; private funding of basic research is limited by appropriability problems, and government support becomes increasingly important to technological progress. Moreover, modern science, while providing many opportunities for niche creativity, is also increasingly "big" science, requiring massive investments whose scale increasingly outstrips the resources of even the largest companies. Finally, public sector support is crucial for the funding of much scientific, engineering, and technical training. With this increasing role of the public sector, grows the need for public/private sector collaboration in establishing priorities.

Cooperation between firms (area 2) is becoming an essential complement to market relations in the growth of knowledge as a productive asset. This is perhaps the fundamental force underlying the development of joint R&D ventures [38]. At a different level of analysis, it helps explain why intense cooperation between vendors and users of advanced systems—rather than arm's length transactions—has become the norm in advanced technology settings [15]. And it is perhaps the insufficiency of both market and bureaucratic coordination models which leads to the extensive network of informal know-how trading by engineers within the same industry [50].

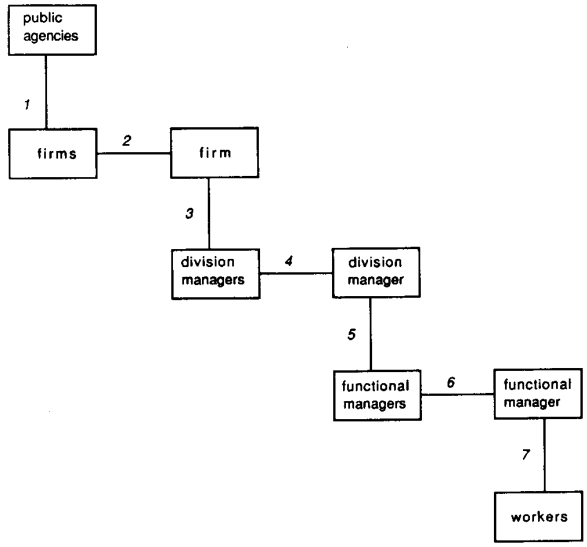

Fig. 1. Potential impact areas of knowledge management.

In the domain of corporate structure (areas 3 and 4), the increasing centrality of technology to competitiveness undermines the effectiveness of both the traditional "U" form (functional organization) of companies run "from the top" and the "M" form of divisionalized companies trying to simulate internally a market system. In order to stimulate entrepreneurial initiative among division general managers, most large corporations have moved away from the centrally planned functional form towards an internal capital market in which rewards and resources go to more profitable divisions [43]. But divisionalized technology-intensive companies are finding it increasingly urgent to surmount their divisions' reluctance to share technological advances [49]. The reluctance is born of the market-simulation decentralization that encourages each division to attempt to look better than the others—a system that unleashes great creativity and initiative in the production of knowledge, but grossly underoptimizes from the company's overall point of view the distribution of knowledge across divisions, since it does not allow the full corporate benefits to be realized from a division's discoveries. As firms attempt to benefit from knowledge synergies through interdivisional sharing of technologies and other forms of knowledge, they are driven to go beyond U and M forms of coordination. Firms typically attempt to combine the two forms, creating complex structures embodying both centralized and decentralized coordination procedures. But increasingly firms seem to be working at a qualitatively different type of response to be added to the existing repertoire: the invention of new organizational processes based on values encouraging collaboration across divisions. Reflecting this shift to coordination through values, many firms are moving towards increasing the subjective component of division general managers' compensation: more space in bonus setting is being left for corporate management's assessment of division general managers' team-player attitude [44].

In the relationship between functional managers and general managers (area 5), the knowledge management vantage point allows a deeper insight into the importance of strategic manufacturing management discussed in Section II-A. When the rate of technological change accelerates, general management suffers information overload and must decentralize the strategy formulation task. But the effectiveness of this decentralization cannot rely exclusively on bureaucratic procedures or economic incentives; these cannot substitute for a genuinely participative strategy process based on shared values.

