A survey of manufacturing flexibility: Implications for e-business flexibility

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Flexibility is an effective means by which an e-business can hedge against uncertainty in a swiftly changing environment. Systems, applications, and business processes—in short, the entire environment supporting e-business—must seamlessly adapt to changes without costly and time-consuming infrastructure overhauls. Decision makers therefore have a growing need for knowledge about e-business flexibility. However, flexibility remains largely an abstraction in the e-business domain, with the term often meaning different things to different people. Whereas very little systematic research has been directed towards the study of flexibility issues associated with e-business, a rich and burgeoning literature on manufacturing flexibility has accumulated over the past 25 years. In this paper we review the existing literature on manufacturing flexibility, and extract from it guiding principles for creating and managing e-business flexibility.

For businesses of all sizes and in almost every industry, e-business on the Internet has become a key interface between organizations and their suppliers and customers. Many factors contribute to success in e-business; for example, functionality, integration, and scalability.[1] One of the most important success factors is flexibility, that is, the ability to hedge against the uncertainty that is an inevitable consequence of the complexities generated by technological advancements. While advances create an ever-larger number of technologies and standards, the Internet adds further layers of complexity by allowing e-business systems to connect with each other. In the process, a proliferating myriad of devices becomes part of the e-business infrastructure, allowing enterprises to connect with employees, customers, and suppliers. Firms today must manage not only desktops, servers, and PCs, but also cell phones, pagers, hand-held computers, and so on. Organizations must also manage products, IT systems, business processes, and extended systems that function well beyond conventional corporate boundaries. The associated connections, dependencies, and interacting e-business systems require flexibility so that systems can adapt themselves to changing technologies and business environments. To address the increasing complexity of computing systems, Horn[2] encouraged academic thinkers and industry leaders to explore autonomic computing, that is, systems capable of managing themselves by adjusting to changing environments and allocating resources to most efficiently distribute workloads. These autonomic systems must be flexible in order to manage themselves; they must be self-configuring, self-optimizing, self-protecting and self-healing.

In this paper, e-business broadly refers to organizations that have re-engineered business processes to take full advantage of advances in telecommunications, computer hardware, and computer software. Viewed in this way, e-business is characterized by several factors. First, e-business is open, in the sense that Internet technology is flexible, easy to use and

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available to all. Flexibility and open standards give great latitude in creating new business models, for example, by linking formerly isolated information domains like logistics, manufacturing, finance, procurement, and human resources. Also, e-business goes well beyond e-commerce (i.e., buying and selling over the Internet), to include back-office and supply-chain systems. As such, e-business allows organizations to create strategic alliances and to outsource functions and processes that fall outside of their distinctive competencies. For this reason, collaboration and cooperation among e-business partners are critical to success. From hosting servers to writing application software to fulfilling consumers' needs, e-business must foster an open and connected team. Speed is also critical for e-business—the early mover advantage has been well documented for technology-intensive businesses[3,4]

Finally, technology is a key component of e-business. Communications and standardization are typically very important issues in e-business technologies. e-business applications are often distributed utilizing Web technology. Security, scalability, interoperability, and support for heterogeneous platforms are fundamental issues. Applications for e-business are often based on evolving or immature technologies, and are not necessarily restricted to current technology. Control of application components may reside outside of the organization, making integration with outside systems important. Time-to-market pressure is typically high, and quality may suffer as a result.

In this context, e-business flexibility determines an organization's ability to adapt to changes and uncertainties in its business environment, both internal and external. In addition to general business flexibility, e-business flexibility reflects an organization's ability to react to those environmental variables that are particularly associated with information technologies and new ways of doing business which are enabled by these technologies.

The dramatic and continuing decrease in the cost of a broad range of technologies (e.g., Internet, wireless, and broadband) and the wide use of standards have created numerous opportunities for increasing e-business flexibility, thereby changing the basis of competition.[5] Flexibility is particularly important in an increasingly volatile business environment characterized by intense, global competition, short product life cycles, increased technological innovation, and time-sensitive customer demand. The focus of competition in global marketplaces is increasingly shifting from cost, quality, and service to delivery, flexibility, and innovation.[6] Systems, applications, and business processes—in short the entire environment supporting e-business—must seamlessly adapt to changes without costly and time-consuming infrastructure overhauls.

In this environment, an understanding of the meaning, sources, and uses of flexibility is critically important. Despite this, very little systematic research has been directed towards the study of flexibility issues associated with e-business. In contrast, a rich body of literature on manufacturing flexibility has accumulated over the past 25 years. In this paper we review the existing literature on manufacturing flexibility, and extract from it guiding principles for creating and managing e-business flexibility.

Solution providers for e-business increasingly promote flexibility as a major value proposition to their customers. For firms to invest significantly to achieve high levels of e-business flexibility, the relationship between flexibility and business performance must be clearly understood. Acquiring adequate flexibility doesn't ensure an organization a competitive edge; e-business flexibility is a function both of technology and of how effectively an e-business system is managed.[7,8] Although flexibility should be appropriately designed into processes, this flexibility must also be well managed, in order to fully realize the associated performance benefits. This paper summarizes principles extracted from the significant literature on the design and management of manufacturing flexibility. Our goal is to both inform and educate e-business managers about the general issues related to flexibility, and to stimulate theoretical and applied research on e-business flexibility. Comprehensive coverage of the various perspectives on flexibility should help e-business managers more intelligently evaluate and invest in the flexibility of their operations.

