CHAPTER 11

Enterprise Resource Planning Systems in Manufacturing*

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1. INTRODUCTION

Enterprise resource planning (ERP) is a class of commercially developed software applications that integrate a vast array of activities and information to support tactical-level operations and operations planning for an industrial enterprise. The term *ERP* refers to the software and not to the related business processes. However, as software, it enables better execution of certain processes. Although often presented as a single package, an ERP system is an envelope around numerous applications and related information. For manufacturers, those applications typically support the operations processes of materials sourcing, manufacturing planning, and product distribution. To its end users, an individual application of an ERP system may appear seamless; however, to those who procure, implement, and/or maintain ERP systems, they are complex software systems that require varying levels of customization and support both centrally and across applications. While ERP systems are commercial applications developed by individual vendors, they can hardly be considered off-the-shelf. They are part of a continuing trend of outsourcing IT solutions in which part of the solution is bought, part is configured, and part is built from scratch. In general, as the scope and complexity of integrated applications have increased from systems supporting a single business unit to systems supporting an entire enterprise and its relationships with business partners, the portions of an IT solution that are bought and configured have increased while the percentage of custom-built software has decreased. Given their broad organizational and functional scope, ERP systems are unlike any other contemporary commercial manufacturing applications. They provide "transaction management," both from the business perspective and from a database perspective. Additionally, they provide a basic level of decision support. Optionally, they enable development of software for higher levels of decision support, which may be offered by ERP vendors or third-party vendors. It is clear that ERP, as a subject, is very complex. Its use marries technology, business practices, and organizational structures. The purpose of this chapter is to present a high-level view of ERP in order to frame a discussion of technological challenges and research opportunities for improving ERP interoperability. Although ERP is relevant to many types of industries (e.g., goods and services) and organizations (e.g., for-profit and not-for-profit), the discussion in this chapter is limited to ERP in manufacturing enterprises. More specifically, the focus of this chapter is ERP that supports the principal operations of a manufacturing enterprise: planning, procuring, making, and delivering products. An ERP system may support other enterprise functions, such as finance management, human resource management, and possibly sales and marketing activities. Detailed analysis of those functions is beyond the scope of this chapter; however, the linkages of those functions with manufacturing-specific functions are not.

This overview looks at ERP by itself and as part of a larger entity (Figure 1). Section 2 discusses ERP internals such as core functions, implementation elements, and technology issues. Additionally,

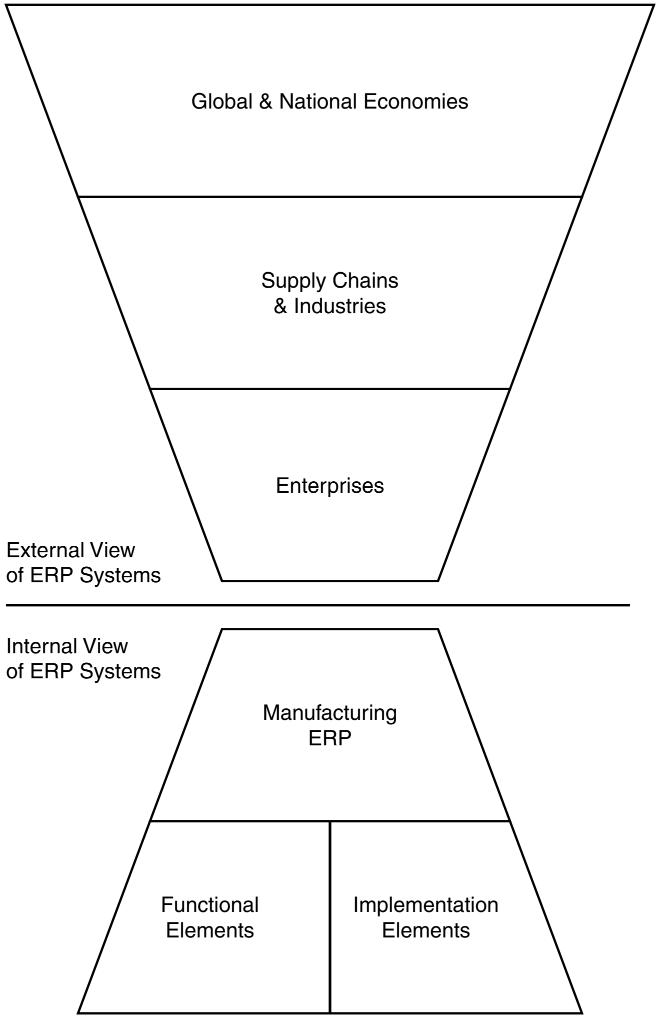

Figure 1 External and Internal Views of ERP.

Section 2 identifies critical integration points for ERP and other applications within manufacturing enterprises. Section 3 discusses ERP and its relationship to three larger entities, namely the U.S. economy, supply chains, and individual manufacturers. Section 4 presents issues and possible resolutions for improving ERP performance and interoperability.

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The concepts presented in this chapter were gathered from a variety of sources, including literature reviews, manufacturing industry contacts, ERP vendor contacts, consultants specializing in the applications of IT to manufacturing, relevant professional and trade associations, and standards organizations.

1.1. Major Business Functions in Manufacturing Enterprises

Manufacturers typically differentiate themselves from competitors along the three major business functions through which they add value for their customers. Customer relationship management

(CRM), the first dimension of competitive advantage, seeks to add value for customers through those processes that involve direct contact with customers before, during, and after sales. The idea is to understand the prevalent needs and concerns of individual customers and groups of customers. Product development, the second dimension of competitive advantage, focuses on product—what and how to produce an object to satisfy the customer's *want.* Operations, the third dimension of competitive advantage, focuses on satisfying *demand*—how much to make, when to make, and where to make—by producing and delivering products in an effective and efficient manner.

Needs, wants, and *demands* are basic concepts underlying modern, market-based economies (Kotler and Armstrong 1999). Needs beget wants, which beget demand. Needs are states of felt deprivation. They are a basic part of our human condition and are physical, social, and individual in nature. The customer's needs include product capabilities, product servicing, user instruction, and business relationships. Wants are the forms taken by human needs as shaped by culture and individual personality. They are described in terms of objects that will satisfy needs. Demands are human wants that are backed by buying power. Identifying needs and translating them into wants in terms of product and process definitions are the objectives of product development. Satisfying demand, given supply conditions as well as product and process definitions, is the objective of operations. This high-level partitioning of manufacturing business functions into CRM, product development, and operations has growing acceptance in manufacturing and related industries (Hagel and Singer 1999). This acceptance has been fostered by the realization that the underlying activities of these high-level functions are those that add value for the customer.

The complex activities of product development seek to satisfy customer want by translating the abstract to the physical through the product development process. As such, in commercial manufacturing enterprises, product development typically starts with an analysis of market opportunity and strategic fit and, assuming successful reviews through intermediate phases, ends with product release. Among other things, product release serves as a signal to operations to begin production and distribution as the necessary design and manufacturing engineering specifications are ready for execution in a production environment.

Operations, on the other hand, consists of processes for satisfying customer demand by transforming products—in raw, intermediate, or final state—in terms of form, location, and time. To accomplish this objective both effectively and efficiently—and thus meet specific, customer- focused, operational objectives—a manufacturing enterprise must have timely and accurate information about expected and real demand as well as expected and real supply. A manufacturer then considers this information on supply and demand with the current and expected states of its enterprise. It is ERP that allows a manufacturer to monitor the state of its enterprise—particularly the current and near-term expected states. In fact, ERP systems often serve as the cornerstone in the emerging information architectures that support balancing external and internal supply and demand forces. ERP systems play both direct and indirect roles in this trend among manufacturing enterprises towards a synchronized, multilevel, multifacility supply chain planning hierarchy.

1.2. Manufacturing Operations Planning

Figure 2 illustrates the emerging synchronized, multilevel, multifacility supply chain planning hierarchy with ERP as its foundation. The goal of this architecture is to enable more efficient and effective execution across plants, distribution systems, and transportation systems. Independently, these planning activities focus on the strategic, the tactical, and the operational (i.e., execution) levels. Collectively, they support the translation of strategic objectives into actions on the plant floor, in warehouses, and at shipping points throughout the extended enterprise. In addition, they provide top management with up-to-date, synchronized information regarding the state of the entire enterprise.

This synchronization is accomplished by transforming information in a meaningful way from one level within the supply chain planning hierarchy to the next. At the strategic level, top management evaluates numerous factors to determine the design or redesign of the supply chain network as well as time-independent sourcing, production, deployment, and distribution plans. These factors typically include the enterprise's business philosophy as well as company, market, technological, economic, social, and political conditions. Supply chain planning at the strategic level involves "what if" analysis particularly with respect to the first three factors: business philosophy, company conditions, and market conditions. A business philosophy might specify maximizing net revenues or return on assets. Assessment of company conditions considers existing and potential aggregates of fixed (i.e., plant), financial, and human resources. When evaluating market conditions, top management analyzes aggregate product/part demand as well as the anticipated capacity of suppliers and transportation channels—also in aggregate terms. Optimization at this level, which usually employs mathematical programming methods, typically yields the location, size, and number of plants, distribution centers, and suppliers as well as product and supply volumes.

