WORKING PAPER

Task Characteristics and Organizational Problem Solving in Technological Process Change

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August 1990

INTERNATIONAL CENTER FOR RESEARCH ON THE MANAGEMENT OF TECHNOLOGY

Massachusetts Institute of Technology Sloan School of Management
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WP # 13-90

Sloan WP# 3109-90-BPS

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This paper develops a framework that distinguishes two key characteristics of technological change in the manufacturing process. While technical complexity refers to the number and uniqueness of new components, systemic shift refers to changes in production principles and relationships. Descriptive evidence from a sample of new process introductions suggests that organizations employ different modes of problem solving to respond to different characteristics of change. Successful projects illustrate the need to fit the problem solving approach used to the characteristics of the task facing the adopting organization.
Research during the last decade has shaken established assumptions about the nature and process of technological change in manufacturing. The introduction of new production processes and equipment was once conceived as a relatively straightforward task of implementing well-defined technical solutions into a static organizational environment (Rice and Rogers, 1980; Lyles and Mitroff, 1980). More recent research suggests that this simplified view ignores the ongoing process of "reinvention" and adaptation by users (Rice and Rogers, 1980). In fact, ongoing problem solving is central to organizations' efforts to prepare for and utilize new process technology (Kazanjian and Drazin, 1986; Gerwin, 1988; Leonard-Barton, 1988).

Technological, organizational, and managerial changes are often needed before new process technologies can be fully utilized (Jelinek and Goldhar, 1984; Gerwin, 1988; Hayes and Jaikumar, 1988).

Yet while recent research on the subject has brought new insights, it has also added to the confusion surrounding the study of innovation. Central challenges of the "new" manufacturing technologies are described in a variety of ways, and it is unclear whether the variation is due to different levels of analysis, different terminologies, or substantive differences in the technologies involved. Studies have variously focused on the complexity, recency, or maturity of the new technology (Gerwin, 1988), the need for new skills (Adler, 1986; Meyer and Goes, 1988), the significance of programmable control (Hayes and Jaikumar, 1988; Kelley and Brooks, 1990), machine or system flexibility (Graham and Rosenthal, 1986; Jaikumar, 1986), the integration of previously discrete manufacturing steps (Hayes and Jaikumar,
1988), and the strategic implications of the new technologies (Jelinek and Goldhar, 1984; 1986).

Further, conclusions about how organizations can respond to the challenges of new manufacturing technologies have been contradictory. For instance, while some studies have emphasized the need for specific, high-level technical skills (e.g. Meyer and Goes, 1988), others underline the need to build generalist capabilities (Hayes and Jaikumar, 1988). Many studies have stressed the need to build cross-functional teams for introducing new process technology (Graham and Rosenthal, 1986; Jaikumar, 1986). Yet other studies have pointed out that interfunctional conflict is aggravated by the introduction of new manufacturing technologies (Gerwin, 1981; 1988). Indeed, the usefulness of functional integration as a response to technological process change remains ambiguous (Tyre and Hauptman, 1990). Similarly, several authors have suggested that close cooperation between equipment vendors and users in an ongoing joint process is important to success in introducing new technologies (Ettlie, 1986; Kimberly, 1986; Leonard-Barton, 1988). Yet research also suggests that the benefits of joint problem solving efforts can be elusive. Collaboration may require previous experience between parties (Ettlie and Rubenstein, 1980), yet new technologies often entail new vendors and vendor relationships (Normann, 1971; Gerwin, 1988). Divergent or ambiguous expectations can further undermine collaboration (Gerwin, 1988; Leonard-Barton, 1988b; Rosenthal, 1984). Finally, despite the acknowledged importance of preparing the new technology and the organization prior to actual implementation (Rogers, 1983; Leonard-Barton, 1988), research suggests that the technology's newness, complexity, or interconnectedness can
make problems in use difficult to anticipate (Jelinek and Goldhar, 1986; Gerwin, 1988).

In sum, despite considerable research, no single theory has emerged that explains the difficulty of learning to use new process technologies; similarly, no coherent set of managerial implications has been set down for dealing with problems. This paper attempts to organize various characteristics of new manufacturing technologies into a coherent framework. The paper then uses findings from an empirical study of new process introductions to describe organizational strategies and behaviors for dealing with different types of process change. The objective of the research was to better understand the problem solving requirements associated with introducing new process technology. In particular, the research explores whether distinct characteristics of technological change require different modes of problem solving within the manufacturing organization.

THEORY: INNOVATION TASKS AND ORGANIZATIONAL REQUIREMENTS

Most studies of technological innovation in organizations have used unidimensional constructs to describe a given technological change and its significance for the adopting organizations. Concepts such as radicalness (Dewar & Dutton, 1986; Ettlie, 1980; Nord & Tucker, 1987), complexity (Rubenstein, 1985) and import (Quinn, 1980) have been used. These constructs are useful as general descriptors, however they fail to illuminate the organizational significance of new technologies because they confound the degree of change with the nature of the change involved. This can lead to seriously flawed results, because different types of change are likely to,
impose distinct kinds of tasks on the adopting organization and to involve very different innovation processes (Downs & Mohr, 1976; Tornatzky & Klein, 1982; Fennell, 1984).

