USING THE BRAIN AS A METAPHOR TO MODEL FLEXIBLE PRODUCTION SYSTEMS

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Manufacturing flexibility is critical for survival in industries characterised by rapid change and diverse product markets. Although new manufacturing technologies make it possible to accomplish flexibility, their potential remains unrealised by firms whose organisational elements do not possess adaptive capabilities. We use the brain as a metaphor to generate insights on how firms might design flexible production systems. We chose the brain as a metaphor because it is a self-organising system capable of responding rapidly to a broad range of external stimuli. The brain as a metaphor suggests that flexibility can be enhanced by employing practices that promote distributed processes occurring in a parallel manner. Such practices lie in contrast to those employed by production systems built on scientific management principles that promote localized processes in a sequential manner. By exploring these contrasting modes of operation, we argue that the brain as a metaphor opens up new avenues for theory development related to the design of flexible production systems.

Many firms compete in industries that require rapid responses to market and technological changes. Market changes reflect unpredictable customer needs for an increasing variety of products, whereas technological changes reflect continual advances that occur with the introduction of new products. In such industries, firms that possess the manufacturing flexibility to introduce modified or new products at minimal cost and lead time will gain a competitive advantage over others.

Indeed, many Japanese firms have capitalized on their manufacturing flexibility to gain worldwide competitive advantage in several industries. In contrast, it appears that U.S. manufacturing firms exhibit an astonishing lack of flexibility despite having invested in flexible manufacturing systems (FMS) (see Jaikumar, 1986). According to Jaikumar, it is not the technology that is to blame for this lack of flexibility, but the management of these systems (cf. Adler, 1988; Jaikumar, 1986; Passmore, 1988; Walton & Susman, 1987). As a result, even though manufacturing

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flexibility is technologically feasible, it remains organizationally unrealized in U.S. firms. To achieve flexibility, Hirschhorn (1984) suggested that firms must go “beyond mechanization” to address managerial and organizational issues related to the design of a “production system.”

How can firms tap the flexibility potential that new technologies make possible? In this article, we use a metaphorical approach to address this question. Specifically, we compare production systems with the human brain to generate insights on how such systems can be vested with the adaptive capabilities found in the brain to achieve flexibility. Our objective is to distill processes that render the brain flexible and map them to a production system. Using this approach, we offer a view of a production system that lies in contrast to those based on scientific management principles (Taylor, 1967). We argue that scientific management principles, appropriate during the mass production era, are ill suited for an era in which flexibility is critical for firm survival.

We first highlight key issues pertaining to manufacturing flexibility. We then discuss the metaphorical approach to map insights from the brain to production systems. Implementing this approach, we establish a metaphorical link between the brain and production systems. We then explore processes that render the brain flexible. These insights form the basis for generating propositions on practices that enhance flexibility. In conclusion, we discuss how the brain as a metaphor opens up new avenues for theory development.

MANUFACTURING FLEXIBILITY

Historically, scientific management principles formed the basis for the design of production systems. Given the emphasis on cost reduction through efficiency, scientific management principles were focused on eliminating variations in the production process through standardized work designs and specialization of labor (Taylor, 1967). Coordination and control were accomplished through hierarchies instituted to ensure that workers adhered to a set of “scientifically” determined tasks that enhanced efficiency.

Taylor (1967) hoped that these principles would liberate those in the workplace by instituting practices that select and train workers to perform tasks in the “one best way,” thereby increasing productivity and wages. However, scientific management principles had the unintended consequence of creating a “control environment” in which employees were recruited and trained to “fit” jobs. These principles also had the intended consequence of creating a trade-off between product variety and production cost (Goldhar & Jelinek, 1983; Hayes & Wheelwright, 1979; Stalk, 1988; Utterback & Abernathy, 1975). Standardized products were produced in a connected line-flow mass production environment, whereas customized products were produced in job shops (Hayes & Wheelwright, 1979).
Recent advances in manufacturing technologies (e.g., flexible manufacturing systems [FMS]) facilitate the manufacture of a variety of products in a continuous flow (Adler, 1988; Kotha & Orne, 1989). However, although new flexible technologies may be necessary, they are by no means sufficient to accomplish flexibility (Hirschhorn, 1984). This insight is best captured by Jaikumar (1986), who asserted that U.S. manufacturers have used flexibility the “wrong way”—for the high-volume production of a few products. In contrast, Japanese firms have used flexibility for the production of a variety of products at lower unit costs (see also Stalk, 1988). In other words, it is not technology that is to blame for the lack of flexibility, but perhaps the management of production systems (see also Adler, 1988).

Several researchers, therefore, have suggested that firms must adopt a “systems perspective” embodying both the social and technical facets of production to achieve flexibility (e.g., Hirschhorn, 1984; Pasmore, 1988; Starbuck & Dutton, 1973; Walton & Susman, 1987). The time for such a broader perspective might be right because new, flexible automation, relative to traditional technologies, provides a receptive framework for developing a “sociotechnical” production system (Hirschhorn, 1984). Indeed, some researchers have adopted a sociotechnical perspective to enumerate organizational factors required for attaining flexibility (e.g., Adler, 1988; Emery & Trist, 1960; Nemetz & Fry, 1988; Walton & Susman, 1987). For instance, Walton and Susman (1987) suggested changes in human resource management practices (e.g., job design, management organization, work-team structure, selection and training, and compensation and appraisal) to obtain the benefits of flexible automation. Others have argued that a system that supports learning and development is important for attaining flexibility in production systems (Adler, 1988; Hirschhorn, 1984; Nemetz & Fry, 1988).

To operationalize these flexibility dimensions, researchers have proposed more than 50 different flexibility types (see Chen & Adam, 1991; Gerwin, 1993; Sethi & Sethi, 1990; and Swamidas, 1988, for reviews). Among these, four types have been identified as the major constructs that capture the dimensions of flexibility required in a production system: mix flexibility, volume flexibility, new product flexibility, and delivery-time flexibility (Slack, 1987; Suarez, Cusumano, & Fine, 1992). These four types of flexibility can be further subsumed under speed and scope flexibility (Parthasarthy & Sethi, 1992). Speed flexibility refers to the rapidity with which a production system can deliver finished products when required, adjust its manufacturing process to the changing product mix and the accompanying volume changes, and modify its product mix. Scope flexibility refers to the breadth of products, including the degree of customization, that a production system offers.