Supply chain operations planning at the tactical level determines the flow of goods over a specific time horizon. Mathematical programming methods yield time-dependent integrated sourcing, pro-

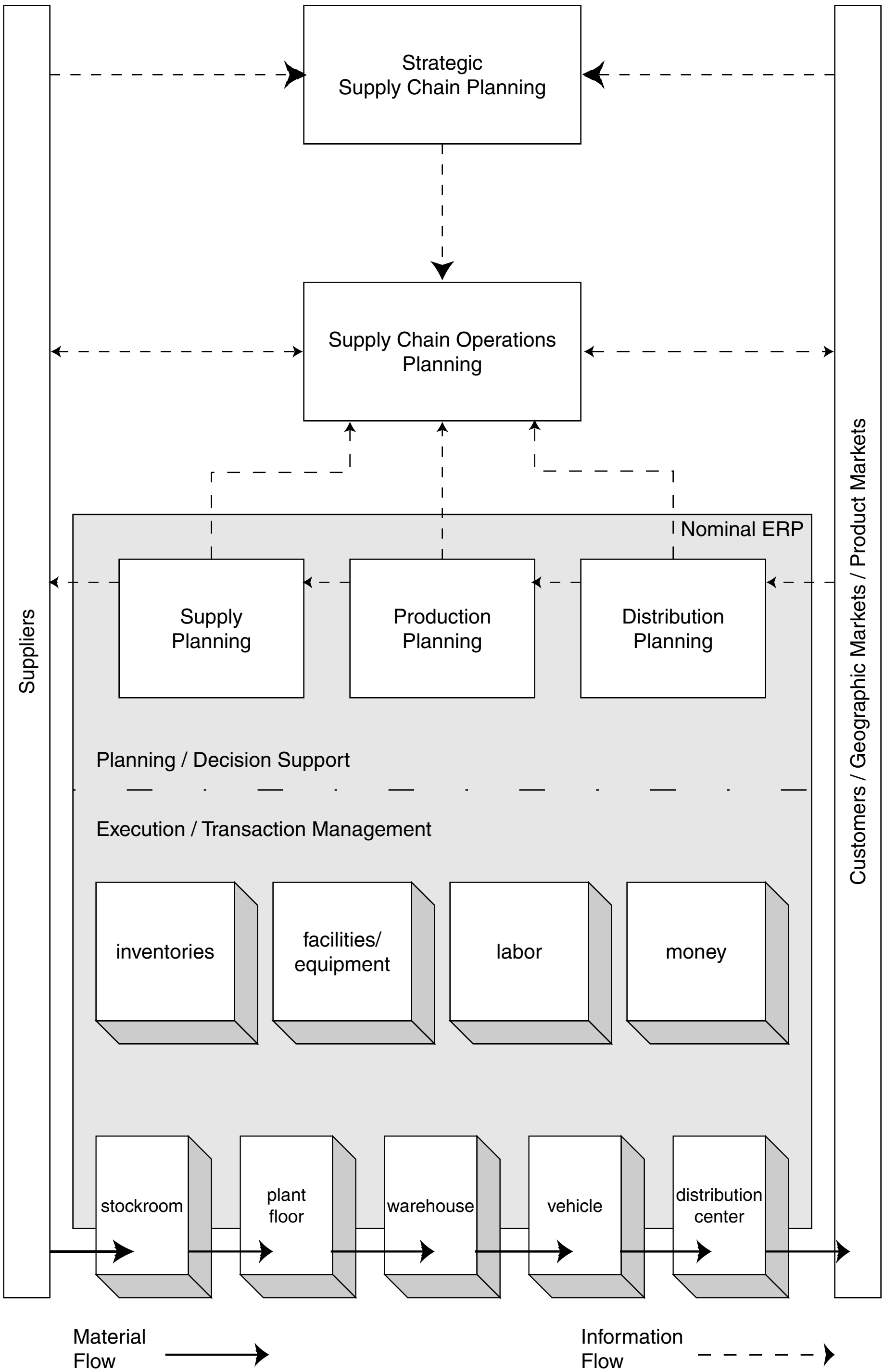

Figure 2 Intraenterprise View of Supply Chain Planning Hierarchy.

duction, deployment, and distribution plans typically designed to satisfy a financial management objective such as minimizing total supply chain costs or maximizing net revenues by varying product mix. Often, once these plans are established, a more detailed level of tactical planning occurs to optimize supply, production, and distribution independently. Frequently, the objective at this lower level of tactical planning is to minimize costs related to inventories and/or major equipment changeovers.

Supply chain planning at the operational level is, in essence, supply scheduling that occurs on a facility-by-facility basis. As such, separate but coordinated schedules are generated for plants, warehouses, distribution centers, and vehicle systems. Planning at this level differs from tactical and strategic levels in that demand actually exists—that is, orders have been placed. These orders need to be scheduled based on the immediate state of resources (i.e., materials, equipment, and labor). The diverse nature of facilities means that the specifics of optimization vary widely at this level, but the objective typically is to maximize throughput in a given facility.

Individually, these layers serve to separate concerns and enable the definition of tractable planning problems for which mathematical and managerial solutions can be obtained. Collectively, these layers of supply chain planning enable manufacturing enterprises more effectively and efficiently to balance supply, resources, and demand. The upper layers buffer the lower layers from sudden shifts in the market, thus allowing for smoother changes in the enterprise's plants, distribution channels, and transportation systems.

1.3. Partitioning the Domain of Manufacturing

The domain of manufacturing is in fact an aggregate of many subdomains of many types. There is no single correct method for decomposing that complex and dynamic aggregate. The method of decomposition depends on the particular objective at hand. Generally speaking, there are four common approaches to partitioning the manufacturing domain. Each looks at a different aspect of the manufacturing enterprise:

1. *Nature of the product:* This approach categorizes manufacturing industries by the general nature of the product itself—fertilizers, pharmaceuticals, metals, automotive parts, aircraft, etc. This is the approach used by industry classification systems such as the North American Industry Classification System (NAIC) (Office of Management and Budget 1997) and its predecessor, the Standard Industrial Classification (SIC) (Office of Management and Budget 1988). In general, this approach is a good mechanism for characterizing market communities, and thus economic estimators, but it is not a particularly good mechanism for characterizing ERP requirements or planning approaches.
2. *Nature of the customer:* Because most manufacturing output is consumed by other industries, many manufacturers are part of the supply chains ending in original equipment manufacturers (OEMs) in a single major industry: automotive, aerospace, shipbuilding, household appliances, computers, etc. The members of the chain produce different kinds of products, using different processes, with different business behaviors, but the behavior of the supply chain itself often is dominated by the demands of the OEMs.
3. *Nature of the process:* This approach characterizes a domain by the organization of the manufacturing facility and the general nature of the manufacturing processes it employs: continuous process, assembly line, discrete batch, job shop, and construction. There is some correlation between the process type and the product type, in that most manufacturers of a given product type tend to use a particular process organization. In general, process type strongly influences the manufacturing-specific aspects of ERP, including both information capture and planning approaches. On the other hand, large manufacturers often use several different process styles for different products and different components of larger products.
4. *Nature of the business in terms of customer orders:* This characterization includes make-to-stock, make-to-order, assemble-to-order, and engineer-to-order. It has a great deal to do with what the detailed business operations are and how operational and tactical planning is done. Clearly this categorization has a tremendous influence on the ERP requirements and on the behavior of the enterprise in its supply chain. More than any other, this characterization determines the nature of the delivery activities and the dependence on supplier relationships.

These last two categories, as differentiators for ERP, warrant more detailed discussion.

1.3.1. Nature of Process

Continuous process refers to a facility in which products are made by an essentially continuous flow of material through some set of mixing, state transformation, and shaping processes into one or more final products. The final form may itself be intrinsically discrete, or it may be discretized only for packaging and shipment. Examples are wet and dry chemicals, foods, pharmaceuticals, paper, fibers, metals (e.g., plate, bar, tubing, wire, sheet), and pseudocontinuous processes such as weaving, casting, injection molding, screw machines, and high-volume stamping.

Assembly line refers to a facility in which products are made from component parts by a process in which discrete units of product move along an essentially continuous line through a sequence of installation, joining, and finishing processes. Examples are automobiles, industrial equipment, small and large appliances, computers, consumer electronics, toys, and some furniture and clothing.