As described by Carlsson[9] and Upton,[10] business decisions concerning flexibility are made at three distinct levels: strategic, tactical, and operational. At the strategic level, a firm determines an appropriate level of investment in flexibility, as well as the types of flexibility in which to invest. Decisions at this level consider the dynamic e-business environment in which the firm operates in order to choose a role for flexibility that reflects the firm's strategic long-term needs. At the tactical level, processes for creating and developing flexibility are constructed. The objective at this level is to determine the extent, measurement, and expected returns of flexibility functions. The operational level then considers the problem of efficiently utilizing flexibility in day-to-day operations, to ultimately capture the potential benefits from investments in increased flexibility. We classify the existing literature according to these three dimensions and present important insights into how all three levels affect e-business flexibility.

The literature on manufacturing flexibility is extensive. Excellent reviews of early work in this area can be found in Sethi and Sethi,[11] Gupta and Goyal,[12] and Buzacott and Yao,[13] while more recent research is summarized in D'souza and Williams,[14] Koste and Malhotra,[15] and Vokurka and O'Leary-Kelly.[16] Of this literature, we review the portion that provides insight into how e-business flexibility should be developed and managed.

The remainder of the paper is organized as follows. The following section summarizes key concepts and perspectives on flexibility. We then review research focused on the strategic, tactical, and operational aspects of flexibility, respectively. We conclude with a summary and suggestions for further research on e-business flexibility.

Concepts and perspectives

Flexibility is a word that is broadly used, but the concept of flexibility remains vague. Kumar[17] attributed at least part of this ambiguity to the many different types or aspects of flexibility on which different studies have focused. Moreover, alternative definitions of flexibility are imprecise and often inconsistent. Swamidass[18] discussed three other reasons why flexibility is so poorly understood: (1) the overlap in scope of terms used by different authors to define flexibility, (2) the fact that some terms used to define flexibility aggregate others, and (3) the fact that even when different researchers use the same term to define flexibility, they may attach entirely different meanings to the term. For these reasons, a universally consistent concept of flexibility has yet to be developed. In this section, we discuss several views on flexibility from the literature, with the objective of developing a well-rounded perspective on flexibility for e-business decision makers.

De Groote[19] defined flexibility as a hedge against environmental diversity and proposed a general framework for analyzing flexibility. The framework consists of three elements: (1) the set of technologies whose flexibility is to be evaluated, (2) the set of environments in which those technologies operate, and (3) a performance criterion for evaluating different technologies in different environments. Note that the terms *technology* and *environment* must be understood very broadly. For example, technology can be used to denote any aspect of an organization's business resources, control procedures, or overall strategy. While flexibility is considered a property of technology, diversity is an attribute of the prevailing environment. The term *diversity* is used to convey the idea of variability, variety, complexity, or uncertainty. In modeling or analyzing flexibility, the distinction between flexibility and diversity is useful. Many existing flexibility models have been naturally interpreted in this context.[20–23]

Business decisions concerning flexibility are made at three distinct levels: strategic, tactical, and operational.

Gerwin[24] proposed a conceptual model that places flexibility within a broad context. The model includes five variables: environmental uncertainty, strategy, required manufacturing flexibility, methods for delivering flexibility, and performance measurement. Flexibility is typically defined as an adaptive response to environmental uncertainty.[12] However, Gerwin expanded this definition by arguing that an enterprise could leverage flexibility to anticipate and prepare for environmental uncertainties through redefinition. For example, a firm can encourage customers to see the benefits of shorter lead times or more frequent new product introductions, and then provide higher levels of service in these dimensions through superior manufacturing flexibility. By creating additional uncertainty for its competitors, a firm can create a significant and sustainable competitive advantage. The Honda case in Reference 25 illustrates this observation. Honda, through rapid introduction of new motorcycles, raised customer expectations with respect to how often new products would become available. Yamaha determined that the competitive uncertainties in trying to overtake Honda were too significant, and ultimately withdrew from the market.

The performance measurement system in Reference 24 ensures integration of the strategic and operational decisions associated with flexibility. At the strategic level, the role of flexibility in addressing specific uncertainties is articulated, whereas the focus at the operational level is on designing processes for delivering flexibility. Clearly, strategic and operational decisions need to be linked. The performance measurement system acts as the bridge between the two, translating strategic flexibility requirements into performance objectives, and evaluating the extent to which the results attributable to flexibility match the performance objectives. For example, an organization can position itself relative to the competition through its responsiveness to customers. This strategic objective can be made operational through performance metrics that capture the time between the placement of a system request by a customer and that request's fulfillment. A well-designed performance measurement system ensures that operational decisions are consistently made to minimize lead times. However, if the operational system is not designed and managed to deliver responsiveness, the lead-time performance realized may not be sufficient to create and sustain competitive advantage. In this case, either the strategy must be modified (de-emphasizing responsiveness in favor of some other competitive attribute that the organization can deliver), or resources must be allocated to improve the lead-time performance of the system.