Emerging research on flexibility suggests that speed and scope flexibility are enhanced by the ability to self-organize (Jaikumar, 1986; Stalk, 1988). Self-organization permits the coordination of activities in the
production of systems without hierarchy by locating initiative in teams (Hackman, 1990). Consequently, self-organization results in the reduction of overhead costs by eliminating the need for elaborate organizational mechanisms. Eliminating elaborate organizational mechanisms can also result in the ability to respond faster to market and technological changes. In other words, self-organizing production systems are highly flexible because they respond to the challenges of speed and variety at low cost.

Building on this idea, we explore the design of self-organizing production systems by employing the brain as a metaphor. We chose the brain as our metaphor because it is a self-organizing system capable of responding rapidly to a broad range of external stimuli (Arbib, 1987; Churchland, 1986). Before proceeding to learn from the brain, we first describe the methodology to transfer insights from the brain to model flexible production systems.

THE MEDIUM OF METAPHORS

We use metaphors to generate insights by comparing two domains (a source and a target) at several levels of generalization (Beer, 1972; Morgan, 1986; Tsoukas, 1991). At each level of generalization, the initial metaphorical insight is progressively refined through a set of homomorphic transformations. Homomorphism represents many-to-one transformations that retain only key facets that link the source and target, while discarding irrelevant facets.

Tsoukas (1991) and Beer (1972) suggested three levels of comparison at which insights can be generated between a source and a target. These levels of comparison include the metaphorical level, the analogical level, and the level of identity. Establishing links between source and target at the metaphorical level is an act of insight (Beer, 1972; Nonaka, 1991). At this level of comparison, it is difficult to benefit from the metaphorical insights because they tend to be abstract. We need a finer level of detail at the analogical level of comparison for the insights to be useful.

Links at the analogical level are established by mapping source to target relationships between objects that constitute source and target. Gentner (1989) proposed the systematicity principle to suggest that only higher order relationships should be mapped between the source and the target. Higher order relationships are those that encompass lower order relationships into a mutually constraining system of relationships. Consequently, mapping higher order relationships implies that lower order relationships are also imported from the target to the source.¹

¹ As an example, Gentner (1983) explored the Rutherford model describing the movement of a planet around the sun. In this model, the set of items that forms a mappable system, between the sun and the planet, include the following lower order relations: (1) the distance between the sun and the planets, (2) the attractive force between them, (3) the revolutions of the planets around the sun, and (4) the size of the sun and planets. She
Tsoukas (1991) and Beer (1972) pointed out that the analogical link between source and target is still inconclusive because it is difficult to determine whether all theoretically significant aspects of the source have been captured by the target. Hence, a third level is required before conclusive comparisons between the source and target can be drawn. This is the level of “identity.” This level provides a theoretical rationale for how the source and target are identical. To uncover this theoretical rationale, transformation from the level of analogy to the level of identity must preserve only core principles that describe both a source and target.

The steps discussed above generate knowledge by comparing one object in terms of another at the levels of metaphor, analogy, and identity. This “transformational” process also is based on the possibility that what constitutes a source and a target can change over time (Arbib, 1989; Gentner, 1989). An object, such as the brain, can inform our understanding of another object, such as the computer, at one point in time. As our understanding of the computer increases over time, it can reciprocally influence our understanding of the brain.

This transformational process need not be an isolated “top-down” movement; it can also be “oscillatory” (Tsoukas, 1991). For example, a source object can be the basis for generating an identity from the level of the metaphor. This identity can then serve as the starting point for generating insights about the target at the level of analogy and metaphor.

We apply these steps to generate insights about flexible production systems by using the brain as a metaphor (see Figure 1 for details). In Step 1, we establish why the brain is an appropriate metaphor to model flexible production systems. In Step 2, we describe brain processes that render it flexible. In Step 3 (i.e., at the level of identity), we distill the “higher order” brain processes that we would then like to map to flexible production systems. From this level of identity, in Step 4, we return to the level of analogy to describe the processes that can render a production system flexible.

THE BRAIN AND FLEXIBLE PRODUCTION SYSTEMS

Metaphorical Links

As illustrated by our ability to think and converse, the human brain is capable of responding on a real-time basis to a constantly changing environment. The brain is also capable of creating new repertoires of perception and behavior as it adapts to environmental change. For example,

captured the dependency between these lower order relations in the law of gravity, the higher order relationship. Employing the *systematicity* principle, she mapped this higher order relationship to understand the movement of electrons around a nucleus. In this way, objects constituting the planetary system (the target) and the atom (the source) are placed in correspondence, high order relationships are mapped (gravitational relation), and attributes of the objects constituting the source and target (such as the yellowness of the sun) are ignored.
the brain can learn entirely new languages. These properties have inspired researchers to use the brain as a metaphor to model systems that require rapid responses to a broad range of stimuli.

Among computer scientists, the brain represents a system that is capable of performing extraordinarily fast computations. A whole new discipline has sprung up in neural networking and artificial intelligence to mimic the brain's parallel and distributed processing capabilities. The brain is also used as a metaphor by organizational scholars to model flexible organizations (cf. Beer, 1972; Hirschhorn, 1984; Morgan, 1986). For Beer (1972), the brain serves as a metaphor for developing a control system that regulates the functioning of a factory. For this reason, Beer entitled his book The Brain of the Firm. In contrast, Morgan (1986) conceptualized the firm as a brain in an attempt to create an organization that disperses "brain-like" capabilities throughout the firm. Conceptualizing the brain as a richly connected information-processing system, Morgan
(1986) articulated several cybernetic principles (e.g., requisite variety, minimum critical specifications, redundancy of functions and learning to learn) that organizations can apply to respond in a "brain-like fashion" to changing external stimuli.

Scholars who employ metaphors realize that a metaphorical representation is but one "constructed reality" that shapes our understanding of a phenomenon. We construct models of something—in this case the brain—to create a model for something else—in this case the computer or an organization (Geertz, 1973). As Arbib (1989: 9) noted in his use of the brain as a metaphor to model neural networks, "A good metaphor is a rich source for hypotheses about a system, but must not be regarded as a complete theory of the system." He also suggested the importance of recognizing the existence of a two-way interaction between the objects being compared (Arbib, 1989: 403). With this caveat, we summarize the considerable knowledge that has been generated by artificial intelligence researchers in their efforts to mimic human intelligence through neural networks.