Discrete batch, also called *intermittent,* refers to a facility in which processes are organized into separate work centers and products are moved in lots through a sequence of work centers in which each work center is set up for a specific set of operations on that product and the setup and sequence is specific to a product family. This describes a facility that can make a large but relatively fixed set of products but only a few types of product at one time, so the same product is made at intervals. This also describes a facility in which the technology is common—the set of processes and the ordering is relatively fixed, but the details of the process in each work center may vary considerably from product to product in the mix. Examples include semiconductors and circuit boards, composite parts, firearms, and machined metal parts made in quantity.

Job shop refers to a facility in which processes are organized into separate work centers and products are moved in order lots through a sequence of work centers in which each work center performs some set of operations. The sequence of work centers and the details of the operations are specific to the product. In general, the work centers have general-purpose setups that can perform some class of operations on a large variety of similar products, and the set of centers used, the sequence, the operations details, and the timing vary considerably over the product mix. Examples include metal shops, wood shops, and other piece-part contract manufacturers supporting the automotive, aircraft, shipbuilding, industrial equipment, and ordnance industries.

Construction refers to a manufacturing facility in which the end product instances rarely move; equipment is moved into the product area and processes and component installations are performed on the product in place. The principal examples are shipbuilding and spacecraft, but aircraft manufacture is a hybrid of construction and assembly line approaches.

1.3.2. Nature of the Business in Terms of Customer Orders

Make-to-stock describes an approach in which production is planned and executed on the basis of expected market rather than specific customer orders. Because there is no explicit customer order at the time of manufacture, this approach is often referred to as a push system. In most cases, product reaches retail outlets or end customers through distribution centers and manufacturing volumes are driven by a strategy for maintaining target stock levels in the distribution centers.

Make-to-order has two interpretations. Technically, anything that is not made-to-stock is made-to-order. In all cases there is an explicit customer order, and thus all make-to-order systems are described as pull systems. However, it is important to distinguish make-to-demand systems, in which products are made in batches, from option-to-order systems, in which order-specific features are installed on a product-by-product basis. The distinction between make-to-demand batch planning and on-the-fly option selection using single setup and prepositioning is very important to the ERP system.

A *make-to-demand* manufacturer makes fixed products with fixed processes but sets up and initiates those processes only when there are sufficient orders (i.e., known demand) in the system. This scenario may occur when there is a large catalog of fixed products with variable demand or when the catalog offers a few products with several options. The distinguishing factor is that orders are batched and the facility is set up for a run of a specific product or option suite. The planning problem for make-to-demand involves complex trade-offs among customer satisfaction, product volumes, materials inventories, and facility setup times.

Option-to-order, also called *assemble-to-order,* describes an approach in which production is planned and executed on the basis of actual (and sometimes expected) customer orders, in which the product has some predefined optional characteristics which the customer selects on the order. The important aspects of this approach are that the process of making the product with options is predefined for all allowed option combinations and that the manufacturing facility is set up so the operator can perform the option installation on a per-product basis during manufacture. This category also applies to a business whose catalog contains a family of fixed products but whose manufacturing facility can make any member of the family as a variant (i.e., option) of a single base product. The option-to-order approach effects the configuration of production lines in very complex ways. The simplest configurations involve prepositioning, in which option combinations occur on the fly. More complex configurations involve combinations of batching and prepositioning.

Engineer-to-order describes an approach in which the details of the manufacturing process for the product, and often the product itself, must be defined specifically for a particular customer order and only after receipt of that order. It is important for other business reasons to distinguish contract engineering, in which the customer defines the requirements but the manufacturer defines both the product and the process, from contract manufacturing, in which the customer defines the product details and the manufacturer defines the process details. But the distinction between contract engineering and contract manufacturing is not particularly important for ERP, as long as it is understood that both are engineer-to-order approaches. In these scenarios, some set of engineering activities must take place after receipt of customer order and before manufacturing execution, and then certain aspects of manufacturing planning can begin.

1.3.3. Combining Nature of Process and Nature of Business in Terms of Customer Orders

Many attempts to characterize manufacturing roll up some combination of the four major categorization approaches (product, customer, process, business) into a single categorization scheme in order to make certain useful generalizations. But because resource planning and ERP systems must deal with important details of the organization's business process, these generalizations do not provide good guidelines for studying the variations in planning and execution information. In particular, no generalization about industries applies to all manufacturing organizations in that industry, and there is no way to roll up the nature of the process with the nature of the business in terms of customer orders. For example, all four business patterns can be observed in the continuous (and pseudocontinuous) processing industries. Even though engineer-to-order (customer-specific recipe) is fairly rare in the chemical and raw metal industries, it is the norm (customer-specific mold) in the injection-molding and casting industries. It does make sense, however, to cross the nature of the process with the nature of the business in terms of customer orders to identify those combined characteristics that have the most significant influence on ERP system requirements. Table 1 identifies 14 distinct categories, out of a possible 20, for which there are known manufacturers in specific industries.

2. AN INTERNAL VIEW OF ERP SYSTEMS

This section describes what ERP systems do and how they do it. Sections 2.1 through 2.3 describe the core functional elements of ERP systems: human resource management, finance management and accounting, contracts management, materials acquisition, materials inventory, maintenance management, order entry and tracking, manufacturing management, process specification management, warehousing, and transportation. Sections 2.4 through 2.6 describe implementation aspects, particularly ERP systems architecture, configuration management tools, and Internet interfaces.

2.1. Scope of ERP Systems in Manufacturing Enterprises

As illustrated in the portion of Figure 2 bounded by the gray box, the functionality of ERP systems encompasses certain interactions among the following elements:

- Four categories of resources (inventories, facilities/equipment, labor, and money)
- Two generic activities (planning/decision support and execution/transaction management)
- Three types of manufacturing operations activities (supply, production, and delivery)
- Five major types of physical facilities (stockroom, plant floor, warehouse, vehicle/depot, and distribution center) through which material flows in manufacturing enterprises

Because there is considerable variation among manufacturers as to which functions in which facilities fall within the scope of an ERP implementation, the gray box does not envelop all physical facilities. Typically, in some way or another, all transactions—all changes of state and many deci-

TABLE 1 Examples per Process and Customer Order Characteristics

	Make-to-Stock	Make-to-Demand	Option-to-Order	Engineer-to-Order
Continuous	refineries	solvents, plastics, alloys	fuels	casting, injection molding
Assembly line	appliances	electric motors, valves	autos, computers	aircraft
Discrete batch	electronic components	windows, auto parts	*no known*	semiconductors, circuit boards
Job shop	*none*	*none*	*none*	metal parts, composites
Construction	*none*	*no known*	aircraft	ships

sions—are captured in an ERP system. Each of these facilities may use additional systems for planning and analysis, execution level scheduling, control, and automated data capture. Some of the planning, analysis, scheduling, and management systems are part of, or tightly connected to, the ERP systems; others are more loosely connected. This variation results from two major factors: systems that are closely coupled to equipment, most of which are highly specialized, and systems that manage information and business processes specific to a particular industry that the ERP vendor may not offer. Because of the historic emphasis on reducing inventory costs, the management of stockroom is, in almost all cases, an intrinsic part of an ERP system. To the contrary, plant floor activity control is almost never a part of ERP. Management of execution activities within warehouses, vehicles/depots, and distribution centers may be handled in a centralized fashion by an ERP system or in a decentralized fashion by an applications specific to those facilities.

2.2. Transaction Management and Basic Decision Support: The Core of ERP

Transactions are records of resource changes that occur within and among enterprises. Through the use of a logically (but not necessarily physically) centralized database, it is the management of these transactions that constitutes the core of an ERP system. More specifically, this transaction database captures all changes of state in the principal resources of the manufacturing enterprise. It also makes elements of the current state available to personnel and software performing and supporting the operations of the enterprise. This scope encompasses all of the numerous resources (i.e., materials inventories, facilities/equipment, labor, and money) and product inventories of all kinds. It also includes the states and results of many business processes, which may not be visible in physical instances (e.g., orders, specifications). The detailed breakdown of this broad scope into common separable components is a very difficult technical task, given the many interrelationships among the objects, significant variations in the business processes, and the technical origins of ERP systems. Nonetheless, it is possible to identify general elements from that complexity and diversity. The functions of a manufacturing enterprise that are supported by transaction management correspond to the major types of resources as follows:

- For inventories, materials inventory and materials acquisition
- For facilities/equipment, manufacturing management, process specification management, maintenance management, warehousing and transportation
- For labor, human resource management
- For money, financial management and accounting
- For product, order entry and tracking

These functions, in whole or in part, make up the core of ERP. The following sections describe each function and its relationship to core ERP. These functions are then discussed in terms of finer-grain execution and planning activities.