By contrast, Abernathy and Clark (1985) and Tushman and Anderson (1986) propose a two-dimensional framework of technological change that distinguishes the technical novelty of an innovation from its compatibility with existing organizational investments in technical know-how, operating procedures, and methods for solving problems. While technical novelty affects the amount and complexity of problem solving required of the user organization, it does not itself affect the usefulness of existing knowledge structures and organizational assumptions as a basis for problem solving. On the other hand, the compatibility of an innovation with existing cognitive and organizational systems may be unrelated to the degree of technical complexity or novelty involved (Abernathy and Clark, 1985). This distinction, and its relevance for understanding the introduction of new manufacturing technologies, is developed below.

Task Characteristics of New Process Introductions

First, the introduction of novel, highly sophisticated technology involves considerable technical complexity for the user organization. Complexity stems from a number of attributes relating to the information load, diversity, and rate of change facing the problem solver (Campbell, 1988). Relevant attributes include the newness or maturity of the technology (Gerwin, 1988; Leonard-Barton, 1988b), the extent to which the technology has been proven in practice (Leonard-Barton, 1988b; Rogers, 1983), the size of the advance over existing "state of the art" (Kimberly, 1986), and the number
of new "subtechnologies" or components involved (Ettlie, 1986; Rice and Rogers, 1980).

When the technical complexity of an introduction is high, problem solving is difficult even though existing operating principles and experimental procedures may continue to be applicable. Problem identification and solution development become more demanding as the number of factors and effects to be considered increases. It is more difficult to predict the outcome of any given action, due to the newness and variety of problems involved (Downs and Mohr, 1976; Gerwin, 1988; Jelinek and Goldhar, 1986).

Important strategies for problem solving in such circumstances include scientific investigation, machine-based computation, and disaggregation of large problems (Jaikumar and Bohn, 1986; Campbell, 1988). In the manufacturing environment, these strategies often require significant improvements in technical skills and procedural discipline (Adler, 1986).

However, skill-building rests on and utilizes existing knowledge bases developed in the organization.

A second basic task characteristic is the degree of "reorientation" required by the new technology (Normann, 1971; Zaltman, Duncan and Holbeck, 1973). Unlike technically complex innovations, which entail significant advance in existing subsystems or components of the technology, innovations that involve significant reorientations eliminate existing subsystems, introduce new ones based on unfamiliar technical principles, or create a new set of relationships among technical and organizational subsystems. Reorientations cannot be accommodated within existing technical, political or organizational frameworks (Normann, 1971) because they destroy existing systems and undermine competencies (Abernathy and Clark, 1985; Tushman and
Anderson, 1986). Organizations faced with reorientations must "unlearn" old approaches in order to develop new types of specialist knowledge, vocabularies, and task arrangements (Hedberg, 1981; Normann, 1971). This, in turn, calls for change in underlying organizational systems: internal goals and values, domain and dependency relationships, and even attention rules and cognitive structures must be reconfigured (March and Simon, 1958; Normann, 1971; Zaltman et al., 1973). New knowledge frameworks and technical subsystems must then be "mapped" onto the organization and integrated with existing systems and structures (Normann, 1971; Kazanjian and Drazin, 1986). For all these reasons, reorientations can be thought of as changes of a systems nature, or what will be referred to as "systemic shifts".

The challenges presented by systemic shifts are very different from those involved in technically complex introduction projects. Because systemic shifts require new ways of looking at problems and the creation of novel problem solving procedures (Rice and Rogers, 1980), they introduce considerable ambiguity into the organization (Jaikumar and Bohn, 1986). The meaning of events or of data is open to multiple, often conflicting interpretations (Daft and MacIntosh, 1981; Daft and Lengel, 1986). Problems and their causes are ill-defined; organizations must first define or formulate issues before they can take action (Lyles and Mitroff, 1980). Formulation processes, in turn, rely on judgement, negotiation, and even disagreement among groups more than rule-based testing and expert decision-making (Thompson and Tuden, 1959; Perrow, 1967; Lyles and Mitroff, 1980).

In the discussion below, these two characteristics of technological change are used as organizing concepts for an investigation of organizational problem solving in response to new process technology. The next section
describes three mechanisms that facilitate problem solving in organizations. The following section describes the research and methodology applied. Finally, the fourth section of the paper presents and discusses results of the research. In particular, it investigates the implications of the two task characteristics identified here for the processes of generating, transferring, and institutionalizing knowledge about new manufacturing technologies.

Organizational Responses to Technological Change

The literature on change in organizations suggests three "response mechanisms" which enable organizations to adapt through problem identification and problem solving, either in advance of technological change or during task execution. These are: 1) preparatory, or early, search undertaken before the new technology is put into use; 2) joint search during the introduction process with technical experts outside the factory, and 3) functional overlap during introduction between engineering and manufacturing groups at the plant level. These mechanisms are not mutually exclusive; an organization may make use of any or all mechanisms in a single introduction project.