**Brain at the Analogical Level**

Many researchers suggest that the brain's ability to process information in a parallel yet distributed manner enables it to respond rapidly to a broad range of stimuli (Anderson, 1988; Arbib, 1989; Calvin, 1990; Churchland, 1986). The ability to process information in parallel is made possible by the brain's layered structure. Parallel processing is facilitated by firing an array of similar types of neurons located in modules, or knowledge areas (see Figure 2). Each neuron integrates input it receives from other neurons to generate an output. This output either excites or inhibits the activities of other neurons through synapses that establish electrochemical connections between neurons. As this process unfolds, learning is manifested by changes in the strength of the connections between neurons in a module. Each module reaches an overall state of activity or passivity rapidly because its constituent neurons operate in parallel.

*Topographical mapping* is another facet of the brain that facilitates parallel processing. Topographical mapping captures interconnections between layers in the brain such that inputs from one layer are mapped to another on a point-to-point basis. This process requires that a unique "address" for each information type exist and that information mapped to the brain be transferred through multiple channels (Calvin, 1990). To topographical mapping of information between the layers in the brain

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2 To understand how the brain uses multiple channels, Calvin (1990: 148) evoked an image of a "ribbon" cable in contrast to a single wire connecting the ignition to the starter motor in an automobile. The electrical connections between the ignition and the starter motor through the ribbon cable are established by transmitting electrical pulses in a multi-channel fashion.
FIGURE 2
Schematic Representation of the Brain

- Brain's layered structure that facilitates topographical mapping
- Modules consist of a redundancy of similar types of neurons. Neurons are the basic building blocks of the brain. Each module is specialized, yet generalized.
- A Module or Knowledge Area
- Topographical mapping of information from the continuously changing environment
- Stimuli from outside the brain

Continuously Changing Environment
enhances flexibility because it permits the transfer of complex information in parallel.

Research also suggests that each brain module takes part in several functions that are dispersed over several parts of the brain's anatomy. This implies that functions such as sight and sound are not localized but are distributed—i.e., several regions of the brain simultaneously participate to execute such functions. As Churchland (1986: 162) noted, "there is a division of labor in the nervous system, but a division made many times over, a division that is fuzzy, overlapping, partially redundant, and increasingly specialized; and moreover, a division of labor that has the potential for reorganization in the event of damage."

For distributed computation to occur, it is important to understand how various brain modules interact to perform a function. Arbib (1989) offered schemas as an intermediate construct between the brain's structure and its functioning to describe how modules interact in a distributed manner. Schemas are similar to computer algorithms in that they represent control block diagrams and flow diagrams. Block diagrams capture the feedback and feedforward loops between simultaneously active subsystems, whereas flow diagrams represent the sequencing of various data-manipulation processes.

Most systems (e.g., thermostats) have feedback and feedforward control mechanisms to ensure that performance is maintained within preset standards. However, the brain is a system in which it is difficult to establish an a priori estimate of its operating parameters because of its continuously changing environment. In such an environment, the brain continuously updates its operating parameters that govern the transformation of information into perception and action. Arbib (1989) labeled this process tuning.

To explain how the brain tunes its operating parameters, Arbib (1989) distinguished between perceptual and motor schemas. Perceptual schemas—activated by cues from both peripheral stimuli and internal context—shape perception. Motor schemas determine an appropriate course of action. The brain tunes its operating parameters by linking perceptual schemas with motor schemas continuously to shape the operation of motor outputs. To explain this tuning process, Arbib (1989) employed an image of two layers of neurons interacting (in parallel) with one another—one being a controller and the other being a controlled surface. As neurons in the controller surface (the input perceptual schema) iteratively arrive at an overall solution, they transmit signals in a topographical manner to corresponding neurons in the controlled surface (the output motor schema). Churchland (1986: 446) suggested that this transfer from one surface to the other can be viewed as matrix multiplication in the brain, leading to its ability to fine tune its motor schemas even as information is received and processed by its sensory schema.

New schemas are formed by creating fresh connections between neurons within a module and between modules in the brain. The repetitive
use of a connection reinforces it; its disuse leads to atrophy. Over time, this process creates a repertoire of schemas. This repertoire represents long-term memory, whereas the activation of a particular schema from this long-term memory represents short-term memory. This ability to create a repertoire of schemas, through the use and disuse of brain pathways, distinguishes humans from other living species (Hirschhorn, 1984).

The preceding description suggests that the brain operates in a parallel yet distributed manner constituting a process of cooperative computation (Arbib, 1989). Cooperative computation begins with the topographic mapping of sensory inputs to specific modules. Acting on external stimuli, adjacent neurons within a module communicate with each other in either an excitatory or an inhibitory fashion to arrive at an initial estimate about the tasks to be performed. This process represents "coarse-grained" computation. Mediated by the particular schemas that are activated, each module communicates with others until a consensus is reached as to the most appropriate course of action. This process, whereby modules evolve to a final solution, represents "fine-grained" computation (see also Hirschhorn, 1984: 92). Thus, the brain does not arrive at solutions by executive fiat. Rather, an overall solution is reached through the iterative interactions of modules that possess only local knowledge.

To explain this style of computation, Arbib (1989) provided an image of a panel of physicians diagnosing a patient. Each physician is a specialist but at the same time has a certain knowledge of general medicine. For example, a heart specialist might base his or her diagnosis mainly on the electrocardiogram but might still be biased by skin pallor and heavy breathing. When a new patient comes up for consideration, the physicians (i.e., modules) are globally decoupled, and each independently makes an initial diagnosis while talking back and forth in an effort to reach agreement.

Links at the Level of Identity

Before proceeding to map these insights to model flexible production systems, it is important to synthesize them into a set of principles that can be applied to the design of flexible systems at the level of identity. In other words, employing the systematicity principle proposed by Gentner (1989), we must capture the "higher order relationships" in the brain that will form the basis for understanding the design of flexible production systems. Our description of the brain has focused on facets that facilitate information processing in a parallel yet distributed manner. Parallel processing enhances speed because it enables simultaneity of activities. Distributed computation enhances the response range over which the brain can function because different parts of the brain can be combined in unique ways to address problems. These two processes together represent cooperative computation.