2.2.1. Materials Inventory

This function is made up of all information on stores of materials and allocations of materials to manufacturing and engineering activities. That includes information on materials on hand, quantities, locations, lots and ages, materials on order and in transit, with expected delivery dates, materials in inspection and acceptance testing, materials in preparation, and materials allocated to particular manufacturing jobs or product lots (independent of whether they are in stock).

ERP systems routinely capture all of this information and all transactions on it. It is sometimes combined with materials acquisition information in their component architecture.

Execution activities supported by materials inventory include receipt of shipment, inspection and acceptance, automatic (‘‘low-water’’) order placement, stocking, stores management, internal relocation, issuance and preparation, and all other transactions on the materials inventory. Except for some stores management functions, all of these are revenue producing.

Planning activities supported by materials inventory include supply planning, manufacturing planning, and manufacturing scheduling.

2.2.2. Materials Acquisition

This function deals primarily with information about suppliers and materials orders. It includes all information about orders for materials, including recurring, pending, outstanding, and recently fulfilled orders, and long-term order history. Orders identify internal source and cost center, supplier, reference contract, material identification, quantity, options and specifications, pricing (fixed or variable), delivery schedule, contacts, change orders, deliveries, acceptances, rejects, delays, and other notifications. It may also include invoices and payments. This also includes special arrangements, such as consignment and shared supply schedules.

ERP systems support part of an enterprise's materials acquisition function by handling all of this information for active suppliers and orders and journalizing all transactions. But they regularly purge closed orders and relationships, using the journal or some other export mechanism to move this information to an archival or data warehouse system. ERP systems generally maintain simple materials specifications directly but typically carry only references to more complex specification documents in some other product data management (PDM) or document management system.

Execution activities supported by materials acquisition include internal requests, placement of external orders and changes, receipt and acceptance of materials, and all other transactions against materials orders. All of these are revenue-producing activities.

Planning activities supported by materials acquisition include supply chain development, supplier identification and qualification, supply planning, manufacturing planning, and cash-flow projections.

2.2.3. Order Entry and Tracking

These functions focus on the customer order through its life cycle. Order entry is the mechanism by which the decision to make product enters the ERP system. It begins with the capture of customer order, including all specifications and options, quantities, packaging requirements, and delivery requirements. It ends with the creation of one or more corresponding manufacturing orders and delivery orders. At that point it becomes order tracking, which follows the customer order through the fulfillment processes (for the surrogate orders) and finally through the payment processes. It is important to note that although manufacturing may be driven directly by customer order, there is a decision point between the entry of the customer order and the release of the associated manufacturing orders, and in most ERP systems they are maintained as separate objects. While this release is often automated, it is a critical business control point and the automation reflects the business rules for the release.

The execution activities supported by order entry and tracking include the revenue-producing activities of customer order capture, production start, and delivery start.

The planning activities supported by order entry and tracking include tactical planning for all of engineering, manufacturing, and delivery, according to the nature of the business as described in Section 1.3.2.

2.2.4. Manufacturing Management

This function deals primarily with the tracking of work through the manufacturing facilities and the management of manufacturing resources that are used in performing that work.

The manufacturing resources include personnel, equipment, and materials. Because each of these is also the subject of another ERP domain (human resources, maintenance, inventory), there is *always* overlap among the concerns. And because many ERP systems developed from manufacturing resource planning (MRP II) systems, which dealt with various aspects of those resources listed above, there is no agreement about where the boundaries are. The one concern that is clearly unique to manufacturing management is the assignment of resources to specific work items. But at some level of planning that depends on resource availability and resource capabilities, which are the boundary areas.

The tracking of work begins with tentative and actual placement of manufacturing orders through the order entry component described above. In general, the manufacturing order information is a part of the manufacturing management component. Planning processes determine which resources (materials, equipment, labor) will be assigned to fulfilling these orders in which time frames and these assignments are captured. Execution processes draw materials (usually tracked as lots) and use equipment and personnel to perform the work. These usages and the flow of work through the facility are captured. Finished goods leave the manufacturing domain for some set of distribution activities, and at this point the completion of the manufacturing orders is tracked.

The execution processes supported by manufacturing management are the revenue-producing processes that convert materials into finished goods, but that support is limited to tracking those processes.

The planning processes supported by manufacturing management are all levels of manufacturing resource planning and scheduling, except for detailed scheduling, as noted above.

2.2.5. Process Specification Management

This function deals with the information associated with the design of the physical manufacturing processes for making specific products. As such, it is an engineering activity and like product engineering, should be almost entirely out of the scope of core ERP systems. But because several information items produced by that engineering activity are vital to resource planning, ERP systems maintain variable amounts of process specification data. In all cases, the materials requirements for a product lot—the "manufacturing bill of materials"—are captured in the ERP system. And in all cases, detailed product and materials specifications, detailed equipment configurations, detailed operations procedures, handling procedures, and equipment programs are outside the core ERP information bases. These information sets may be maintained by ERP add-ons or third-party systems, but the core contains only identifiers that refer to these objects.

For continuous-process and assembly-line facilities, the major process engineering task is the design of the line, and that is completely out of scope for ERP systems. What ERP systems maintain for a product mix is the line configurations (identifiers) and equipment resources involved, staffing and maintenance requirements, the set of products output, the production rates and yields, and the materials requirements in terms of identification and classification, start-up quantities, prepositioning requirements, and feed rates.

For batch facilities, the major process engineering tasks are the materials selection, the routing (i.e., the sequence of work centers with particular setups), and the detailed specifications for operations within the work centers. The materials requirements, the yields, and the routings for products and product mixes are critical elements of the ERP planning information. The detailed work center operations are unimportant for planning, and all that is captured in the ERP core is the external references to them, the net staffing and time requirements, and the assigned costs of the work center usages.

For job shop facilities, the major process engineering tasks are materials selection, the routing, and the detailed specifications for operations within the work centers. The materials requirements and yields for specific products are critical elements of the ERP planning information. The routing is often captured as a sequence of work center operations—unit processes, each with its own equipment, staffing and time requirements, associated detail specification identifiers, and assigned cost. The detailed unit process specifications—operator instructions, setup instructions, equipment control programs—are kept in external systems.

No execution processes are directly supported by process specification management. All levels of resource planning are directly and indirectly supported by this information.

2.2.6. Maintenance Management

This function includes all information about the operational status and maintenance of equipment, vehicles, and facilities. *Operational status* refers to an availability state (in active service, ready, standby, in/awaiting maintenance, etc.), along with total time in service, time since last regular maintenance, and so on. The ERP system tracks maintenance schedules for the equipment and actual maintenance incidents, both preventive and remedial, and typically an attention list of things that may need inspection and refit. Any maintenance activities include both technical data (nature of fault, repair or change, parts installed, named services performed, etc.) and administrative data (authorization, execution team, date and time, etc.). In addition, this component tracks the schedules, labor, and work assignments of maintenance teams, external maintenance contracts and calls, and actual or assigned costs of maintenance activities.

In those organizations in which machine setup or line setup is performed by a general maintenance engineering group rather than a setup team attached to manufacturing operations directly, it is common to have such setups seen as part of the maintenance component rather than the manufacturing component. Similarly, operational aspects of major upgrades and rebuilds may be supported in the maintenance component of the ERP system. These are areas in which the behavior of ERP systems differs considerably.

This component supports sourcing, manufacturing, and delivery activities indirectly. Maintenance, per se, is purely a support activity.

Planning activities supported by maintenance management include all forms of capacity planning, from manufacturing order release and shipment dispatching (where immediate and expected availability of equipment are important) up to long-term capacity planning (where facility age and statistical availability are important).

2.2.7. Warehousing

This function deals with the information associated with the management of finished goods and spare parts after manufacture and before final delivery to the customer.

For products made-to-stock, this domain includes the management of multiple levels of distribution centers, including manufacturer-owned/leased centers, the manufacturer's share of concerns in customer-owned/leased centers, and contracted distribution services. The primary concerns are the management of space in the distribution centers and the management of the flow of product through the distribution centers. Thus, there are two major elements that are sometimes mixed together: the management of the distribution center resources (warehouse space, personnel, and shipping and receiving facilities) and the management of finished product over many locations, including manufacturing shipping areas, distribution centers per se, and cargo in-transport. Distribution center and product (family) includes tracking actual demand experience, projected demand and safety stocks, units on hand, in-flow and back-ordered, and units in manufacture that are earmarked for particular distribution centers. The primary object in product distribution tracking is the shipment because that is the unit of product management at the factory, in transportation, and through all distribution centers, except possibly the one nearest the final customers. For shipments, what is tracked is the product content, the ultimate recipient, the current location, and the associated delivery/shipping orders.

For certain products made-to-order (both made-on-demand and option-to-order), the distribution center approach is used because it facilitates planning and use of delivery resources and usually because a sizable part of the manufacturer's product line (such as spare parts) is made to stock. In these cases, the information managed is similar to the made-to-stock case, but actual demand and safety stock concerns are replaced by tracking specific customer orders. Customer orders are part of shipments up to the final distribution center, and final delivery to customer is tracked from there.