1. Preparatory Search is significant because it occurs in advance of the actual change. It involves investigation and modification of both the new technology and relevant aspects of the receiving organization before the technology is installed in the factory (Rice and Rogers, 1980; Rogers, 1983; Van de Ven, 1986). Adaptation may include changes to existing manufacturing procedures (Bright, 1958) and support systems (Gerwin, 1988). Coordination with the developers of the new equipment is an important aspect of
preparatory search, allowing mutual adaptation of source and user during the early phase of the project (Gerwin, 1988; Leonard-Barton, 1988).

The second and third response categories both involve real-time mechanisms for adapting to problems and opportunities which develop as the organization gains experience with the new technology:

2. **Joint Search** refers to interorganizational collaboration during the introduction process. Important external actors include equipment developers or vendors (Kimberly, 1986; Gerwin, 1988) as well other members of a plant's "technical organization set" such as component or tooling suppliers, competitors, or customers (Evan, 1966). Research suggests that joint work with members of the external organization set can account for "a major part of the company's problem solving capability with respect to the new technology" (Lynn, 1982: 8).

3. **Functional Overlap** refers to interfunctional collaboration within the user organization during the introduction process. It involves linking relevant functions to create "overlapping subsystems" or multifunctional teams for dealing with change (Galbraith, 1973; Landau, 1969). Several authors suggest that, especially where new technologies bring fundamental changes to existing manufacturing systems, problem solving requires shared efforts among production personnel as well as technical and other groups (Gerwin, 1988; Jaikumar, 1986; Perrow, 1967).

**RESEARCH METHODOLOGY**

**Site and Sample Selection**

Following Downs and Mohr (1976) this research examines multiple innovations, taking as the unit of analysis the innovation within a specific
organizational setting (i.e., the introduction project). The study was carried out in a large, global company and involved three major divisions located in Italy, West Germany, and the United States. Two to three plants were studied in each division, representing a cross-section of operating facilities. Historical and contextual differences among individual plants were taken into account by defining "the organization" as a single factory at a given point in time (Barley, 1986). Issues of construct validity stemming from cultural differences were dealt with through preparatory field work to develop measures and vocabulary appropriate to the different contexts studied. (For a more detailed discussion of cross-cultural measurement issues and performance differences see Tyre [forthcoming]). The design facilitated access to detailed information about projects and the problems encountered (Rogers, 1983: 361; Graham and Rosenthal, 1986).

The sample of projects studied includes all of the new process introductions identified where the technology was "new" in some way to a particular factory and which: 1) were recently completed or nearing completion at the time of the study; and 2) represented a total capital investment of greater than $50,000 (in constant 1986 U.S. dollars); and 3) involved participants who were available for interview. Forty-eight projects comprise the sample; there was no indication of selection bias among plants or regions. The sample includes a spectrum of technological process change, from improved versions of existing equipment to introductions of novel technologies and production systems. Production technologies include metal turning and precision machining equipment, assembly and inspection systems, thermal treatment and metal forming equipment, and handling systems.
Methodology and Data Gathering

The introduction of new process technology into existing plants is a complex, unfolding process. Both longitudinal and cross-sectional perspectives are needed to understand the problems of technological change and organizations' responses to them (Barley, 1986; Van de Ven and Rogers, 1988). To meet these competing demands, multiple methods were used. Descriptive information about projects and problem solving processes was developed through repeated open-ended and semi-structured interviews with project managers, other project participants, managers, and technical staffs. In each case the project manager was identified during early field work as the person who had the "most direct, day-to-day responsibility for bringing the new technology up to speed in the factory". Other project participants, identified by plant management and principal informants, included operating and technical personnel involved in the introduction but not responsible for it. An average of three project participants were interviewed in each case. Each interview lasted from one to four hours; respondents were interviewed between two and four times over the course of a year or more. In addition, an average of two plant-level managers (typically the plant manager and a technical manager) and a division manufacturing manager were also interviewed in each case. Technical staff involved in initial development of 12 of the 48 projects studied were interviewed at the start of the research. In addition, specific data on project characteristics and outcomes were collected through a written questionnaire. Documentary evidence about plant operations and innovation projects was obtained from company archives.

Thirty eight of the 48 projects were recently completed at the time of the study, while 10 were completed during the course of the research. While
concern about retrospective biasing of responses could not be eliminated entirely, it was reduced by using multiple respondents in different organizational roles, by multi-method triangulation, by phrasing questions in terms of concrete events, and by referring to contemporary project documentation (especially for information on project objectives and outcomes).

Variables and Measures

Quantitative measures and qualitative descriptions were developed for each of the following. Quantitative measures are described in detail in Tyre and Hauptman (1990). They include:

(1) Project Attributes: The nature of the introduction task, in terms of the level of reported technical complexity and systemic shift. Dollar cost was also measured to control for the physical size of the introduction task.

(2) Response: The degree to which the three response mechanisms (preparatory search, joint search, and functional overlap) were used in the innovation project.

(3) Outcome: The success of the introduction project, in terms of the time required to complete the project and the operating benefits achieved.