Cooperative computation results in the brain's ability to self-organize (Arbib, 1989; Churchland, 1986). Self-organization is a process whereby a
system evolves through endogenous means involving the cooperative computation of a multitude of individual units. These units possess only local knowledge but are able to produce global solutions through their interaction. This ability to self-organize represents an identity that, when applied to any system, can result in flexibility (Ashby, 1962; Beer, 1972; Sahal, 1979). We wish to map this self-organizing principle found in the brain to production systems to achieve flexibility.

Having already compared the brain with production systems at the metaphorical level, we are now left with the task of mapping insights from the brain to flexible production systems at the analogical level. Our efforts lead to several propositions. Although these propositions are consistent with emerging literature on flexibility, they offer insights that can open new avenues for exploration.

Production Systems at the Level of Analogy

The notion of cooperative computation as applied to flexible production systems implies distributed processing of activities occurring in parallel. We argue that distributed processing enhances the scope flexibility of production systems, whereas parallel processing enhances their speed flexibility. We establish these arguments by comparing flexible production systems with traditional production systems that were designed with scientific management principles (see Table 1 for a comparison). Specialization through division of labor and standardization and hierarchy are key building blocks of scientific management. Specialization results in localized processing of activities; hierarchy results in sequential processing. In the following sections, we explain how these processes result in compromising scope and speed flexibility.

Traditional production systems are designed to deal with environmental change by buffering their production cores with inventories (Thompson, 1967). These inventory buffers decouple production systems from their environments, thereby creating production systems that are "islands into themselves" (Hackman, 1990). In such a system, customer demands are serviced by drawing upon an inventory of finished goods. This mode of operation, labeled as "speculation" (Stern & El-Ansery, 1982), commits the system to a predetermined course of action based on a forecast of the future. Production is undertaken to stock inventories by engaging the services of highly specialized functional areas (e.g., design, engineering, manufacturing) in a sequential manner coordinated through a hierarchy. In contrast, flexible production systems must possess the ability to "postpone" the creation of products until customer requirements are known. At the extreme, production commences only after the production system senses stimuli originating from customers, i.e., just in time.

Topographical mapping is a key process in the brain that enhances its ability to sense and respond to external stimuli just in time. Topographical mapping in the brain requires that there exist a unique address for each type of stimulus and that information be mapped on a
TABLE 1
Traditional Versus Flexible Production Systems

<table>
<thead>
<tr>
<th>Organizing Principle</th>
<th>Traditional Production Systems</th>
<th>Flexible Production Systems</th>
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</thead>
<tbody>
<tr>
<td>Hierarchical control</td>
<td>• System decoupled from environment through inventory buffers and other mechanisms</td>
<td>• System tightly coupled with the environment</td>
</tr>
<tr>
<td></td>
<td>• “Speculation”</td>
<td>• “Postponement”</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Structure and Processes</th>
<th>Sequential and localized processing</th>
<th>Parallel and distributed processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homomorphic mapping</td>
<td>• Isomorphic mapping</td>
<td></td>
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<tr>
<td>Single-channel processing</td>
<td>• Multi-channel processing</td>
<td></td>
</tr>
<tr>
<td>Hierarchical structure</td>
<td>• Dynamic network structure</td>
<td></td>
</tr>
<tr>
<td>employing permanent</td>
<td>• employing temporary connections</td>
<td></td>
</tr>
<tr>
<td>connections</td>
<td></td>
<td></td>
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<tr>
<td>Specialized division of labor</td>
<td>• Shared division of labor</td>
<td></td>
</tr>
<tr>
<td>Integrated product designs</td>
<td>• Modularized product designs</td>
<td></td>
</tr>
<tr>
<td>Intermittent tuning of system parameters</td>
<td>• Continuous tuning of system parameters</td>
<td></td>
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<tr>
<td>Intermittent updating of</td>
<td>• Continuous updating of routines and competencies</td>
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<td>routines and competencies</td>
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Outcome Focus
Efficiency
Speed and scope flexibility

point-to-point basis in a multi-channel manner. The presence of a unique address for each stimulus allows for a one-to-one mapping—a process that we label as isomorphic mapping in a production system. Multi-channel mapping implies that stimuli are mapped through multiple conduits simultaneously. We suggest that production systems too must be designed to promote these two facets of topographical mapping to enhance speed and scope flexibility.

To understand how isomorphic mapping in a multi-channel manner can enhance flexibility, it is important to note that the production system’s environment consists of many customer groups, each requiring a different mix of product attributes. From this perspective, a production system services a multi-dimensional attribute space (DeSarbo & Rao, 1986; Green, 1975). As the number of attributes increases, so does the complexity confronting the production system. If the diversity of product attributes required by customers is greater than the competencies a system possesses, then its capability for achieving scope flexibility is compromised (Ashby, 1965). Under these conditions, the production system has to aggregate the different customer attributes into fewer categories. This practice represents a homomorphic “many-to-one” transformation, best illustrated by Ford Motor Company’s offer to sell any color car as long as it was black. In contrast, for isomorphic mapping to occur, the diversity of competencies that a production system possesses should match the di-
versity of product attributes sought by customers. This allows a one-to-one mapping of customer attributes to corresponding value centers in the production system. This discussion leads to the following proposition:

**Proposition 1:** Production systems that undertake isomorphic mapping will exhibit greater scope flexibility relative to those that undertake homomorphic mapping.

The second facet of topographical mapping (i.e., multi-channel processing) enables the brain to process information in parallel, thereby enhancing the rapidity with which it can respond to stimuli. Similarly, the extent to which a production system also employs multi-channel mapping enhances its speed flexibility. Multi-channel mapping in a production system is a process by which information about customer needs is transmitted in parallel to different value centers. For instance, a product with two attributes—functionality and cost—must evoke responses in the design and manufacturing departments, respectively.

von Hippel (1994) offered the notion of "sticky data" to explain why production systems must employ multi-channel mapping to accomplish speed flexibility. Data are sticky when there are costs associated with replicating and diffusing "location-specific" information. He argued that sticky data can have a significant impact on the locus of problem solving, sometimes requiring that problem-solving activity shift to the location where sticky data reside. He also suggested partitioning problems so that subparts of the problem are directed to specific sites where appropriate sticky data reside.

As in the brain, this approach requires multi-channel processing in which information is directed to specific locations in the production system. Directing specific parts of a problem to appropriate locations through a multi-channel transfer process obviates the need for transferring location-specific information from one place to another. As a consequence, the rapidity and accuracy of responses increase.