For most products made-to-order, the warehousing component manages information only for finished goods in factory holding areas awaiting shipment and shipments that are in transportation to the customer. In this case, each shipment is associated with a particular customer at creation, and it may be associated with one or more manufacturing orders even before manufacturing starts. For shipments, what is tracked is the product content, the customer order, the current location, and the associated delivery/shipping orders. In many make-to-order cases, the manufacturing holding areas are managed as manufacturing resources instead of warehousing resources, and the shipments are managed as part of order tracking, thus eliminating the warehousing component.

Execution activities supported by warehousing are the revenue-producing delivery of finished goods via distribution centers and the support activities of distribution center management. The primary planning activities supported by warehousing are distribution planning and distribution requirements planning.

2.2.8. Transportation

This function includes all aspects of movement of parts and finished goods among manufacturing facilities and distribution centers as well as final delivery to customers. It can be subdivided into the management of vehicle fleets, transportation service contracts, and shipping orders.

All manufacturers manage shipping orders—the decision to move shipments of parts and finished goods from one facility to another in the process of fulfilling customer orders. What is captured for the order is the associated shipments, the starting and ending locations, the means of transfer, the nominal pickup and delivery times, and the associated authorizations. The means of transfer can be by owned vehicles or transportation service contracts, or a combination.

For transportation service contracts, what is tracked is the contractual information, the shipping and housing orders placed under those contracts, the states of those orders and corresponding states of the internal shipping orders, and the shipments themselves. In addition, the system tracks other actions under the contract, including payment authorizations, change orders, delays, misdeliveries, damaged and misplaced goods, and shipments not accepted.

The management of vehicle fleets, for enterprises that have their own, entails the capture of maintenance and spare parts information and the capture of vehicle staffing, routes and schedules, and current orders, states, and locations. In general, the activities are the same as those of contract shipping organizations, but the manufacturer's transportation fleet has only one customer and usually a small and mainly predefined set of destinations.

Execution activities supported by transportation include movement of parts between manufacturing centers and movement of spare parts and finished products to customers and distribution centers, all of which are revenue producing. The supporting activities of managing transportation fleets and services are also supported.

Planning activities supported by transportation include delivery planning, transportation resource planning, and transportation route planning.

2.2.9. Human Resource Management

The human resource management (HRM) component includes the management of all information about the personnel of the manufacturing enterprise—current and former employees, retirees and other pensioners, employment candidates, and possibly on-site contractors and customer representatives. For employees, the information may include personal information, employment history, organizational placement and assignments, evaluations, achievements and awards, external representation roles, education, training and skills certification, security classifications and authorizations, wage/salary and compensation packages, pension and stock plan contributions, taxes, payroll deductions, work schedule, time and attendance, leave status and history, company insurance plans, bonding, and often medical and legal data. For contract personnel, some subset of this information is maintained (according to need), along with references to the contract arrangement and actions thereunder.

The HRM system is often also the repository of descriptive information about the organizational structure because it is closely related to employee titles, assignments, and supervisory relationships.

The execution activities supported by the HRM system are entirely support activities. They include the regular capture of leave, time, and attendance information and the regular preparation of data sets for payroll and other compensation actions and for certain government-required reports. They also include many diverse as-needed transactions, such as hiring and separation actions of various kinds, and all changes in any of the above information for individual personnel. But the HRM system supports *no* revenue-producing function directly, and it often plays only a peripheral role in strategic planning.

2.2.10. Finance Management and Accounting

This function includes the management of all information about the monies of the enterprise. The primary accounting elements are grouped under accounts payable (all financial obligations of the organization to its suppliers, contractors, and customers); accounts receivable (all financial obligations of customers, suppliers, and other debtors to this organization); and general ledger (the log of all real and apparent cash flows, including actual receipts and disbursements, internal funds transfers, and accrued changes in value). In reality, each of these is divided into multiple categories and accounts. While smaller organizations often do finance management under the heading *general ledger,* larger ones, and therefore ERP systems, usually separate the finance management concerns from general ledger transactions. They include fixed asset management (acquisition, improvement, amortization, depreciation of plants, facilities, and major equipment); financial asset management (cash accounts, negotiable instruments, interest-bearing instruments, investments, and beneficial interests [e.g., partnerships]); and debt management (capitalization, loans and other financing, and "assignments of interest" [e.g., licenses, royalties]).

The major enterprise execution activities supported by the finance management component are contracting, payroll, payment (of contractual obligations), invoicing, and receipt of payment. Payroll is a supporting activity, but payment and receipt are revenue producing.

The primary financial planning activities supported are investment planning, debt planning, and budget and cash flow planning and analysis.

2.3. Interaction Points

It is the intent of many ERP vendors to provide the information systems support for all the business operations of the manufacturing enterprise, and ERP systems have gone a long way in that direction. But there are still several areas in which the manufacturing organization is likely to have specialized software with which the ERP system must interface. The primary mission of the ERP system is to provide direct support to the primary operations activities (materials acquisition, manufacturing, product delivery) and to the planning and management functions for those operations. The software environment of a large manufacturing enterprise includes many other systems that support nonoperations business functions. This includes product planning and design, market planning and customer relations, and supply chain planning and development. Additionally, software that supports the detailed manufacturing processes and the control of equipment is so specialized and therefore so diverse that no ERP provider could possibly address all customer needs in this area.

On the other hand, the wealth of data managed within the ERP core, as well as its logical and physical infrastructure and the demand for those data in many of these related processes, open the door for integrating these other functions with the ERP system. This is the situation that leads to demands for open ERP interfaces.

Moreover, as the ERP market expands to medium-sized enterprises, the cost of the monolithic ERP system has proved too high for that market, leading ERP vendors to adopt a strategy using incremental ERP components for market penetration. This strategy in turn requires that each component system exhibit some pluggable interface by which it can interact with other component systems as they are acquired. While ERP vendors have found it necessary to document and maintain these interfaces, thus rendering them open in a limited sense, none of the vendors currently has an interest in interchangeable components or standard (i.e., public open) interfaces for them. But even among components there are "forced" ERP boundaries where the medium-sized enterprise has longer-standing enterprise support software (e.g., in human resources and finance). These also offer opportunities for standardization.

At the current time, the most significant ERP boundaries at which standard interfaces might be developed are depicted in Figure 3.

2.3.1. Contracts Management

Contractual relationships management deals with the information associated with managing the formal and legal relationships with suppliers and customers. It consists of tracking the contract development actions; maintaining points of contact for actions under the agreements; and tracking all formal transactions against the agreements—orders and changes, deliveries and completions, signoffs, invoices and payments, disputes and resolutions, and so on. ERP systems rarely support the document management function, tracking the contract document text through solicitation, offer, counteroffer, negotiation, agreement, amendments, replacement, and termination. They leave that to a legal or

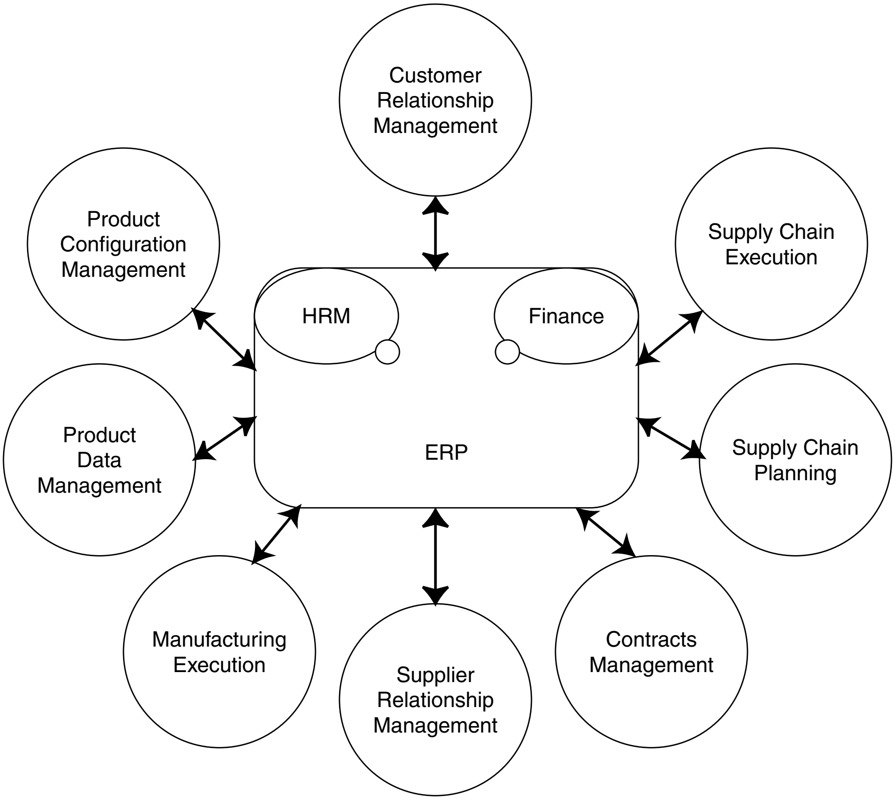

Figure 3 Opportunities for Standard ERP Interfaces.

business document management system and carry only references into that system where needed. They do routinely capture all transactions against agreements, but they often capture them in different places. Only a few centralize all these transactions under contracts management.