In addition, the researcher used the critical event method to elicit description of the nature of the problem solving process and the roles of the individuals involved in each case. In particular, a list a possible problem categories (such as tooling development, software modification) was used to elicit detailed description of the nature of the change, the critical problems encountered, and the way they were solved (or not solved).
Similarly, respondents were asked to mention a particular problem (or set of problems) in which each one was involved, and to describe their role in the solution process.

Illustration of Constructs

Respondents' descriptions of the changes they faced were consistent with the theoretically derived constructs of technical complexity and systemic shift. Interviews revealed a perceived difference between the novelty of specific technical features, and a shift in the system principles or operating "philosophy" involved. The latter could include discontinuous changes in the conversion technology used, such as moving from traditional metal shaping techniques to thermal forming technologies, but it could also include new ways of organizing production flows to achieve new manufacturing priorities. Thus, respondents distinguished introduction projects reflecting a new focus on lead-time or flexibility from equally ambitious projects aimed at improving performance in terms of traditional criteria of cost and quality. Similarly, moving from a segmented batch production process to an integrated flow was perceived differently from changes in more localized features of the technology, even when both changes were significant.

For example, one case involved the company's first use of a flexible robot cell in production. The technology itself was not new, and the robotic elements employed were relatively simple. However the cell represented a fundamental change within the factory, both in terms of the basic technology (robotics instead of hard tooling) and the movement toward a flexible flow of production. As the project manager described:

Our expertise has always been in optimizing the tooling. Now, we have to learn about systems control, programming, and managing a flexible line.
There are new relationships between computer programmers, tooling, and production.

Another case which was classified as a major systemic shift involved moving from traditional metal removal processes to thermal forming of precision metal parts. According to the project manager:

We were starting from scratch with a totally different processing approach from what has been used in this application. Our deep experience in turning operations just was not relevant here -- this system presented a totally new set of problems.

Comments made by respondents to describe extreme examples of both technical complexity and systemic shift are displayed in Figure 1.
Two Characteristics of Technological Process Change

**SYSTEMIC SHIFT**

<table>
<thead>
<tr>
<th>TECHNICAL COMPLEXITY</th>
<th>NOVELTY OF MACHINE FEATURES AND DESIGN</th>
<th>CHANGE IN PRINCIPLES OF PRODUCTION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>high</td>
<td>low</td>
<td>high</td>
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<tr>
<td>&quot;THE NEW MACHINE REPRESENTED A QUANTUM LEAP IN PRECISION AND CONTROLLABILITY. THE RESULT WAS ONE OF THE MOST COMPLEX FINISHING PROCESSES THERE IS. AT FIRST, WE COULD NEVER REALLY PREDICT THE OUTCOME.*&quot;</td>
<td>&quot;EVERYTHING ABOUT THE WAY YOU PRODUCE WITH THIS NEW TECHNOLOGY IS DIFFERENT; IT'S LIKE HAVING A RESEARCH PROJECT, NOT JUST A PRODUCTION MACHINE.*&quot;</td>
<td></td>
<td></td>
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<tr>
<td>&quot;SOME ADJUSTMENT IS ALWAYS NECESSARY AT THE OPERATOR LEVEL, BUT THIS WAS NOT REALLY 'A HAPPENING'.&quot;</td>
<td>&quot;IT WAS NOT THAT THE SPECIFIC TECHNICAL SOLUTIONS WERE SO HARD TO DEVELOP, BUT THAT WE HAD TO LEARN A WHOLE NEW APPROACH TO MANUFACTURING.*&quot;</td>
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</tbody>
</table>
RESULTS:

ORGANIZATIONAL PROBLEM SOLVING AND NEW PROCESS TECHNOLOGY

Relationships among project attributes, organizational responses, and project outcomes were analyzed using both quantitative and qualitative data. Quantitative results provided some evidence for the idea that different kinds of change call for different organizational responses (see Tyre and Hauptman [1990]). Both preparatory search and joint search proved to be effective as general responses to technological process change, regardless of whether the project was characterized by technical complexity or systemic shift. On the other hand, functional overlap was shown to be effective in dealing with systemic shifts, but not for responding to high levels of technical complexity. Indeed, the use of higher levels of functional overlap in dealing with technical complexity was associated with both longer time periods for introducing the technology and lower levels of operating improvement.

In the balance of this paper, descriptive evidence is used to explore these relationships in greater detail. Findings are summarized in Figure 2. The next section explores the surprising result that higher levels of functional overlap can lead to poorer project outcomes. Subsequent sections explore the roles of preparatory search and joint search. Evidence indicates that these response mechanisms are used in different ways to respond to different types of innovations. Indeed, different kinds of introduction tasks may demand very different problem solving approaches in terms of the experimental strategies employed, the form and content of the communication flows, and the way shared tasks are coordinated.
FIGURE 2
Relationship Between Use of Response Mechanisms and Project Outcome Given Characteristics of Change