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3 A value center represents a collection of similar activities undertaken by humans and machines to convert basic raw materials to finished goods. The isomorphic mapping process is illustrated by Quality Function Deployment (QFD). QFD is a mapping technique for the development of new products through interfunctional planning and communication (Hauser & Clausing, 1988). This mapping process is illustrated by considering a grid in which one axis details customer expectations and the other represents every conceivable product characteristic. At the points on the grid where the vertical and horizontal axes intersect, the developers assign a degree of correlation between the market need and the product characteristics. The completed chart provides guidelines that designers and others can use to develop the most appropriate product.

4 Sticky data emerge because of encoding, coupling, and diffusion costs. Encoding costs arise because of difficulties associated with embedding and recontextualizing transferred knowledge at the receiving site. Coupling costs arise because of difficulties associated with integrating transferred knowledge with complementary knowledge at the receiving site. Diffusion costs arise because of difficulties associated with transferring data from one site to another.
In contrast to multi-channel mapping, single-channel mapping carried out in traditional production systems implies that customer requirements for different product attributes are channeled through one conduit to a single location. This information is then sent to various value centers. For example, information gathered by the marketing research department is fed to the corporate planning department, which, in turn, directs such information to various value centers.

Single-channel processing leads to delays and inaccuracies for several reasons. First, when data are sticky, distortions arise as information is sent from a centralized location to value centers. Information distortion can result in companies’ producing products with attributes not valued by customers. These products then have to be reworked to match customer needs, thereby slowing the production process. Second, single-channel processing implies that information about multiple product attributes is transmitted and acted upon sequentially, thereby slowing the information transmission process. Third, single-channel processing is more susceptible to information overloads than a system that possesses multi-channel capabilities. Information overloads, which may occur especially during periods of environmental change, can clog the single-channel system, thereby compromising the operation of the entire production system. These facets of single-channel processing result in compromising the speed flexibility of the production system, thereby leading to the following proposition:

**Proposition 2:** Production systems that employ multi-channel mapping will exhibit greater speed flexibility relative to those that employ single-channel mapping.

Multi-channel mapping in an isomorphic fashion allows the production system to mimic the process of topographical mapping in the brain, thereby enabling speed and scope flexibility. Therefore, a production system must be designed to promote these processes not only between customers and manufacturers, but also between manufacturers and suppliers. To visualize this, we suggest that the production system be viewed as consisting of several layers, each representing an agglomeration of value-creating activities and value centers. In Figure 3, we show three such layers: the distributor, manufacturer, and supplier.

This image of the production system organized in layers lies in contrast to the image of a value chain offered by Stern and El-Ansery (1982). Their conceptualization evokes an image of manufacturers and vendors linked through a single point of contact, thus permitting only sequential processing through a single channel. In contrast, the proposed layered structure emphasizes the need for multiple points of contact among vendors, manufacturers, and customers to promote multi-channel mapping in an isomorphic fashion.

Besides connections between layers, the brain also connects modules and neurons that constitute a module. These connections provide the
Illustrative Schematic Representation of a Proposed Flexible Production System

A typical value center consists of value-creating activities. Each value center is specialized yet generalized.

A rich network of connections between and among value centers.

Customer segments representing the multi-dimensional attribute space.

Multiple customer attributes mapped in an ideological manner.

Marketing — Manufacturing — Design.

Marketing — Manufacturing — Design.

Marketing — Manufacturing — Design.

Rich network of connections between and among value centers.

Supplier value chain.

Production value chain.

Distributor value chain.
potential for interactions between different modules in the brain. Similarly, production systems should connect value centers and activities within centers because they facilitate the distributed processing of information in parallel. Specifically, connections between the value centers help each value center engage in its own activities while being aware of the activities undertaken by others elsewhere. Connections within each center (between activities) allow the spontaneous initiation of activities, depending upon whether reinforcing or inhibiting signals are received from adjacent units within the center. This signaling process is illustrated by kanbans (i.e., signaling devices) used in just-in-time manufacturing. The activation of any value-creating activity is contingent upon the dispensing of kanbans between work activities. If a kanban is dispensed by an activity, it triggers a response from an adjacent activity. The lack of a kanban from an activity dampens the response from an adjacent activity. Eventually, a value center reaches a state of activity or passivity, depending upon the overall balance of excitatory or inhibitory activities that occur between value-creating activities. As in the brain, this process unfolds rapidly because information is processed in parallel.

These connections between different parts, in the brain and in the production system, are necessary for self-organization because they enable spontaneous linkages between the constituent parts. However, as several authors pointed out, the spontaneous interactions between constituent parts of a system can create confusion and a loss of focus (Eccles & Crane, 1988; Hirschhorn, 1984; Pasmore, 1988). Despite this potential for confusion, the brain is able to retain its focus by employing schemas that determine which of the brain’s connections get exercised. These schemas function by enabling temporary connections between modules to create novel knowledge combinations to address complex issues.

Similar to schemas in the brain, organizational routines, such as communication protocols and standard operating procedures, help orchestrate the functioning of various value centers, thereby enabling self-organization in the production system. By serving as a guiding framework, organizational routines ensure that activities carried out by individual value centers are coordinated and integrated with others’ efforts (see also Eccles & Crane, 1988; Hackman, 1990; Hirschhorn, 1984). Thus, organizational routines ensure that the activities of individual value centers are not dissipated through a lack of focus.

The impact of such rich connections along with organizational routines is the creation of a dynamic network structure of reciprocally interdependent activities that can be rapidly reconfigured to meet changing customer needs. As Eccles and Crane (1988: 134) stated,

"Having everybody report to everybody else serves to flatten the hierarchy, since it disperses authority. . . . The complex web of reporting relationships also contributes to flexibility. Because many ties already exist, responding to changing circumstances requires simply strengthening some ties while
weakening others, rather than creating completely new ties while dissolving others.

As Eccles and Crane (1988) suggested, the dynamic network structure functions by establishing "strong" and "weak" ties between various value centers that transcend firm boundaries. Strong ties, formed between centers that interact frequently, are essential for carrying out day-to-day production activities. Weak ties are important to establish what Hirschhorn (1984: 92) called "fringe awareness." Under changing conditions, the continuous feedback received by a system at the fringe of awareness, along with conscious planning at the "center of awareness," enables a system to respond flexibly.