2.3.2. Supplier Relationship Management

This activity includes information on contractual arrangements with suppliers and points of contact, relationship history (orders, fulfillments, disputes, resolutions), business evaluations, and technical evaluations of products and capabilities, including certifications for specific materials. For specific materials (or product families), there are approved supplier lists that identify suppliers from whom the organization may order that material, often with preference ranking or ranking criteria.

2.3.3. Customer Relationship Management

As mentioned previously, the objective of CRM is to add value for customers through those processes that involve direct contact with customers before, during, and after sales. This function encompasses marketing and sales activities related to the identification and characterization of markets, the characterization of product opportunities within those markets that are consistent with the strategies and expertise of the enterprise, and the development of those markets into a customer base that generates recurring demand for the products of the enterprise. ERP systems may support demand planning activities that make projections for existing products with target volumes and time requirements as well as projections for new products or product modifications. ERP systems may also support customer inquiries as to product lines and company capabilities as well as inquiries and negotiations for alternative supply arrangements. As discussed in Section 2.2.3, ERP systems always support customer orders for existing products, customer order changes and cancellations, and inquiries about customer order status.

2.3.4. *Product Configuration Management*

A product configurator tracks the design of product options from desired features to manufacturing specifications. It captures product planning, pricing, and engineering decisions about option implementations and interoption relationships. The sales configurator component tells the sales staff what option combinations a customer can order and how to price them. The manufacturing configurator converts the option set on a customer order to a specification for bill of materials, station setup, prepositioning requirements, batching requirements, and process selections.

In "to-order" environments, an ERP system may include a product configuration function. A product configurator captures customer-specified product options in make-to-demand, option-to- order, and engineer-to-order environments. In those environments, product configurators connect the front office with the back office. In make-to-demand and option-to-order environments, product configurators link sales with manufacturing operations. In engineer-to-order environments, product configurators are a conduit between sales and engineering.

2.3.5. *Product Data Management*

While ERP systems are the principal repository for all operations data, they contain only fragments of product and process engineering data. One of the reasons for this is that the ERP core is short transactions with concise data units, while engineering data management requires support for long transactions with large data files. As ERP systems have grown over the last 10 years, PDM systems have grown rapidly as the product engineering information management system, especially in mechanical and electrical parts/product industries. The rise of collaborative product and process engineering in the automotive and aircraft industries has led to increasing capture of process engineering information in the PDM. Product engineering software tools, particularly CAD systems, are used to design tooling and other process-specific appliances, and these tools often have modules for generating detailed process specifications from the product definitions (e.g., exploded bills of materials, numerical control programs, photomasks). These tools expect to use the PDM as the repository for such data. Moreover, increased use of parts catalogs and contract engineering services has led to incorporation of a significant amount of part sourcing information in the PDM. Many ERP vendors are now entering the PDM product market, and the interface between PDM and ERP systems is becoming critical to major manufacturers and their software providers.

2.3.6. *Supply Chain Execution*

Although ERP systems may offer a one-system solution to supporting the operations of a given enterprise, one cannot expect that solution to extend beyond the walls. The information transactions supporting the materials flows from suppliers to the manufacturing enterprise and the flows of its products to its customers are becoming increasingly automated. Although basic electronic data interchange (EDI) transaction standards have been in existence for 20 years, they are not up to the task. They were intentionally made very flexible, which means that the basic structure is standard but most of the content requires specific agreements between trading partners. Moreover, they were made to support only open-order procurement and basic ordering agreements, while increased automation has changed much of the behavior of open-order procurement into automated catalogs and automated ordering and made several other supplier–customer operation techniques viable in the last several years. Thus, there is a need for ERP systems to operate, via upgraded e-commerce interfaces, with the ERP systems of the partners in the supply chain.

2.3.7. *Supply Chain Planning*

Until recently, ERP-supported planning algorithms focused on the internal behavior of the enterprise in managing its production and distribution, treating both customers and suppliers largely as black boxes with documented behaviors. The new concept is resource and market planning that focuses on the participation of the enterprise in various supply chains; thus, it can be effective only if it is part of a joint planning effort of multiple partners in those chains—the enterprise, its peers in the chain, its customers in the chain, and its suppliers. The joint planning activity must be supported by information interchanges between the decision-support software in (or linked to) the separate ERP systems of the partners. Algorithms for performing such joint planning are emerging, and first-generation software to support those algorithms is now available under the title advanced planning and scheduling (APS). Further development of these algorithms and interfaces is a necessary element of the future of ERP systems.

2.3.8. *Manufacturing Execution*

At some point, the gathering of manufacturing resource status information and work-in-process information becomes specific to the resource and the particular manufacturing task. It requires specialized systems to implement the specialized data-capturing technology and convert those data into resource planning, job planning, and tracking information. Further, particularly in discrete batch and job shop environments, the resource scheduling process itself becomes deeply involved with the details of the manufacturing tasks and the resource setups. Finally, a great deal of information gathered on the manufacturing floor is used to improve the process and product engineering as well as the characterization of machine capabilities, process yields, product quality, and so on. This domain is now loosely called manufacturing execution systems. Such systems deal with the details of data gathering, conversion, and assessment for specific purposes and industries. Future ERP systems must expect to interface with such companion factory management systems in a significant number of customer facilities. The need is to share resource planning information, resource status information, and order/job/lot release and status information.

2.3.9. Human Resource Management

Although it is considered a part of ERP, human resource management (HRM) systems have already penetrated the medium-sized enterprise market in many industries, of which manufacturing is only a subset. As ERP systems grow out of the manufacturing industry to other business areas, the need for interfacing with established HRM systems becomes apparent. And this makes standard interfaces to the HRM component more attractive to ERP and HRM vendors and customers.

2.3.10. Finance

In a similar way, most businesses, large and small, have long since built or acquired financial management software to support their business practices. Moreover, those practices and the related legal requirements vary significantly from country to country and, to a lesser extent, from state to state. For ERP systems, this means no "one size fits all" customers or even all business units of a single customer. Thus, interfaces to specialized and in-place financial software packages will continue to be a requirement.

2.4. Elements of ERP Implementations

The previous section addressed the functional aspects—the "what"—of ERP systems. This section deals with the "how" of ERP, specifically the generic software elements of current commercial ERP systems. It does not address the rationale used by a specific manufacturing enterprise to manage its own ERP selection, deployment, and upkeep. However, it covers briefly some of the tools for managing an ERP system. Additionally, it describes the generic architectures used by ERP vendors.

The basic elements of an ERP implementation include the core transaction system, packaged decision support applications provided by the ERP vendor, in-house or third-party extended applications, and a collection of tools for managing various aspects of the system (Figure 4). Each of these software elements reside in a computing environment that is typically distributed and possibly multiplatform.

2.4.1. Core ERP—Transactions

The ERP core consists of one or more transaction databases as well as transaction services. As described in Section 2.2, these services include capturing, executing, logging, retrieving, and monitoring transactions related to materials inventories, facilities/equipment, labor, and money.