Gerwin[24] also considers four generic flexibility strategies: adaptation, redefinition, banking, and reduction. Adaptation represents a defensive approach, incorporating the traditional use of flexibility to adjust to uncertainty. Redefinition is defined as the proactive use of flexibility to change the basis of competition, as in the Honda case. Banking involves the strategic investment in flexibility, which is then held in reserve for future needs, thus creating new options for the organization. With a reduction strategy, the organization uses other means for reducing environmental uncertainty (e.g., through long-term contracts with customers and suppliers, design for manufacturability, or preventive maintenance), thus decreasing the need for flexibility.

Review of research on manufacturing flexibility

Excellent reviews of various types of manufacturing flexibility are presented in References 11 and 12. The following sections summarize key concepts from these articles that prove useful in broadening the perspectives of decision makers on flexibility. Specifically, research on the strategic, tactical, and operational aspects of manufacturing flexibility is reviewed, and the application of these aspects to e-business is discussed.

Manufacturing capacity can be classified according to two types: dedicated and flexible. Dedicated capacity is best suited for mass production of a single product, with specialization resulting in lower unit costs. On the other hand, flexible capacity is most appropriate for small batch production of many products. By more easily accommodating design changes, demand uncertainties, and shifts in the product mix, flexible capacity provides an organization with the ability to rapidly introduce new products, reducing the need for inter-period inventories and expanding product scope to assist in competing in new markets.[26] Flexibility viewed in this way reflects a system's ability to deal with changing circumstances[27] or environmental instability.[28]

Mandelbaum[29] described two types of flexibility. Action flexibility refers to the ability to adapt to changes through intervention from outside of the system. In contrast, state flexibility defines a system's ability to operate well in many different circumstances without outside intervention. Buzacott[30] extended this concept of flexibility by considering the nature of the changes and disturbances, both internal and external, with which flexible capacity can cope.

Slack[31] proposed a multidimensional perspective on flexibility, arguing that flexibility has three dimensions, (1) the range of possible configurations a system can adopt, (2) the cost of migrating from one configuration to another, and (3) the time needed to make the transition. One system is more flexible than another if it can handle a wider range of configurations, accommodate change in a shorter amount of time, or make the transition at lower cost. The time and cost dimensions are inversely related, in that the time to make a transition may be shortened at extra cost, and the cost of making a transition may be reduced by allowing more time for the change. Due to its multidimensional nature, flexibility is inherently difficult to measure. Because flexibility is most often not an end in itself, the impact of flexibility should be measured with respect to other performance criteria such as product quality, volume, and delivery.

Gupta and Buzacott[32] extended Slack's notion by characterizing flexibility in terms of sensitivity and stability. Sensitivity refers to the level of change a system can accommodate before corrective action is required. Stability refers to the magnitude of change that a system can handle while still maintaining normal performance. Defined in this way, sensitivity and stability represent the minimum and maximum magnitude of change for a system within which the property of flexibility holds.[33] Similarly, Upton[10] stressed the difference between robustness and agility. The former emphasizes the ability to maintain the status quo despite changes; the latter emphasizes the ability to initiate change rather than react to it.

A flexible e-business must be able to take advantage of new and innovative ways of using Internet technologies.

Upton[34] suggests that there is usually more than one way to meet a given flexibility requirement. For example, a firm can develop the ability to offer a great variety of products through a set of dedicated plants and/or subcontractors. The same level of flexibility can be achieved by supplying the same set of products from a single flexible plant. Similarly, the flexibility of quick response to customer orders can be achieved through building up appropriate levels of inventories or developing advanced manufacturing capabilities that enable just-in-time production.

Application of research to e-business flexibility. The concepts of flexibility described in the previous section help to characterize what e-business flexibility might mean for an organization. Because of its openness, a flexible e-business must be able to take advantage of new and innovative ways of using Internet technologies, and to effectively respond to threats and opportunities created by an ever-larger e-business world. Because of the connected nature of e-business, e-business flexibility must also include the ability to generate, process, store, and share information and data (both internal and from partners), as well as the ability to create and join e-business networks. e-business flexibility also captures the ability to adapt to changes and problems through collaboration and cooperation with e-business partners. The ability to respond quickly and dynamically to an ever-changing environment represents additional facets of e-business flexibility. Finally, a flexible e-business must manage the risks associated with technologies and technological innovation by addressing issues associated with scalability, compatibility with open standards, and ease of integration with other systems and platforms.