In contrast to the process described above, traditional production systems have been designed as hierarchical structures in which value centers are selectively linked with others (representing a chain of command), and each value center is, at best, sequentially interdependent with activities undertaken by other centers of the hierarchical system. Such a hierarchical structure creates rigidities because system evolution is governed through time-consuming exogenous processes. This discussion is the basis for the following proposition:

**Proposition 3:** Production systems organized as a dynamic network will exhibit greater speed and scope flexibility relative to those that are organized as a hierarchy.

The brain is able to create a dynamic network through distributed processing because each brain module can undertake functions performed by other modules. Thus, even though modules are specialized, they have generalized capabilities; that is, the division of labor in the brain is fuzzy, overlapping, and partially redundant (Churchland, 1986). Similarly, distributed computation in production systems will be facilitated if value centers possess generalized capabilities despite being specialized in particular tasks. This is what Imai, Nonaka, and Takeuchi (1985) labeled as "shared" division of labor.

Shared division of labor facilitates speed flexibility in several ways. First, because of its generalized competencies, each center can operate semi-autonomously, keeping the requirements of other centers as

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5 Granovetter (1973) has shown that centers that exhibit strong ties can become isolated from other sources of information unless they also create weak ties with others outside their own group. Weak ties—those that arise through occasional contacts—are an important way of linking centers with strong ties with other centers, thereby avoiding merging them into a larger group of strong ties (see also Eccles & Crane, 1988: 132).

6 Multi-skilling is one manifestation of shared division of labor. It implies the acquisition of skills that cut across functions. In environments in which product variety and speed require fluid responses, multi-skilling overcomes the rigidities that set in from the division of labor (Adler, 1988; Eccles & Crane. 1988; Hayes & Wheelwright, 1988; Pasmore, 1988; Walton & Susman, 1987).
constraints even as they attempt to address their tasks. Hirschhorn (1984: 92) called this "holistic" knowledge. Because of this holistic knowledge, value centers can evolve together rapidly through mutual accommodation to meet customer requirements. Second, holistic knowledge enables each value center to engage in self-diagnosis and defect correction, thereby speeding the value-creation process. Third, because of holistic knowledge, specific value centers can take on tasks that other centers perform. As a result, value centers can be easily redeployed to perform a variety of tasks, depending upon customer demands.

In contrast, traditional production systems have been guided by "specialized" division of labor. Representing localization of value activities, specialized division of labor implies that each value center possesses competencies to perform only a narrow range of tasks. Although specialization leads to economies of scale, it results in compromising speed and scope flexibility. This is because specialization makes it difficult to reconfigure value centers to perform other tasks. Moreover, specialization leads to coordination through hierarchy because different value centers do not have an adequate appreciation of the functions performed by other centers. Inevitably, coordination through hierarchy results in delaying value creation. This discussion is the basis for the following proposition:

Proposition 4: Production systems employing the concept of shared division of labor will exhibit greater speed flexibility relative to those employing specialized division of labor.

The brain's ability to engage in parallel yet distributed computation is facilitated by its ability to link different modules with others in novel ways. Similarly, a production system's ability to work in a parallel yet distributed manner is also enhanced by a company's adopting modularized product designs (Pine, 1993; Wheelwright & Clark, 1992). Modularized product designs exhibit two properties. First, modularization involves the creation of end-products through components with standardized interface specifications. This feature reduces the time required to integrate components to produce end-products. Consequently, different parts of the product-development activities can evolve relatively independent of each other in a parallel yet distributed manner, thereby enhancing speed flexibility. Second, modularization involves the creation of component redundancy for each part. This feature enables the production system to mix and match various components to create a variety of products, thereby enhancing its scope flexibility.

In contrast, traditional production systems used integrated product designs. Integrated product designs synthesize several parts—which would have been independent in a product with a modular design—into a single part. Integrated product designs compromise scope flexibility because they reduce the options available to mix and match modularized components to create product variety. Integrated designs compromise
speed flexibility during manufacturing as different value centers are unable to work in parallel to create modules that can be assembled just in time. This discussion is the basis for the following proposition:

**Proposition 5:** Production systems that employ modularized product designs will exhibit greater speed and scope flexibility relative to those that employ integrated product designs.

How can a production system rapidly and reliably sense the mix of product attributes required to fulfill customer needs? The cooperative computation style of the brain suggests that the process should evolve through the cooperative interactions of different value centers. In this process, no predetermined plans bind value centers to a particular course of action. The cooperative computation style exploits information as it becomes available at each value center. Based on inputs received through the multi-channel mapping process, each value center formulates tentative hypotheses about the specific attributes required by customers. Information thus received forms the basis for a set of generic activities that each value center undertakes. These generic activities provide the foundation for future refinements that the system can undertake when more information becomes available.\(^7\) For example, the Benetton Company, sensing the demand for sweaters, initiates activities for the creation of “generic” (plain light-gray color) sweaters and postpones the dying process until exact fashion trends become clearer.

Mediated by organizational routines, each value center can begin tuning its activities to arrive at an overall configuration of product attributes. This is an iterative process whereby each center constrains other centers and, in turn, is constrained by them. As different value centers evolve to an overall understanding of the mix of product attributes required by customers, they are able continuously to update operating parameters that govern their conversion processes.

Sahal (1979) labeled the ability to update operating parameters to cater to environmental shifts as “homeorhesis.” Homeorhesis represents the capacity of a system not merely to return to its state before the occurrence of a disturbance, but to seek new development pathways through

\(^7\) This form of cooperative computation is illustrated by examining the overlapping program phases employed by many Japanese manufacturing firms during the new product-development process (see, for example, Imai et al., 1985). Historically, new product-development efforts or activities were carried out in sequence with different parts of a flexible production system, such as marketing, design, engineering, and manufacturing, sequentially actuated over time. In contrast, an overlapping product-development process requires the involvement of all the functions at the early stages of new product development. Even though some functions may be underutilized at different periods during the product-development process, the overlap between the various phases and consequent parallel yet distributed processing of information speeds up the development and introduction of new products.
successive instabilities (see also Hirschhorn, 1984). In contrast, traditional production systems are regulated through a process of homeostasis. This represents a control mode of operation in which deviations of performance from operating standards trigger feedback that initiate changes in activities, thereby regulating the system’s functioning. In these systems, operating parameters are only updated sporadically because of built-in system rigidities. Consequently, a certain configuration of operation parameters commits the production system to a particular mode of operation for a long duration of time, irrespective of changing customer demands, thereby compromising speed flexibility.