<table>
<thead>
<tr>
<th>TECHNICAL COMPLEXITY</th>
<th>SYSTEMIC SHIFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFECT: IMPROVED PERFORMANCE</td>
<td>EFFECT: IMPROVED PERFORMANCE</td>
</tr>
<tr>
<td>&quot;SUCCESS... BECAUSE WE MADE A SPECIAL EFFORT TO DEFINE EXACT SOLUTIONS TO ONE OF THE MAJOR UNKNOWNS.&quot;</td>
<td>&quot;IT REQUIRED A LOT OF DISCUSSION... WE WERE TRYING TO CREATE SOME FLEXIBLE SOLUTIONS THAT COULD BE REFINED LATER.&quot;</td>
</tr>
<tr>
<td>EFFECT: IMPROVED PERFORMANCE</td>
<td>EFFECT: IMPROVED PERFORMANCE</td>
</tr>
<tr>
<td>&quot;UNDERSTANDING POTENTIAL SOLUTIONS AND THEIR RAMIFICATIONS IS VERY COMPLEX.&quot; NEEDED ACCESS TO SPECIALIZED EXPERTISE.</td>
<td>THE VENDOR'S CHIEF ENGINEER &quot;PRACTICALLY LIVED ON THE PLANT FLOOR... WE DID A LOT OF BRAINSTORMING.&quot;</td>
</tr>
<tr>
<td>EFFECT: POORER PERFORMANCE</td>
<td>EFFECT: IMPROVED PERFORMANCE</td>
</tr>
<tr>
<td>&quot;WE WERE WASTING TIME TRYING TO SOLVE PROBLEMS ON THE PLANT FLOOR... TIME TO DO ENGINEERING WORK WAS SQUEEZED OUT.&quot;</td>
<td>&quot;EVERYONE VOICED THEIR OPINION... TOGETHER, WE BEGAN TO RECOGNIZE NEW CAUSE AND EFFECT RELATIONSHIPS.&quot;</td>
</tr>
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</table>
Divergent Effects of Functional Overlap

Despite the widely acknowledged importance of "worker involvement" in the change process, analysis suggests that high levels of functional overlap between production and technical personnel can actually detract from project performance when introductions involve considerable technical complexity. Where functional overlap was associated with unsuccessful projects, it appears to have interfered with the systematic experimentation and inquiry needed to develop solutions to new and highly complex problems. Where it was most successful, functional overlap was used to define open-ended questions or to explore new relationships.

1. Functional Overlap for Dealing with Systemic Shifts. Introductions of new process technology characterized as major systemic shifts presented the factory with unstructured problems. Typically, key variables and even important parameters had not been identified. The chief difficulty often lay in defining problems and their source. Direct observation of the process was necessary to capture and sort the rich and often confusing information generated during production. In the words of one manager responsible for a major systemic shift, "At first we just had to run a part and see what happened... Together, we started to think. Over time, we began to recognize new things, to see new cause-and-effect relationships as we saw (the system) work."

Intensive brainstorming among people with different perspectives or areas of expertise was important for this kind of problem definition and pattern identification. In one project involving a major systemic shift, equipment was attended by three-person teams composed of a process engineer, a service technician, and an expert operator. Each individual was required to keep a
daily log of problems or irregularities encountered. Weekly meetings provided an opportunity for the entire project group to examine the data. The project manager explained,

"During these meetings we could identify a particular pattern of events over days or weeks of production. Everyone voiced their opinions about what was really going on. That's how we traced a lot of problem to their source."

As predicted by Gerwin (1988), conflict among individuals from diverse perspectives facing ambiguous problems was frequent. But working through the disagreements was often an important part of the problem solving process. As one project manager said, "Once we got through with all the finger-pointing, we had an effective group. We began to understand the issues on all sides."

Successful groups evolved in the way they understood the technology and its implications for the organization. In the words of one project manager, "This work requires a new mentality of production, but also a new mentality of working with each other." The project groups which proved most capable of developing powerful insights into previously ill-defined manufacturing processes went beyond traditional notions of "interfunctional teams". Rather, functional roles were completely redefined inside the group to create core problem solving units with largely undifferentiated responsibilities (Metcalf, 1981; Imai et al, 1985). Working in such groups, individuals were forced to integrate their existing areas of expertise to create a new way of understanding the technology and its implications for the factory. As one participant pointed out, "In the process of working together there was a lot of cross-training and cross-learning. On day one, everyone was an expert in his own area. On day 100, each person was an expert in the system." In undertaking significant systemic shifts, project teams were often introducing not only new task structures but also new competitive thrusts at the plant.
level. As one project manager described, "This project is more than the machines themselves. It is creating a large capability that (the Company) can build on. We are developing an important competitive weapon." Another project involved the introduction of a flexible robot cell. The project laid the groundwork for the later introduction of a fully flexible line by creating new technical capabilities and process knowledge, and developing new working relationships within the plant and with a new set of equipment vendors.