To illustrate how this framework for flexibility can be applied to e-business settings, consider the distinction made between dedicated and flexible capacity. In a manufacturing context, capacity represents the maximum workload a system is capable of handling, measured as output per unit time. Analogues for e-business include computational capacity (measured, for example, as the average processing speed of a processor), network capacity (measured by its communications bandwidth), and e-commerce capacity (measured as the number of customer transactions that a system can process per unit time). Resources for e-business such as computing power, bandwidth, and e-commerce capability can (in principle) be considered either dedicated or flexible, in the sense that these resources can be configured to serve one or many purposes. For example, if a computer is used only for human resource (HR) applications, the computer's capacity is dedicated exclusively for this purpose. However, if the same machine is configured for both HR applications and customer billing, then the computational capacity is flexible in that its processing power can be directed towards either application. As with manufacturing flexibility, e-business flexibility captures the ability of a system's resources to be used for alternative purposes without a significant cost penalty, and is a result of system design and management.

Strategic aspects of flexibility. Decisions made at the strategic level determine an organization's total investment in flexibility, as well as the types of flexible resources in which it invests. These strategic decisions must take into account the dynamic e-business environment in which the organization operates in order to define a role for flexibility that reflects the firm's strategic long-term needs. The literature reviewed in this section highlights the concepts and issues that should be considered in strategic flexibility decisions.

Flexible resources allow an organization to hedge against uncertainty, but at a higher investment cost than that associated with dedicated resources. Therefore, investment decisions concerning flexibility have to carefully resolve various cost/benefit trade-offs. Decision makers often rely on intuitive judgments to determine whether the strategic benefits associated with flexibility justify the corresponding investment. As noted by Kaplan,[35] even very careful application of traditional return-on-investment analysis often fails to capture the strategic benefits of flexibility.

To make sound strategic decisions, decision makers need to thoroughly understand the benefits of flexibility. As noted in the previous section, many of the benefits of flexibility are intangible, and thus difficult to quantify. Research on scheduling with resource flexibility (see References 36 and 37) has characterized the impact of resource flexibility on system performance. These studies showed that complete resource flexibility (i.e., when each resource unit can be allocated to any and every stage of the production process), if properly utilized, can improve throughput performance by more than 60 percent with an average improvement of more than 20 percent compared to systems with no flexibility. Daniels, Mazzola and Shi[38] extended this work to systems where resources are partially flexible, namely, that each unit of resources can be assigned to a subset (but not necessarily all) of the stages in a production process. A key result is that the vast majority of the operational benefits associated with complete flexibility can be captured with a relatively small investment in flexibility, so long as this flexibility is distributed and managed intelligently. Indeed, the diminishing marginal returns exhibited by investments in resource flexibility are sufficiently pronounced that in most cases a completely flexible system is not justified.

Jordan and Graves[39] developed similar principles concerning the benefits of process flexibility that result from the ability to build different products in the same plant. Consistent with the results in Reference 38, a key insight is that limited flexibility (where each plant builds only a few, but not all, products), distributed in the right way, can achieve most of the benefits of total flexibility (where each plant builds all products). These findings demonstrate the benefits that accrue when investments in flexibility are properly targeted and the associated flexibility is well managed.

The extension of these results to the domain of e-business is straightforward. Because an e-business is comprised of a set of business processes that typically span multiple functions within an organization, and often multiple organizations within the supply chain, it is the flexibility of these processes that determines overall e-business flexibility. As stated earlier, organizations can design and manage their business processes to be more or less flexible, to the extent that the resulting systems are or are not capable of responding to the different demands that may be placed on them, without incurring significant additional costs. The principle developed earlier indicates that much of the available benefit associated with e-business flexibility may be realized by introducing only a small amount of flexibility into the underlying business processes.

To illustrate this concept, consider a technical support center whose role is to respond to a wide variety of incoming customer questions and problems. An inflexible process would be characterized by individual employees each capable of handling only a single type of request. The system would then be managed by routing different types of requests to the appropriate employees. Clearly, the performance of such a system in providing timely response to customer inquiries would depend critically on how well the volume of each type of request corresponded with the capacity of the employees assigned to handle those requests. Flexibility can be introduced into this system by training individual employees to handle multiple requests. Such a system might be particularly effective if the mix of requests received varied widely over time. The results described above indicate that large improvements in responsiveness might be realized with the relatively minor expense of such cross-training.

This rationale may apply even if humans are not an integral part of the process. For example, when expert systems are substituted for employees in the previous example, the organization must still decide if distinct portals should be built for each major type of customer request, or if a smaller number of portals can be supported by a more complex (but consequently more flexible) combination of hardware and software.

Jordan and Graves[39] further explored two factors that affect the benefits of flexibility: correlations among product demands and system-wide capacity relative to expected total demand. Their results indicate that the benefits of process flexibility decrease as the correlations among product demands grow, and that the benefits of flexibility are greatest when capacity and expected demand are roughly in balance. Furthermore, there is no single flexibility plan that optimizes the benefits of flexibility; thus, decision makers can choose among alternative flexibility plans to minimize investment and manufacturing costs, or to satisfy other objectives.