The brain continuously updates its operating parameters by linking its perceptual and motor schemas in a manner that allows sensory inputs continually to shape the operation of motor outputs. The electro-chemical connections used by the brain to establish these links consume very little energy (Hirschhorn, 1984). This facet of the brain distinguishes it from other systems—such as organizations controlled by hierarchy—that expend so much energy in the control function that the control system begins impeding the activities of the units it controls (Hirschhorn, 1984).

In the production system, this continual parametric adjustment requires that "perceptual" routines continually shape "motor" routines. This is possible in production systems that have the capacity to process information even while taking part in the conversion process (Zuboff, 1984). From this perspective, flexible production systems can be viewed as consisting of two types of networks superimposed on each other—one representing material flow and transformation (motor routines), and the other representing information flow and transformation (perceptual routines). As in the brain, the information network serves the function of the perceptual schema that continually tunes operations of the material network (see also Ashby, 1960). Because it is electronic, the information network enables the material network to tune its operating parameters on a real time basis with a minimal consumption of energy. This continuous tuning of value activities as new information becomes available enables a production system to respond flexibly to changing environmental conditions. This discussion is the basis for the following proposition:

**Proposition 6:** Production systems that continuously tune their operating parameters that govern the value-creation process will exhibit greater speed flexibility relative to those that intermittently tune their operating parameters.

A facet of the brain's operation that must be considered is the potential for blind spots and rigidities. The very perceptual schemas that enable the brain to make sense of external stimuli can also create blind spots by selectively focusing the brain on certain stimuli while ignoring others. Moreover, motor schemas can commit the brain to an unwarranted course of action.
Similarly, organizational routines, too, can create blind spots (Henderson & Clark, 1990) and commit an organization to a course of action that is not in tune with its environment (Allison, 1972). Moreover, as captured in the notion of absorptive capacity (Cohen & Levinthal, 1990), the existing stock of competencies affects an organization’s ability to perceive, assimilate, and act upon data. The powerful influence of routines in shaping perception and committing organizations to a mode of operation is illustrated by the delay of many U.S. firms in shifting to “just-in-time” routines despite evidence of its superiority over “just-in-case” routines.

A brain preserves its vitality despite the potential for blind spots and rigidities by assimilating new knowledge and creating new schemas. Over time, a brain develops a broad knowledge base and a repertoire of schemas. The wider the knowledge base and the repertoire of schemas, the greater its ability to recognize and respond to a wide variety of stimuli. Similarly, flexible production systems must possess a repertoire of organizational routines and competencies to overcome potential blind spots and rigidities. Building upon the notion of absorptive capacity, we suggest that the broader the existing base of competencies and routines, the greater the production system’s ability to perceive and assimilate external stimuli. A broad base of competencies and routines also enhances the production system’s ability to respond to a wide range of customer demands (Ashby, 1965). Therefore, these capabilities enhance scope flexibility.

Moreover, as in the brain, a production system’s ability to preserve its vitality is contingent upon whether it continuously updates its competencies and routines (Hayes & Wheelwright, 1988; Pasmore, 1988). One way to accomplish this is to institute major reorganizations periodically (Eccles & Crane, 1988; Hammer, 1990). Reorganization provides an opportunity for a firm to seek new developmental pathways; a procedure that Eccles and Crane (1988: 143) likened to the “annealing process used in crystal formation.” In this way, periodic reorganization helps overcome rigidities that might otherwise set in. This discussion is the basis for the following proposition:

Proposition 7: Production systems with a broad base of competencies and routines that are continuously updated will exhibit greater scope flexibility relative to those that possess a narrow base of competencies and routines that are updated intermittently.

The value of the metaphorical approach that we have adopted lies in our ability to generate insights that can be mapped from a target to a source. These insights, as transferred from the brain to flexible production systems, are summarized in Table 2. However, the utility of the insights gained from a metaphor, and the boundary conditions over which these insights are valid, must be empirically established. Toward this
TABLE 2
Vesting Production Systems with Flexibility

<table>
<thead>
<tr>
<th>Principles</th>
<th>Why is it required?</th>
<th>How is it achieved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Channel Mapping</td>
<td>Overcome sticky data problem</td>
<td>• Use multiple decentralised conduits for information acquisition and transmission</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Employ cross-functional teams</td>
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<tr>
<td>Isomorphic Mapping</td>
<td>Match environmental complexity with internal diversity</td>
<td>• Create a diversity of competencies in value centers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Employ QFD and other similar techniques</td>
</tr>
<tr>
<td>Dynamic Networks</td>
<td>Enhance fluid responses to continuously changing customer needs</td>
<td>• Create temporary connections between and among value centers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Employ distributed processing of product and process information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Integrate value centers through rich connections</td>
</tr>
<tr>
<td>Modularity</td>
<td>Rapidly create product variety</td>
<td>• Mix and match components through</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— component redundancy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— standardized component interfaces</td>
</tr>
<tr>
<td>Shared Division of Labor</td>
<td>Reduce the need for a hierarchy by fostering self-organization</td>
<td>• Employ equipment with additional capabilities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Employee multi-skilling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Overlap phases in product development</td>
</tr>
<tr>
<td>Tuning</td>
<td>Continuously modify the value-creating processes in accordance with changing customer demands</td>
<td>• Employ concurrent engineering principles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Use CAD/CAM and CNC machine using a distributed “architecture”</td>
</tr>
<tr>
<td>Updating of Routines and</td>
<td>Enable the system to evolve with the changing environment</td>
<td>• Employ re-engineering and rapid prototyping concepts</td>
</tr>
<tr>
<td>Competencies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In addition, we propose indicative ways to operationalize the constructs that constitute our core propositions in the following section.

**RESEARCH DIRECTIONS**

We conceptualized flexibility as comprising two components—speed and scope. Speed flexibility represents the rapidity with which a production system is able to reconfigure itself to meet the changing demand for new products and existing products (Slack, 1987). It might be reflected in the frequency with which new or modified products are introduced and in the time taken by a production system to fulfill custom orders (see also Chen & Adam, 1991). Scope flexibility represents the range of final products that a production system can deliver. Researchers can assess scope flexibility by tracking the variety of final products that a production sys-
tem produces (e.g., Jaikumar, 1986; Tombak, 1988) and assessing its ability to deliver customized products (Parthasarthy & Sethi, 1992).