2. Functional Overlap for Dealing with Technical Complexity. The role of functional overlap was very different where projects were characterized primarily by technical complexity. In these cases the problems encountered were quite involved, requiring considerable engineering development and experimentation. Large, complex tasks often had to be divided to be solved. Coordination and communication between production personnel and engineers were important, but could be accomplished through existing formal and informal channels. A project engineer who ran a very complex but highly successful introduction project described a clear division of labor:

The production supervisor ran the tests and provided me with the results. I analyzed the results and, with our tooling vendors, developed tooling designs that achieved our high-precision objectives. It was hard work, but each knew what he had to do.

On the other hand, more intensive interactions between production and technical personnel often distracted engineers from their development efforts. In one technically complex introduction a knowledgeable project engineer worked directly with operators on the line during the startup period. Production pressure precluded searching very far for new solutions, or examining and testing new ideas before they were implemented. According
to the project engineer:

We worked very closely with production personnel. But once we ran into problems, I found I was working day and night just trying to attend to production details. Time to do important engineering work was squeezed out by everyday work with the machines and operators.

While problems were not necessarily hard to identify, developing solutions required specialized skills, concerted efforts and repeated experiments over time. In one highly complex case the project engineer described the vicious circle in which he found himself:

The foreman, department manager, and the setter all helped a great deal, and suggested many useful modifications. But we were wasting time fixing problems on the floor instead of going back to the fundamental engineering issues. The real problem was that we never got all the technical experts involved to focus on the specific problem of internal configuration.

Finally, rich and intensive communication between engineers and operators could not substitute for precise and well-documented information about events on the plant floor. As the corporate director of quality pointed out in reference to one very complex introduction:

Even if they get everyone in the plant working on that line, they will not get it running properly. That plant has not developed the discipline of managing quality and precision production. They have no tradition of measuring it, charting it, and tracking it.

Many such comments underline the need in cases of high technical complexity to narrowly define individual tasks, to collect and carefully analyze data, and to focus on developing solutions to specific problems.

Two Modes of Preparatory Search

Similar themes emerge in participants' descriptions of their preparatory activities in different kinds of projects. These descriptions support Gerwin's point that preparation involves not only specifying and testing the new equipment, but also "developing the required infrastructure...that can
properly maintain and control the innovation" (1988: 94). However the focus and nature of the development process were very different for different kinds of introduction projects.

I. Preparatory Search for dealing with Technical Complexity. Several successful cases illustrate effective use of preparatory search for coping with high levels of technical complexity. In these situations preparation involved isolation of critical areas of technical uncertainty, and focused efforts to develop new solutions, procedures, or capabilities.

For example, one project involved the introduction of an advanced CNC turning system. Project members identified their biggest challenge as the early development of tooling systems that would exploit the precision of the new microprocessor-based control systems. A major tool study was undertaken, involving people in and outside of the plant who "brought the necessary specialized knowledge and specific techniques." According to the project manager:

For me, this was one of our most successful projects because we made a special effort to define exact solutions to one of the major unknowns about the new equipment, before we had to deal with the problems of the actual introduction.

Successful project managers carefully delineated those aspects of process performance that must be achieved by the vendor prior to delivery, and those that could be more effectively dealt with at the plant level. According to one such manager:

You need to understand what absolutely must be accomplished by the vendor, and what issues the plant is better able to cope with. It was the vendor's job to bring the equipment to a certain level of functionality. But getting the exact finish and cycle times we needed is really something the factory knows more about. So, while the vendor was fine-tuning the machine prior to qualification, we were figuring out better ways to make his tooling perform at our levels.
2. Preparatory Search for Dealing with Systemic Shifts. In cases characterized by considerable systemic shift the most effective instances of preparatory search involved exploration of a more fundamental set of questions regarding the nature of the new technology, its potential capability, and its implications for the existing production process. Project participants prepared themselves to deal with the kind of questions they would face in using the new technology by absorbing new areas of knowledge and by creating new links to new external sources of expertise (Normann, 1971; Nord and Tucker, 1987). The process involved considerable discussion and interaction within and outside the plant.

For example, in the introduction of an automated material feeding system, the department head explained that "the technology is only about half of what is going on here. This system really involves a new mentality of production". During the planning phase the project manager worked closely with hardware and software vendors, but he also spent considerable time on the plant floor, working with production supervisors. As he explained:

There were no experts in this technology in the plant, so creating a vision of what the new system should do, and trying to comprehend how it would affect everything else in the plant, required a great deal of discussion. I had to learn more about our production system, and also I had to study several areas of technology new to me. Because we could not foresee exactly how the new technology would work in the factory, we were not trying to create exact solutions. Rather, we were trying to create some 'flexible solutions' that could be refined as the plant gained experience.

In another case, involving the first introduction of flexible robot technology into a plant, participants recognized that success required rethinking old ideas about stability and flexibility in the production process. In preparation, an expert operator devoted some six months to learning about robot technology. First, he worked with a technical manager
in the company who was an expert in control systems software; next, he "lived with the (robot) vendor" for several months, bringing his intimate knowledge of the manufacturing process to the job of learning about the new equipment. Finally he returned to the plant where he acted a link among operating and technical personnel and the outside robot vendor.

Two Modes of Joint Search

Similarly, problem solving interactions between plant personnel and outside technical experts after initial startup were very different for different kinds of projects.