Fine and Freund[26] investigated the trade-offs between the cost of acquiring flexible capacity and the benefit gained in a firm's ability to respond to demand uncertainties. They derived the optimal investment policy for flexible capacity, and tested the sensitivity of the optimal policy to the cost of flexibility, the distribution of demand across products, and the level of risk. Van Mieghem[40] extended this model by incorporating product prices (margins) into the analysis. These studies highlight the importance of price and cost differentials across products, which in addition to demand distributions, significantly affect the optimal investment in and value of flexibility. In addition to providing a hedge against demand uncertainties, technology that enhances product flexibility allows for revenue improvement by exploiting margin differentials. In essence, product flexibility provides an option to produce and sell more profitable products at the expense of less profitable products.

In the presence of demand uncertainties, an asset that is used in producing a single product becomes risky, in the sense that its economic value depends on uncertain market demand for the product it has been designed to produce. Sanchez[41] suggested that flexible resources (i.e., assets with multiple uses in production) have greater economic value (which, in principle, can be determined using options theory). In general, the option value of a flexible resource increases with the number of alternative products that the asset can be used to produce, and decreases with the cost and time of switching the flexible asset from the production of one product to another.

Recent research suggests that investments in complementary assets (e.g., infrastructure, user training, applications, and business processes) are critical to understanding the return on IT investments (see References 22, 42, and 43). In addition to consideration of costs and benefits, strategic decisions concerning flexibility also need to consider the complementary nature of different types of flexibility. For example, decisions regarding product and process flexibility are interrelated, with process flexibility essentially laying the foundation for product flexibility. However, excessive investment in process flexibility can be wasteful if a sufficient variety of products cannot be designed to take advantage of the flexible process.

A framework for evaluating and modifying the flexibility of a given system is provided by Gerwin.[24] In deciding how much flexibility is appropriate, a distinction is drawn between required, potential, and actual flexibility. Required flexibility is the amount of each specific type of flexibility that is needed, given current conditions. Potential flexibility represents what can possibly happen under an appropriate environmental setting. Actual flexibility refers to the outcomes realized by operating the flexible system. The outcomes are evaluated by metrics used in real-life implementations, and the values obtained depend on the experience of the organization running the flexible system. Inappropriate amounts of flexibility are indicated by significant discrepancies among the required, potential, and actual amounts, with misalignments occurring primarily when required flexibility is greater than potential flexibility, when potential flexibility is greater than actual flexibility, and when potential flexibility is greater than required flexibility.

While the presentation here has inevitably centered on manufacturing concepts such as demand distribution and price and cost differentials, the conclusions and principles derived are certainly applicable to the domain of e-business. For example, when designing an e-commerce portal to sell products online, the demand distribution reflects the variety in the types of transactions that the system must handle. Similarly, price and cost differentials across products capture the difference between the benefit (e.g., profit of the transaction) and the cost (e.g., time and resources consumed in processing the transaction). Other manufacturing concepts can be similarly modified to create a fully relevant analogue for e-business.

Tactical aspects of flexibility. At the tactical level of decision-making, the means by which flexibility is created and allocated within the system is determined. Issues considered here include where flexibility should be added, how flexibility within the system should be measured and modified, and what potential returns can be expected from investments in flexibility.

Daniels, Mazzola and Shi[38] explored the impact of partial resource flexibility on production scheduling and manufacturing performance. They developed a matrix representation of the stages in the system to which each individual resource can be assigned, defined metrics to measure both the amount and mix of flexibility within the system, and characterized distributions of flexibility that consistently yield good performance. To extend these results to the e-business domain, system stages should be interpreted as applications for which e-business resources can be used. For example, a set of servers $S=\{1, 2, \ldots, m\}$ might be deployed for a set of business applications $A=\{1, 2, \ldots, n\}$ (e.g., database, commerce portal, access control, firewall, etc.), in which case system flexibility can be captured with a binary matrix indicating which servers can perform which business applications. Specifically, the matrix $F=(I_{sa})$, where $s \in S$ and $a \in A$, is defined as:

$$I_{sa} = \begin{cases} 1, & \text{if server } s \text{ can perform application } a; \\ 0, & \text{otherwise.} \end{cases}$$

In this setting, a server is flexible if it is able to run multiple applications. If a powerful server (e.g., IBM's DEEP BLUE* supercomputer) can handle all of the applications, then the server is considered fully flexible.

To illustrate, consider a system with four servers and four applications, and suppose that

$$F = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix}$$

In this example, server 1 can perform only application 1 and is thus inflexible. Server 2 and server 3 are partially flexible because both can perform a subset of applications—{1, 2} for server 2 and {3, 4} for server 3. Server 4 is fully flexible in that it can perform all applications.

In addition to finding that the vast majority of the potentially substantial benefits associated with full flexibility can be captured with partially flexible resources, Daniels, Mazzola and Shi[38] found that system performance for a given level of flexibility can vary widely according to the distribution of flexibility. Significantly, the authors also showed that some distributions of partial resource flexibility result in performance that is considerably worse than that associated with a totally inflexible system. Finally, of the many ways in which a given amount of flexibility can be distributed throughout a system, distributions that allocate flexibility as evenly as possible, across both individual resources and stages of the system, consistently yield superior operational performance.