2.4.2. Packaged Decision Support Applications

In addition to transaction management, ERP vendors provide decision support applications that offer varying degrees of function-specific data analysis. The terms *decision support application* and *decision support systems* (DSS) refer to software that performs function-specific data analysis irrespective of enterprise level. That is, decision support includes applications for supply, manufacturing, and distribution planning at the execution, tactical, and strategic levels of an enterprise. There is considerable variability among ERP vendors regarding the types of decision support applications that they include as part of their standard package or as add-ons. At one end of the spectrum, some vendors provide very specific solutions to niche industries based on characteristics of the operations environment (i.e., process and business nature) as well as enterprise size in terms of revenue. For example, an ERP vendor at one end of the spectrum might focus on assembly line/engineer-to-order environment with decision support functionality limited to manufacturing and distribution planning integrated with financials. At the other end of the spectrum, an ERP vendor could offer decision support functionality for supply, manufacturing, and distribution planning at all enterprise levels for a host of operations environments for enterprises with varying revenues. While such a vendor offers an array of decision support tools, one or more tactical level, function-specific applications (i.e., supply, manufacturing, distribution) are typically part of a standard ERP implementation (Figure 2). The others

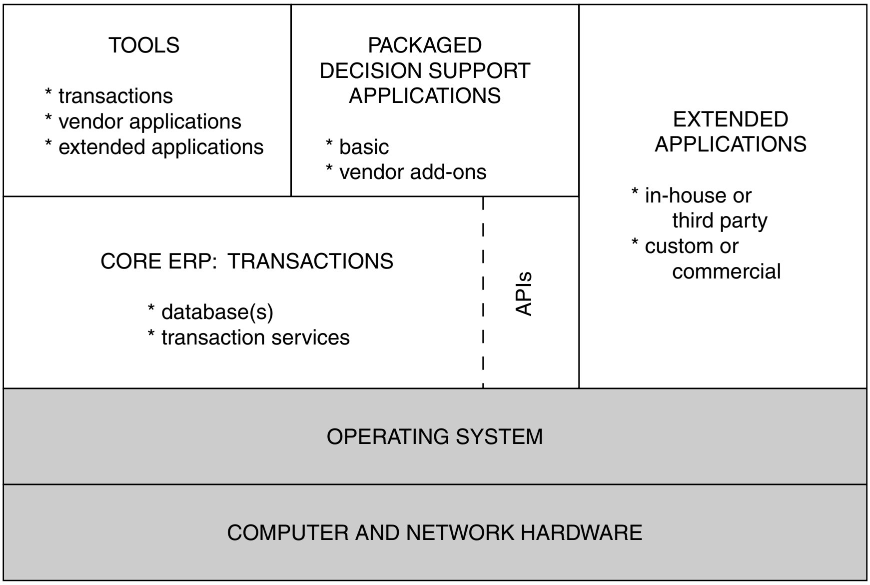

Figure 4 Basic Implementation Elements of ERP Systems.

tend to be considered add-ons. While a vendor may offer these add-ons, a manufacturer may opt to forgo the functionality they offer altogether or implement them as extended applications, either developed in-house or procured from third-party software vendors.

2.4.3. Extended Applications

The wealth of data in ERP systems allows many manufacturing enterprises to use ERP as an information backbone and attach extended applications to them. The motivation for such applications is that manufacturers typically see them as necessary to achieve differentiation from competitors. These applications may be developed in-house or by a third party. A third party may be a systems integrator who develops custom software, or it may be a vendor who develops specialized commercial software. As discussed in Section 2.3, these add-ons may provide additional functionality for customer and supplier relationship management, product data management, supply chain planning and execution, and human resource management. Regardless of the source, these applications must integrate with the ERP. Application programmer interfaces (APIs) are the common mechanism for integrating extended applications with the ERP backbone, and specifically the ERP core. Even among their partners and strategic allies (i.e., certain systems integrators and third-party software vendors), ERP vendors discourage the practice of integrating their standard applications with extended applications because of potential problems with upward compatibility. Because APIs to the ERP core have a longer expected lifetime, APIs are presently the most common approach to accessing information in the ERP system.

2.4.4. Tools

Given the enormous scope of the system, ERP can be a challenge to set up and manage. As such, ERP and third-party vendors provide software tools for handling various aspects of these complex systems. These tools generally fall into two categories: application configuration tools, which support the setup and operation of the ERP system itself, and enterprise application integration (EAI) tools, which support integration of the ERP system into the enterprise software environment.

2.4.4.1. ERP Configurators In an effort to decrease the amount of time and effort required to install, operate, and maintain an ERP system, vendors may provide a variety of application configuration tools. These tools vary in complexity and sophistication, but they all perform essentially the following tasks:

- *Define the computing topology:* Query the manufacturing administrator about the enterprise computing environment, the operating platforms, and the number, locations, and kinds of user workstations. Direct the setup program to install the appropriate versions of the ERP core and packaged modules on the server and workstation platforms.
- *Define the information base:* Query the manufacturing administrator about the specifics of their business information environment and assist in developing specialized information models (based on the vendor's generic ERP models) to support those business specifics. Automatically configure the ERP databases and transaction formats accordingly.
- *Define tasks and workflows:* Query the manufacturing administrator about the specifics of their business processes, map individual tasks to users across organizations, applications, and systems, and assist in developing specialized workflow models and decision support models. Then automatically configure the ERP workflow/task models, decision support invocations, and report formats.
- *Define security and control requirements:* Query the manufacturing administrator for user classifications by task responsibilities and authorizations. Define the user privileges, activity logging requirements, and security controls.

2.4.4.2. Enterprise Application Integration Unlike application configuration tools, which are part of an ERP vendor's suite and centered on the ERP system as the integrator of business processes, enterprise application integration (EAI) tools are actually a non-ERP-specific category of software tools whose primary function is to support business processes by linking up distinct software systems in the overall enterprise computing environment. As such, they view ERP as one part of a manufacturer's entire IT solution. But many of these tools come with predefined interfaces to specific ERP systems (some are provided by ERP vendors) and are designed primarily to link other software systems and applications with the ERP system.

This is a relatively new and fragmented class of software, employing a number of techniques of varying sophistication and providing quite variable capabilities. One view of EAI is as "a selection of technologies to address a number of applications integration problems" (Gold-Bernstein 1999). In this perspective, EAI technologies include platform integration solutions (messaging, message queueing, publish-and-subscribe, and object request brokers), message brokers (translations and transformation, intelligent routing, and application adapters), some graphical user interface (GUI) tools to define routing and mapping rules, and process automation and workflow.

A simplified view of a typical EAI architecture is provided in Figure 5. The EAI package consists of a number of application-specific adapters, each of which is capable of extracting data from and providing data to a particular application software package in some form convenient to that application. The adapter may also communicate directly with a central EAI engine that moves data sets between the adapters in some message form. In many cases the message is just a file, while in some cases the sole function of the adapter is to command the application to input or output a particular file. In some architectures, the adapter is responsible for converting the application information to or from a common interchange model and format used by the EAI package. In others, each adapter produces information in a convenient form and the engine is responsible for the conversion of the messages or files between the adapters, using a common reference model or an application-to-application-specific translation, or both.

Most EAI packages are designed primarily to solve intraenterprise communication problems. Many provide some mechanisms for Web-based access as a means of interaction with customers and suppliers.

2.5. ERP Architectures

For purposes of illustration, the ERP community refers to tiers when describing the general logical architectures of ERP systems. While the notion of tiers generally implies a hierarchy, such is not the case with tiers in present-day ERP architectures. Advances in distributed computing technologies enable more open communication among components. Instead, these tiers are the basic types of logical elements within an ERP implementation and thus provide a means for describing various ERP execution scenarios.

Figure 6 illustrates the five tiers of ERP architectures: core/internal (often called data), application, user interface, remote application, and remote user interface. A common intraenterprise scenario involves the data, application, and user interface tiers. This scenario does not preclude application-to-application interaction. Similarly, common interenterprise scenarios include an internal user or application requesting information from an external application or an external user or application requesting information from an internal application. The Internet is the conduit through which these internal/external exchanges occur. Additionally, in many ERP systems web browsers have emerged as the platform for both local and remote user interfaces.

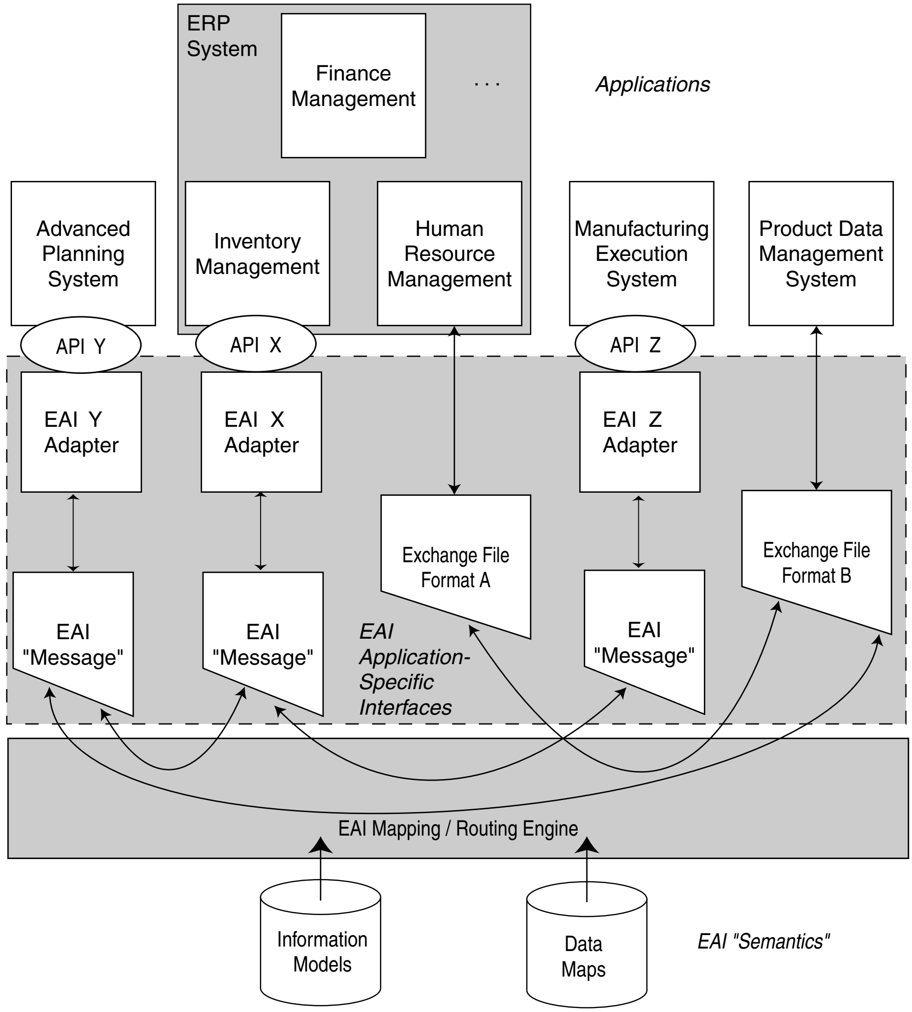

Figure 5 EAI Systems Architectures.