1. Joint Search for Dealing with Systemic Shift. When systemic shift was very high, it was difficult to call on outsiders to develop specific solutions because plant personnel themselves were unclear about the source and nature of the problems they were encountering. They did not have the vocabulary to describe the situation verbally. In such cases, outside experts were most helpful when they became an integral part of the introduction effort.

For instance, the introduction of a new metal hardening process represented a major systemic shift. While many of the technical features were familiar, the configuration and integration of system components was completely new to the plant. The project leader explained that:

After the system was delivered, the vendor practically lived here -- he literally slept on the floor many nights. About four people, including the vendor, formed a core team. At first, it was a "black art" -- okay, we understood the process in terms of the scientific principles, but we did not understand the interrelationships of all the pieces on the plant floor. So, many of the problems we faced were pretty vague. It was not possible to gather data and figure things out logically -- we did a lot of brainstorming.
2. Joint Search for Dealing with Technical Complexity. On the other hand when technical complexity predominated, successful joint search involved an orderly process of generating and testing potential solutions. Plant personnel and outside experts cooperated in focused problem solving efforts aimed at specific problems. Interaction was supported by existing systems for capturing and transmitting relevant information about the production process and its capabilities.

For instance, a novel grinding and honing line was designed to achieve part tolerances which until that time had been considered unattainable. But the basic production principles and operating procedures were well understood. The project manager, a senior plant engineer, explained that,

Doing the experimental runs was an orderly process. We knew which tests to run and how to run them. But at this level of precision, understanding potential solutions and their implications is very complex. Our tools suppliers did not know our process, but they understood the ramifications of slight changes in tool hardness or shaft designs. It would not have been possible to find good solutions by ourselves.

During the testing phase this engineer was in close contact with his suppliers, making almost daily telephone calls to discuss possible new tool designs and their implications. Together, they did a great deal of what the project manager called "mental simulation" of potential solutions before trying them on the line. But supplier personnel did not become part of the core problem solving team, nor was it necessary for them to gain intimate knowledge of the production environment.

**CONTRASTING MODES OF PROBLEM SOLVING**

Evidence from the projects studied here suggests that the introduction of new process technology calls for considerable problem solving at the plant level. However different characteristics of change appear to require
different problem solving strategies and behaviors. These divergent modes of problem solving are outlined in Figure 3. For introductions characterized by high levels of technical complexity, successful problem solving tends to be highly focused. Project members disaggregate complex introductions into simpler, solvable task elements (Kaufmann, 1988). Existing activities provide insight into the basic relationships involved, however actual solutions lie outside previous experience. Considerable experimentation is necessary in order to generate and test solution alternatives. Effective experimentation is systematic and logical; simulation is useful because, while the problem is defined and the objectives known, specific outcomes are difficult or impossible to predict (Daft and Lengel, 1986; Jaikumar and Bohn, 1986).

Problem solving activities in these cases tend to be dominated by engineers. Much of the direct communication that takes place is between specialists (Delbecq, 1967). Personnel directly responsible for production activities play a supporting role, albeit an important one; their willingness and ability to run tests in real production time, and to feed back results and additional observations to engineers, is crucial. However, synthesizing these inputs is generally the job of engineers -- that is, individuals who are trained in and responsible for specific technical areas (Delbecq, 1967). In such technically complex projects it is typical to find two distinct processes running in parallel. At one level, manufacturing operations generate new information about existing solutions; at the same time, small teams of technical experts use this information to generate and select new solutions alternatives. Formal communication channels are used to transmit
## FIGURE 3

Contrasting Modes of Problem Solving to Address
Different Characteristics of Process Change

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<tr>
<th>TECHNICAL COMPLEXITY</th>
<th>SYSTEMIC SHIFT</th>
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<tr>
<td>• FOCUSED EXPERIMENTATION.</td>
<td>• OPEN-ENDED EXPLORATION.</td>
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<tr>
<td>• MENTAL AND PHYSICAL SIMULATION OF</td>
<td>• OBSERVATION AND BRAINSTORMING ABOUT</td>
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<td>SOLUTION ALTERNATIVES.</td>
<td>INTERPRETATIONS.</td>
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<tr>
<td>• PUSH KNOWLEDGE BEYOND EXISTING LIMITS.</td>
<td>• DEVELOP NEW WAYS OF UNDERSTANDING AND</td>
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<td></td>
<td>NEW ORGANIZATIONAL RELATIONSHIPS.</td>
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<tr>
<td>• ENGINEERING DOMINATED PROBLEM SOLVING</td>
<td>• PROBLEM SOLVING REQUIRES INPUT FROM</td>
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<tr>
<td>AND DECISION MAKING.</td>
<td>MULTIPLE FUNCTIONS.</td>
</tr>
<tr>
<td>• SMALL GROUPS OF EXPERTS EACH BRINGS</td>
<td>• INTEGRATED TEAM DEVELOPS A &quot;SYSTEM&quot;</td>
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<tr>
<td>SPECIALIZED KNOWLEDGE.</td>
<td>PERSPECTIVE.</td>
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<td></td>
<td>• DIRECT AND INTENSIVE TEAM INTERACTIONS.</td>
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<td>• STRUCTURED INTERACTIONS;</td>
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<tr>
<td>DYADIC OR MEDIATED COMMUNICATIONS.</td>
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clear and comparable data between areas while minimizing distractions (Daft, Lengel and Trevino, 1987).