In determining how much flexibility is needed and where it should be added to respond most effectively to manage uncertain demand, Jordan and Graves[39] found that (1) a limited amount of flexibility added in the right place can capture virtually all of the potential benefits of total flexibility, (2) creating fewer, longer plant-product chains (i.e., groups of plants and

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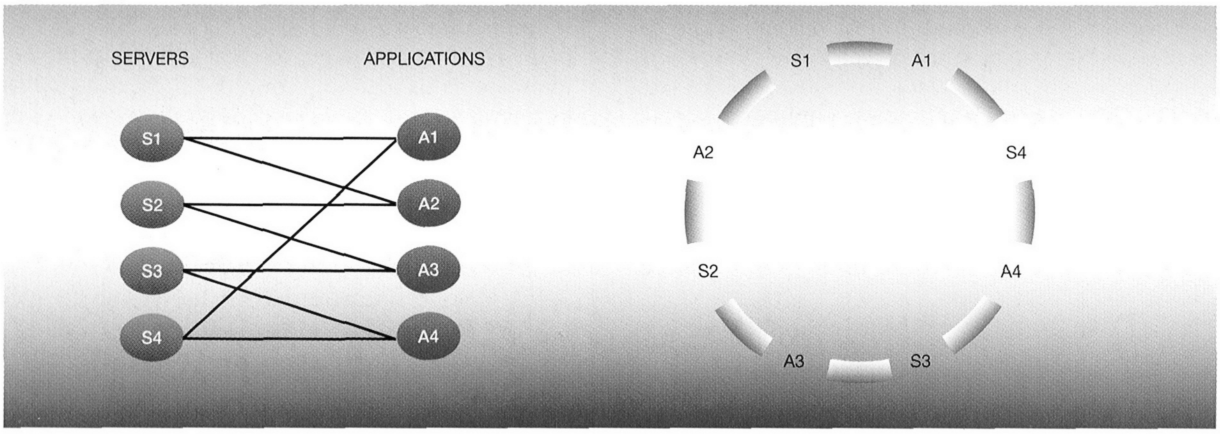
products which are assigned to each other) is an effective means for adding flexibility, and (3) after a plant-product chain has been created, additional flexibility should be added in a way that either better balances the assignment of products to plants or establishes a circuit. However, the benefits associated with adding flexibility within a chain diminish rapidly. The authors also propose a simple measure of flexibility, that is, the maximal probability, taken over all sets of products, that there is simultaneously unfulfilled demand for some products and excess capacity at some plants building other products.

To understand the e-business analogue to the plant-product chain, consider the bipartite graph involving e-business resources (e.g., the servers used as an example previously) and purposes for which these resources can be used (e.g., business applications). A chain is then formed by identifying a continuous path in the bipartite graph that creates a cycle of maximal length without creating subcycles. Modifying the matrix F from the earlier example, a chain can be formed by configuring server 1 to perform business applications 1 and 2, server 2 to perform applications 2 and 3, server 3 to perform applications 3 and 4, and server 4 to perform applications 4 and 1 (with the last server assigned both the first and last application for completeness). This provides additional coverage for every application while maintaining a relatively low investment in flexibility. The bipartite graph depicting this distribution of flexibility and the associated server-application coverage chain are shown in Figure 1.

Gerwin[24] outlined a four-phase procedure for implementing desired changes in flexibility. Phase I es-

Figure 1 Bipartite graph for a 4-server, 4-application system and the associated chain



tablishes which dimensions of flexibility require attention; phase II identifies gaps between the actual and ideal levels of flexibility; phase III determines how to close these gaps; and phase IV involves continuous monitoring and assessment.

Because of the multiple dimensions of flexibility, metrics are generally difficult to define. Gupta and Goyal[12] identified several approaches for measuring flexibility. For example, flexibility can be assessed by monitoring the economic consequences of a system's ability to adapt to changes. Alternatively, system flexibility can be measured on the basis of selected performance criteria, e.g., range of system configurations, cost, and time. Flexibility can also be measured by the number of possible states that a system can handle, and these states can be diagrammed using a Petri net. Finally, flexibility can be evaluated from information-theoretic and decision-theoretic perspectives. Gupta and Somers[44] discuss 34 items affecting manufacturing flexibility from the literature and provide another excellent review on the measurement of these items in the context of manufacturing flexibility.

There are numerous types of manufacturing flexibility addressed in the literature (see References 29 and 45–47). For example, 11 types of flexibility are proposed in Sethi and Sethi:[11]

1. Machine flexibility refers to the variety of operations that a machine can perform without incurring substantial costs or prohibitive amounts of time in switching from one operation to another.
2. Market flexibility is defined as the ease with which a manufacturing system can adapt to changing market conditions.
3. Production flexibility is the set of products that a manufacturing system can produce without adding major equipment or capacity.
4. Material-handling flexibility refers to the ability of a material-handling system to move different part types through the manufacturing system, including loading and unloading of parts, inter-machine transportation, and storage of parts under various environmental conditions.
5. Operation flexibility is the ability of a product to be produced in different ways.
6. Process flexibility is defined as the ability of a manufacturing system to produce different products without major setups.
7. Product flexibility refers to the ability of a manufacturing system to produce different products or various product mixes.
8. Routing flexibility is the ability of a manufacturing system to produce a product by alternative routes through the system.
9. Expansion flexibility is defined as the amount of overall effort needed to increase the capacity and capability of the manufacturing system when required.
10. Volume flexibility refers to the ability of a manufacturing system to be profitable within a wide range of product output levels.
11. Program flexibility is the ability of a system to

run virtually unattended for a long period of time.