Take also the area of design/manufacturing relations (in area 6). The discussion in Section IV-A highlighted the fact that manufacturing engineering's rapidly increasing technological complexity is pushing firms to upgrade manufacturing engineering's skill profile and therefore to equalize design and manufacturing engineering status. The knowledge management perspective suggests that this equalization of status has a deeper significance as well. The integrative capacity of new technologies (Section II-B) allows direct linkages of computer-aided design and computer-aided manufacturing, which in turn puts a premium on joint problem solving by design and manufacturing engineers; but joint problem solving presupposes a collaborative relationship between peers, and is blocked by the traditional status hierarchy that ranks design over manufacturing. Alone or in combination, administrative fiat and normal budgeting procedures cannot create and sustain this collaborative relationship. A combination of these mechanisms with a profound values reorientation appears to be the increasingly necessary prerequisite for an effective design/manufacturing interface.

In job design (area 7) the knowledge intensity of new technologies dictates a greater problem-solving component to operators' jobs than traditional Taylorist approaches would suggest. With automation, the number of operators per unit output might fall, but there is typically no net reduction in average operator skill requirements; on the contrary, higher skills of a new type are usually called for. Training, organization, renumeration, etc., will need to evolve to reflect this change [22], [32]. Conversely, if the operator is modeled as a problem solver, rather than an effort-supplier, machine design may have to be adjusted to reflect these new tasks.

Leaving the framework of Fig. 1, three underlying traditional dichotomies are progressively undermined.

First, as knowledge intensity rises, *manufacturing* comes to look a lot more like a *service* operation [26]. Cost reduction programs that encourage mangers to slash overhead expenses run the risk of crippling critical longer term technical development capabilities. Overhead functions in manufacturing—especially the technical functions—are not amenable to unambiguous control or measurement: as knowledge workers, cooperation is at the core of their task. And indeed, even direct workers become knowledge workers.

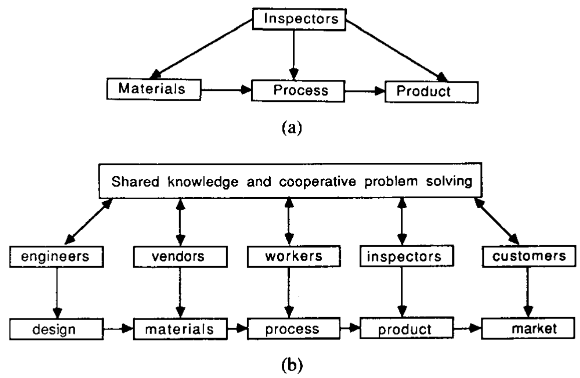

Fig. 2. (a) The traditional quality approach. (b) The new quality approach.

Second, the dichotomy between *fab/assembly* operations and *continuous process* operations becomes increasingly obsolete. As the level of automation rises, the span of operations integrated within the automatic system is expanded and fab/assembly becomes more continuous [2]. Simultaneously, the programmable nature of the new equipment increases the *flexibility* of continuous process operations, weakening the traditional association of automation and *rigidity*.

Finally, viewing the production process from a knowledge vantage point also foregrounds the ideas of learning by doing, learning by using, learning by failing [31], and learning across a series of projects [51]. As a knowledge-generating activity, product and process development are necessarily and centrally experimental. By their nature, they cannot conform to *a priori* first-order expectations expressed in the command, "Do it right the first time." The firm needs to reconceptualize its objective function as encompassing not only *production* but also *learning* [25].

B. A Practical Example

The area of quality control shows clearly the value of the knowledge-management vantage point in understanding certain emergent trends.

The traditional view of quality control was based on "inspecting quality in," with statistical acceptance of each incoming lot and QC inspectors spread down the manufacturing line. Quality knowledge was embedded in inspection routines and applied in a one-way relationship. The new approach is based on "building quality in": vendors are qualified, therefore their incoming shipments need not be inspected; employees inspect their own work; and customers' input is actively solicited [14]. There is a two-way information flow and new knowledge of the process and the product is continually created by active collaboration of all the participants.

Fig. 2 presents primitive "knowledge maps" of the two approaches. Expanding on the suggestions of Klein and Betcher [27], it is clear that the key difference between the two quality approaches lies in who is considered to be an active agent in the quality-control knowledge-generation process.