Major systemic shifts, on the other hand, call for a much more open-ended process of exploration. Problem formulation is a central issue; it involves extended observation of the new technology and its interactions with the existing production process. As Daft and Weick (1984) note, "Equivocality is reduced through shared observation and discussions until a common grammar and course of action is agreed on" (page 291). Disagreement and conflict resolution are an important part of this definition process (Daft and Lengel, 1986). In the words of a manager quoted in one study, "Until you have disagreement, you don't define" unstructured problems (Lyles and Mitroff, 1980: 109). Further, the definition process shapes both the technology and the organization (Daft and Weick, 1984). Individuals from diverse areas are brought together to "map" new subsystems or relationships in the production process; in so doing, they alter existing technical, organizational, and cognitive structures (Metcalf, 1981; Normann, 1971).

IMPLICATIONS AND CONCLUSIONS

The framework proposed here distinguishes an innovation's technical complexity from its compatibility with existing manufacturing and organizational systems. The framework proved to be valuable for understanding technological change in the manufacturing environment. It was demonstrated that manufacturing organizations facing different kinds of process change may use similar generic response mechanisms, such as preparatory search and joint search, however they are likely to employ very different modes of problem solving, as outlined in Figure 3. Successful
projects illustrated the need to fit the problem solving approach to the nature of the introduction task. Open-ended exploration and the integration of diverse perspectives in a multi-functional team were useful for dealing with systemic shifts in manufacturing technology. However, technically complex changes called for more structured forms of experimentation; in these situations, testing and deliberation by technical experts across multiple disciplines was more useful than cross-functional integration between engineers and production personnel. This result is consistent with theory in the areas of organizational information processing (Daft and Lengel, 1986; Daft and Weick, 1984), group process (McGrath, 1984), and organizational behavior (Perrow, 1967; Thompson and Tuden, 1959). However this research extends these ideas to a set of problems which has received little scholarly attention. While the research on technological innovation in manufacturing currently suffers from a confusing diversity of viewpoints and conclusions, it appears that the concepts of technical complexity and systemic shift provide a coherent way to understand the specific behavioral requirements of many new manufacturing technologies.

This framework also provides insight into the extraordinary problems of managing "radical" change in the manufacturing environment (Gerwin, 1988; Nord and Tucker, 1987). For analytical clarity this discussion has highlighted introductions where either technical complexity or systemic shift dominated; radical changes, on the other hand, exhibit both characteristics simultaneously. Because different aspects of these projects call for very different modes of problem solving, successful project teams must be fluid and adaptive in their structure and approach.
Yet groups tend to adhere to familiar ways of organizing and approaching problems (Allen and Marquis, 1963; Delbecq, 1967; Gersick, 1988). Radical changes therefore call for active management by an individual who is, in Delbecq's words, "highly sensitive to differences in the decision-making tasks faced by the team, and can verbally redefine both his own and his subordinates' roles in a fashion congruent" with different problems during phases of the project (1967: 330). As argued by Delbecq more than 20 years ago, developing ways to incorporate problem solving flexibility into projects should be an important managerial priority.

This paper also demonstrates that the richness of a plant’s response to technological change cannot fully be conveyed by generic response mechanisms such as early plant involvement (preparatory search), cooperation with suppliers or other outside experts (joint search), or even cross-functional participation. These response mechanisms have received considerable attention in the literature, and indeed use of the mechanisms has been shown to relate to project success. However, in order to understand why these mechanisms were effective under different conditions of change, it was necessary to examine the fine structure of problem solving approaches and behaviors. In the past, this perspective has been applied to decision making in the realms of managerial strategy setting (Mintzberg et al., 1976), research and development (Allen, Lee and Tushman, 1980), and product planning and design (Normann, 1971; Clark and Fujimoto, 1987). However this study demonstrates that a focus on the fine structure of problem solving is also relevant to the management of technological change at the plant level.

Indeed, because the manufacturing environment provides an opportunity
to study multiple projects with measurable outcomes, it provides an excellent laboratory for the study of technological problem solving and change. Further work holds promise for improving our conceptual and practical understanding of technological innovation and its application.
ENDNOTES

1. This is closely related to the widely-used notion of "compatibility" between the organization and the technology (Rogers and Shoemaker, 1971; Rogers, 1983; Leonard-Barton, 1988). Compatibility, however, is often used to refer to a broader set of issues, including the relative technical sophistication of the innovation and the user; therefore, the concept of compatibility does not clearly differentiate between the degree of relative complexity and the size of the reorientation involved in a given innovation.
REFERENCES


Rubenstein, A. et al. 1985. Effectiveness of the interface between R&D and production. Final report to the productivity research program, Engineering division of the National Science Foundation (Grant MEA-8207373).


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