Many of these concepts of flexibility can be applied to e-business by substituting e-business processes for manufacturing systems in the definitions above. For example, market flexibility might refer to the ease with which an online process can adapt to changing market conditions; product flexibility might reflect how easily this process can accommodate a mix of demands placed on it; and volume flexibility might capture the ability of a process to function effectively over a wide range of transaction volumes.

More recent research on flexibility dimensions can be found in D'souza and Williams,[14] who listed four dimensions: variety flexibility, process flexibility, volume flexibility, and material-handling flexibility. Each of these dimensions has associated with it two attributes, range and mobility. Note that these flexibility dimensions are defined at various levels: some at the overall system level, some at the subsystem level, and some at the system component level. From the perspective of the entire business, Koste and Malhotra[15] proposed a five-tier hierarchy for classifying flexibility dimensions: the strategic business unit tier, the functional tier, the plant tier, the shop floor tier, and the individual resource tier. In making tactical decisions, we emphasize the importance of first identifying the tier and level where flexibility should be added, and then determining the specific type of flexibility in a top-down fashion.

Operational aspects of flexibility. Investing in the right amount and mix of flexibility is a necessary condition for realizing a competitive advantage. However, the strategic and tactical decisions discussed in the previous sections only create the potential for an organization to capture the benefits of flexibility. The actual return on investment in flexibility depends on how it is utilized in daily business operations. The utilization of flexibility spans almost all functions of a business, including procurement, planning, production, marketing, sales, and services. Most of the existing literature addresses utilization issues associated with production; however, research into the role and utilization of flexibility in other business functions would also likely expand our understanding of flexibility.

Daniels and Mazzola,[36] Daniels, Hoopes and Mazzola,[37] and Daniels, Mazzola and Shi[38] studied operational aspects of resource flexibility from a scheduling perspective because production scheduling is an important and challenging manufacturing function that must be performed often. These studies modeled environments where resources are flexible, in the sense that individual resource units can be assigned to multiple stages in the production process. When processing times depend on the amount of resource allocated to a task, flexible resources can be used to break processing bottlenecks, thereby enhancing system effectiveness and efficiency. However, scheduling with flexible resources is very complex, involving three interrelated problems: job sequencing, resource assignment, and operation-start-time determination. The job-sequencing problem determines the order in which jobs should be processed in the system. The resource-assignment problem allocates an appropriate amount and mix of resources to each job over time, which consequently determines the processing time of each operation. The start-time-determination problem translates a given job sequence and resource assignment policy into a schedule by explicitly specifying the start time of each operation. The effective utilization of flexible resources is thus dependent on the close coordination of solutions for these three subproblems. The procedures used to find optimal, or even good, policies involve advanced optimization techniques, heuristic algorithms, and simulation approaches.

In e-business, scheduling is the determination of when and how to process e-business tasks such as authorization and authentication, traffic routing, data queries, accepting orders, delivering products or services, and so on. As such, scheduling is a critical factor affecting the effectiveness and efficiency of an e-business. The e-business analogue for job sequencing is the sequence in which e-business activities or tasks should occur. Similarly, resource assignment involves determining which e-business resources (e.g., CPU, communications bandwidth, and IT professionals) should be assigned to execute each e-business activity or task. Finally, the operation-start-time problem specifies when each activity or task should begin and end.

While there are many types of flexible resources, labor (because of the inherent flexibility of the human worker) offers perhaps the most common example of a widely available flexible resource. When workers are cross-trained to perform multiple tasks, they acquire the flexibility to be assigned to multiple stages of the production process, for example, in response to shifting workload bottlenecks. The ubiquity of worker-staffed production lines offers strong motivation for the study of practical workforce assignment policies.[8] We therefore review several studies in which workers are assumed to have full flexibility. The objective is to provide general insight into the operational aspects of flexibility.

Bartholdi and Eisentein[48] studied the "bucket brigade" policy, where each worker carries an item from stage to stage, processing it at successive stations and passing the item off to a worker in a subsequent process; the worker then collects the next item from a proceeding process and repeats the operation. The authors found that: (1) without careful management, the system could easily become chaotic (e.g., the positions of workers in the system may become unpredictable and unstable), (2) under certain conditions, there exists a fixed point in the system where the system achieves an equilibrium in which workers always work on the same portion of the system, and (3) if workers are sequenced from slowest to fastest, the system's fixed point is unique, and equilibrium is achieved eventually, regardless of the starting positions of the workers.