Such explicit knowledge maps highlight what might be called the first rule of knowledge management: data should flow to those who are best equipped to synthesize it and to distill effective knowledge from it. This is the underlying novelty of Deming's approach: draw the work force not only into the production of widgets, but also into the production of knowledge about the improvement of widget-making processes [12].

One might thus schematize the optimal relationship between data and knowledge as parallel to and dovetailing with that which classically is considered optimal in the relationship between responsibility (for) and authority (over): there should be a close correspondence of all four terms: knowledge, data, responsibility, and authority. This is a new way of stating one of the themes of the sociotechnical systems approach to organizational design [39].

VI. A New Strategy for Research

If this characterization of the emergent knowledge management issues is accurate, then we confront a serious problem in management research. The MS/OR type of analytic deductive model building that has been the mainstay of research clearly has a role to play. But as the more strategic concerns and the knowledge management tasks become more central, an increasing proportion of the critical issues must fall outside the range of such methods.

Analytic models are simply intractable when confronted by the irreducible complexity of human cooperation based on continually evolving shared values. The simple analytic learning models explored by Bohn [7] and by Fine [16] are very thought provoking, but they only model the *effects* of learning and such models will succumb to intractability when they turn to explicit models of learning's multiple *causes*. Simulation might offer an alternative approach, except that the degree of complexity of the phenomena in question would render simulation results opaque. I therefore believe that we need to cast our theoretical reference nets more widely and adopt more inductive and qualitative techniques, putting the analytic models in a subordinate role.

One might object that the recent developments in agency theory and information and transaction cost analysis show a promising analytic way forward in addressing precisely such organizational issues as cooperation and motivation. These approaches have helped focus attention on some of the areas that, for lack of tools, have too often been ignored by economics and other formal modeling approaches. These new theories provide a new language with which to address many of the classical organizational problems. Indeed, it is a language far richer than that previously available to analytically oriented researchers. It is a language which nevertheless remains several orders of magnitude less rich than that of classical, more "literary," organizational theory. This relative poverty would more easily be accepted if these models' simplicity enabled analytic research methods to generate important new insights. But in reality, tractability constraints still cripple all by the simplest efforts in analytic model building. MS/OR seems therefore to have an important role to play in modestly circumscribed tactical areas; but qualitative approaches might be optimal for the study of the broader managerial areas.

Teece and Winter [47] have recently argued for a similar diagnosis. They point out that traditional economic approaches cannot capture the real-world complexity of the truly central factors, amongst which they list: dynamic competition, the critical role of know-how, the internal structure of the firm, the role of entrepreneurial creativity, the institutional molding of markets, and the real-world cost formation process. Several years ago, similar concerns were voiced by Ackoff [1].

How then should research on knowledge management proceed? At least in these early stages of development, the optimal research strategy will, I submit, be more inductive and qualitative than deductive and formal. An inductive, exploratory approach can help identify the more effective knowledge-management practices, and we can then bootstrap ourselves by developing greater conceptual clarity on the nature of those practices. In this exploratory phase, when we are grasping for useful theoretical frameworks and conceptual constructs, the optimal research strategy will probably prove to be more qualitative than formal.

Can such research generate worthwhile results? What kind of science will be generated by this research? Many operations and technology management researchers would undoubtedly identify the natural sciences as their model of rigor. Explicit models, quantifiable variables, and hypothetico-deductive methods all assure the relatively easy reproduction of our professional norms.

But if it is through the network of social interactions within and between firms that the increasingly critical knowledge assets are produced and distributed, then should we not take the bull by the horns and adopt methods that are adequate to the social core of the phenomena we are studying? Let me therefore suggest that we should meditate on the example of another discipline, history. As a discipline, history has its own rigor and its own norms of evidence and objectivity: scrupulous attention to all data of any type that may contribute to an understanding of the phenomenon in question, without regard for the disciplinary barriers that distinguish economics, geography, psychology, etc. These norms are such that controversy and basic disagreement in evaluating research is perhaps marginally more common than in formalized and the quantitative sciences. But only marginally.

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