Multi-channel processing might be evidenced by the presence of multiple points of contact between the different layers of a production system (i.e., customers, distributors, suppliers, and manufacturers). Multi-channel processing also requires that researchers examine the degree to which information between the layers is processed in a parallel manner.

Whether a production system is capable of isomorphic mapping can be gauged by assessing the range of competencies it possesses relative to the diversity of product attributes required by customers. The gap between what is required by customers and what the production system can create provides a measure of the system's capability to map isomorphically. Assessing whether a production system employs techniques such as the "quality function deployment technique" (Hauser & Clausing, 1988) is also indicative of its ability to map isomorphically.

Dynamic network properties may be assessed by a system's ability to create temporary teams and the extent to which lateral, rather than hierarchical, integration mechanisms are employed. Measures such as the degree of formalization, delegation, specialization, and integration that place firms along a continuum between organic and mechanistic organizations (e.g., Dean, Yoon, & Susman, 1992; Van de Ven & Ferry, 1980) and integrative mechanisms (e.g., task teams) proposed by Galbraith (1973) may be employed with appropriate modifications. The extent to which information processing is centralized or decentralized can also be assessed.

Researchers can operationalize the notion of modularity by using the dimensions of modularity described by Pine (1993) and Wheelwright and Clark (1992). The degree to which component redundancies are used for mixing and matching components to achieve product variety and the extent to which standardized interface specifications are employed can also be used to operationalize this construct.

Researchers may gauge the emphasis placed on shared division of labor at three levels—the individual, group, and production system. At the individual level, researchers may focus on the degree to which employees are multi-skilled, the extent to which machines and equipment possess capabilities that go beyond those required to perform one task, and the extent to which job rotation is practiced within the production system. At the group level, the employment of redundancies in new product-development teams may be assessed. At the production system level, the concept can be gauged by evaluating the extent to which firms possess competencies in which others (i.e., suppliers) might specialize.

Tuning is a measure of the rapidity and ease with which a production system can change its production parameters to accommodate product mix changes. The application of concurrent engineering principles via the use of CAD and CAM may provide an indication of a production system's ability to tune its production parameters on a real-time basis.
The degree to which routines and competencies are regularly updated can be measured by examining whether re-engineering and rapid prototyping principles are employed. Re-engineering alludes to a firm’s ability to fundamentally redesign business processes using modern information technologies (cf. Hammer, 1990). Rapid prototyping alludes to a process whereby customer feedback is incorporated into prototypes through product experimentation and learning (Wheelwright & Clark, 1992). The frequency with which organizational routines and competencies (e.g., scheduling routines, inventory control routines, and new product-development routines) are modified and the amount of resources (e.g., time, people, equipment, and money) allocated for acquiring new skills and competencies, through training and other programs, may also provide measures related to this construct. Additionally, researchers can assess whether the organization has instituted a pay-for-learning system of job classification (Hirschhorn, 1984). Under this system, workers get paid more as they learn more skills, and everyone can reach the top production system rate.

Our premise is that technology alone is insufficient to realize flexibility. It is therefore important that researchers control for the adoption and extensive application of new technologies such as FMS. Additionally, researchers must control for other variables such as industry effects that might have an impact on speed and scope flexibility.

CONCLUSION

We began by asking why some firms have not attained flexibility despite having invested in flexible manufacturing technologies. The answer, we suggested, may lie in the fact that flexible manufacturing technologies are necessary but not sufficient to accomplish flexibility. To the extent that the flexibility of a system is constrained by its most rigid part, firms will not be able to realize flexibility even if they were to employ flexible manufacturing technologies. As several authors have noted, flexibility can be accomplished only by adopting a broader systems perspective in which organizational practices are designed to tap flexibility that new technologies make possible (see Adler, 1988; Eccles & Crane, 1988; Hirschhorn, 1984; Pasmore, 1988; Walton & Susman, 1987).

Viewing production systems from this perspective requires design principles that are different from scientific management principles employed to design traditional production systems. Scientific management principles, manifest in the specialized division of labor and coordination through hierarchy, have served U.S. manufacturers well in the design of mass production systems capable of responding in a “machine-like manner” to human instructions. However, efforts to create organizations that respond in a machine-like manner to human instructions have created large, obdurate systems. As Hackman (1990: 477) stated:
To the extent designers embrace a machine model for the production of flexible production team(s), they are unlikely to reap the very benefits to which they aspire—benefits that well-designed and well-led work teams are in fact capable of providing.

Here we can see why investing in technology alone will not lead to flexibility. The scientific management paradigm is fundamentally incompatible with efforts to design flexible production systems (see Hackman, 1990; Hirschhorn, 1984). Discovering the "one best way" to accomplish tasks through specialization results in fragmentation rather than synthesis, and therefore, is antithetical to self-organization through teamwork (Hackman, 1990). Making incremental changes within this paradigm is unlikely to lead to new insights about manufacturing flexibility. U.S. manufacturing firms need a new paradigm that can generate novel insights on how to accomplish flexibility.

We offered the brain as a metaphor to create such a new paradigm. Brain processes that enhance its ability to respond rapidly to a broad range of stimuli lie in contrast to localized and sequential processing found in traditional production systems. Specifically, brain processes unfold in a parallel yet distributed manner through a cooperative computation process. Cooperative computation enhances self-organization capabilities, the key to realizing flexibility in any system.

These observations have important implications for theory and practice that must be directed at identifying how U.S. manufacturing firms can carry out value creation in a parallel yet distributed manner. Production systems must be designed to abandon hierarchical modes of command and control to facilitate parallel processing. Production systems must also be designed to break down barriers that isolate functional activities so that value-creating centers can be combined in novel ways to address customer needs, thereby facilitating distributed processing. Most importantly, in the image of the brain, production systems must be designed to foster a learning environment in which the system is able to evolve incrementally from initial inputs.

We have tapped only a small fraction of the insights that the brain as a metaphor has to offer. Existing knowledge about the brain provides a rich theoretical base for generating new insights on flexibility. Equally important, researchers continue making new discoveries about the brain that can provide additional insights on flexibility. Thus, using the brain as a metaphor to model flexible production systems not only provides us with a knowledge base to work from, but a knowledge base to work with.

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