Using both queuing theory and simulation, Zavadlav, McClain, and Thomas[49] extended the work of Bartholdi and Eisentein to situations with uncertain processing times. They established that a bucket brigade system could buffer itself against variation by altering the work assignment dynamically. Such a system is capable of adapting quickly and automatically to environmental changes (for example, worker absences). The authors refer to the system as self-buffering, self-balancing, and self-flushing. These results show that flexible resources (e.g., labor), if appropriately managed and utilized, can result in an autonomic system,[2] where a system can be self-managed through self-configuration, self-optimization, self-protection, and self-healing.

Oyen, Senturk-Gel, and Hopp[50] studied two other workforce assignment policies. An "expedite" policy assigns all workers to one operation at any given point in time. Under a "pick-and-run" policy, an individual or team of workers picks up one job, processing the job throughout the process until the job is completed; the team then returns to the beginning of the line to repeat the process. By establishing several analytical properties of the policies, this study highlights that different strategies for utilizing flexibility can lead to substantial differences in system performance.

Shi[8] simulated the performance of seven workforce allocation policies, including bucket brigade, expedite, and pick-and-run. The simulation results suggest that the most effective way to utilize a given level of flexibility is strongly environment-dependent, in that a policy that works well in one setting might perform poorly in a different setting. This implies that simply borrowing a best practice from another environment may not yield a workable solution. Study of the specific environmental setting of a best practice is required to determine the most appropriate way to utilize flexibility for maximum benefits.

Investing in the right amount and mix of flexibility is a necessary condition for realizing a competitive advantage.

While workforce allocation policies studied in the manufacturing literature can be directly applicable to the management of e-business employees, the results also provide insight into the operational aspects of e-business flexibility. For example, that bucket brigade systems are capable of adapting quickly and automatically to environmental changes suggests that automated e-business is possible. Moreover, other e-business resources, for example, computational power, storage, and communications bandwidth, are inherently flexible in the sense that each can be deployed for multiple purposes with little or no changeover cost. These flexible resources can be utilized in an almost infinite number of ways. The results described in this section suggest that the chosen resource allocation policy can have a significant impact on e-business performance; e-business managers must consider the specifics of their business environment in determining the most effective way to utilize flexibility.

Conclusions

The evolution of technology has made the environment surrounding e-business more complex and volatile. This volatility motivates the creation and management of e-business flexibility to hedge against the uncertainties inherent in a swiftly changing environment. By reviewing some of the relevant literature on manufacturing flexibility, this paper provides a synthesis of knowledge on flexibility which is useful for e-business practitioners, as well as for future theoretic and applied research on the topic.

What has been learned about manufacturing flexibility can significantly aid decision-making regarding e-business flexibility. The frameworks reviewed in the section "Concepts and perspectives" are not specific to manufacturing flexibility—these can be directly applied to concretize what is meant by e-business flexibility. Similarly, with some modifications, the questions, issues, and insights presented in the section "Strategic aspects of flexibility" and subsequent sections can be applied to e-business flexibility. In particular, the principles developed in these sections serve as logical starting points for modeling the strategic, tactical, and operational decisions that an enterprise must make with respect to e-business flexibility.

However, the observation that e-business flexibility is still a poorly understood concept itself motivates continuing research. For example, further study is required to establish a solid and widely accepted taxonomy of e-business flexibility. The structures presented for manufacturing flexibility represent a good starting point; however, further investigation is required to establish the extent to which these definitions of flexibility are relevant for e-business. These definitions may need to be modified or even replaced by measures that more completely capture the idiosyncrasies of the e-business environment. For example, additional work is required to determine how to define and measure flexibility in the security, scalability, and system compatibility of an e-business infrastructure.

The e-business manager would also benefit from insights and analytical tools that help frame e-business flexibility decisions at the strategic, tactical, and operational levels. For example, IBM has recently emphasized grid computing, where users can access diverse computing resources much like a utility. If grid computing is viewed as a flexible resource, in the sense that elements of the grid can be used for multiple tasks, then questions similar to those posed in the study of manufacturing flexibility must be addressed. How much flexibility should be built into the grid? How should that flexibility be distributed across networking, database, computing power, application, and human assets (e.g., staff and end users)? For a given amount and distribution of flexibility, how should the resources within the grid be allocated to maximize the return on investment in flexibility?

Empirical research, including case and field studies, also promises to generate significant insights into the practical implications of e-business flexibility. Empirical research on manufacturing flexibility[16] provides a guide for the design of empirical work on e-business flexibility.

As noted previously, an e-business system is complex, including infrastructure, applications, IT systems, business processes, standards, and strategy. Additional research is needed to understand the meaning of flexibility in each of these subsystems, how flexibility interacts across subsystems, and the impact of different flexibilities and their interactions on overall system performance. In addition, to develop efficient and effective methodologies for delivering flexibility, additional research is needed to understand better the impact of different types of flexibility on the subsystems of an e-business.

Results reviewed in this paper should help e-business managers appreciate the importance of flexibility in their businesses. Future research should be directed towards further helping decision makers understand how flexibility can improve business effectiveness, how a desired level of flexibility can be achieved, and how flexibility can be leveraged in daily operations to create and maintain a competitive advantage. As the future e-business environment becomes more volatile and complex, enterprises will increasingly find e-business flexibility a key to survival, growth, and success.

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