2.6. ERP and the Internet

The emergence of the Internet as the primary conduit for exchange of ERP-managed information among trading partners has spawned the term *Internet-based ERP.* This term does not convey a single concept but may refer to any of the following:

- Internal user-to-ERP-system interfaces based on web browsers
- External user-to-orders interfaces based on web browsers
- Interfaces between decision support software agents of different companies that support supply chain operations
- Interfaces between decision support software agents of different companies that support joint supply chain planning

The increasingly commercial nature of the Internet and the development of communication exchange standards have had significant impact on ERP systems. In describing this impact, the term *tier* is used in the context of ERP architecture (Section 2.5).

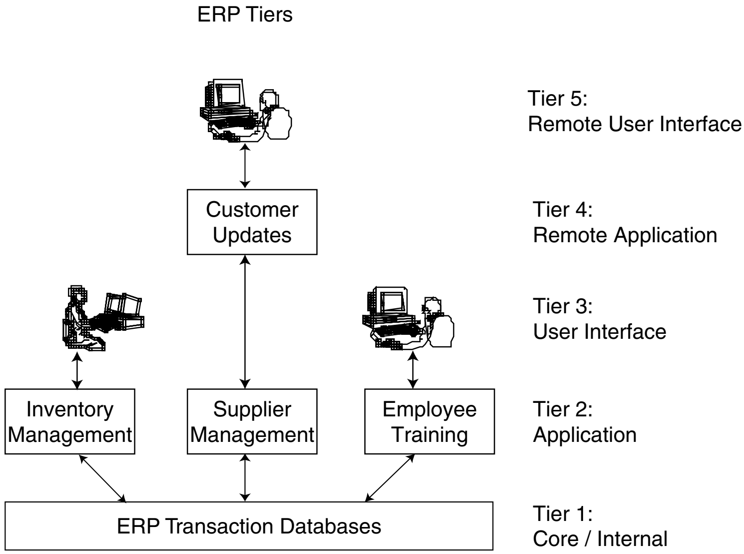

Figure 6 Tiers in ERP Architectures.

2.6.1. Internal User-to-ERP Interfaces

Also called application hosting, this approach employs user interfaces (Tier 3) based on Internet/Web technologies, notably Java, the Hypertext Markup Language (HTML), and the Extensible Markup Language (XML). In this scenario, ERP vendors as well as systems integrators take on a new role as application service providers (ASPs). This is an important change in the product architecture of ERP, in that the ERP vendor no longer has to maintain the dedicated workstations or the workstation software for users so connected. It also means that the ERP vendor cannot price that part of its services by station but instead uses transaction volume metrics. This differs from other impacts by being purely intranet-based (i.e., all such connections are from within the enterprise and thus subject to alternative controls and security mechanisms).

2.6.2. External User-to-ERP Interfaces

In this scenario, a remote user (Tier 5), via an interface based on Web technologies, accesses application service modules (Tier 2). This is a widely used approach among ERP vendors and CRM vendors. It differs from the first by having many electronic business technical concerns, including access authorization and data filtering, secure sockets, and contract and payment references. The critical question here is whether the functions supported include order entry or just order tracking and how the Web services are related to internal orders management. The CRM system may act as a staging system with no direct connect between the Web interface and the ERP system itself.

2.6.3. B2B Supply Chain Operations Interfaces

This scenario involves communication between a remote application and a local application (i.e., Tier 4 and Tier 2). The actual exchange is usually based on EDI or some XML message suites,* using file transfers, electronic mail, or some proprietary messaging technology to convey the messages. This scenario is significantly different from the above in that neither of the communicating agents is a user with a browser. Rather, this is communication between software agents (decision support modules) logging shipment packaging, release, transportation, receipt, inspection, acceptance, and possibly payment on their respective ERP systems (with some separate Tier 3 user oversight at both ends). Special cases of this include vendor-managed inventory and consignment management, which illustrate the use of the Internet in direct support of an operations process.

*E.g., RosettaNet (RosettaNet 2000), CommerceNet (CommerceNet 2000), Electronic Business XML (Electronic Business XML 2000), Open Applications Group Interface Specification (OAGIS) (Open Applications Group 2000).

2.6.4. Joint Supply Planning (Advanced Planning and Scheduling) Interfaces

This scenario also involves communication between a remote application and a local application (i.e.,Tier 4 and Tier 2) with the exchange based on a common proprietary product or perhaps an XML message suite. Again the communicating agents are software systems, not users with browsers, but their domain of concern is advanced planning (materials resource planning, distribution resource planning, etc.) and not shipment tracking. There are very few vendors or standards activities in this yet because this represents a major change in business process. This scenario illustrates use of the Internet in direct support of a tactical planning process.

3. AN EXTERNAL VIEW OF ERP SYSTEMS

This section illustrates ERP systems in a larger context. Section 3.1 provides some current thinking on the apparent macroeconomic impacts of IT, with a yet-to-be-proven hypothesis specific to ERP systems. Section 3.2 describes the relationship of ERP specifically with respect to electronic commerce, supply chains, and individual manufacturing enterprises.

3.1. ERP and the Economy

Much has been written and said about the emerging digital economy, the information economy, and the New Economy. It is the authors' view that the information economy must support and coexist with the industrial economy because certain fundamental needs of mankind are physical. However, while these economies coexist, it is clear that the sources of wealth generation have changed and will continue to change in fundamental ways. In the last 50 years, the U.S. gross domestic product (GDP), adjusted for inflation, has grown more than 500% (Figure 7). While each major industry has grown considerably during that period, they have not grown identically. Confirming that the economy is a dynamic system, the gross product by industry as a percentage of GDP (GPSHR) saw significant changes in the last half of the 20th century (Figure 8). GPSHR is an indication of an industry's contribution (or its value added) to the nation's overall wealth. While most goods-based industries appear to move towards a kind of economic equilibrium, non-goods industries have seen tremendous growth. The interesting aspect of ERP systems is that they contribute to both goods- and non-goods-based industries in significant ways. In fact, for manufacturers, ERP plays a critical role in extending the existing industrial economy to the emerging information economy. In the information economy, ERP accounts for a significant portion of "business applications" sales, not to mention the wealth generated by third parties for procurement, implementation, integration, and consulting. While these are important, in this chapter we focus on the use of ERP in manufacturing. Therefore, the following sections describe how ERP and related information technologies appear to impact the goods-producing sectors of the current U.S. economy.

Macroeconomics, the study of the overall performance of an economy, is a continually evolving discipline. Still, while economists debate both basic and detailed macroeconomic theory, consensus exists on three major variables: output, employment, and prices (Samuelson and Nordhaus 1998). The primary metric of aggregate output is the gross domestic product (GDP), which is a composite of personal consumption expenditures, gross private domestic investment, net exports of goods and services, and government consumption expenditures and gross investment. The metric for employment is the unemployment rate. The metric for prices is inflation. While these variables are distinct, most macroeconomic theories recognize interactions among them. It appears that the use of information technology may be changing economic theorists' understanding of the interactions among economic variables, particularly for predicting gross domestic product, unemployment, and inflation. It is important to gain a deeper understanding of these changes because their impact would affect government policy decisions, particularly those involving monetary policy and fiscal policy.

In the current record domestic economic expansion, real output continues to increase at a brisk pace, unemployment remains near lows not seen since 1970, and underlying inflation trends are subdued. During this period, inflation has been routinely overpredicted while real output has been underpredicted. Conventional economic theory asserts that as real output increases and unemployment decreases, significant pressures mount and force price increases. Yet, in this economic expansion, inflation remains in check, *apparently* due in part to IT-enabled growth in labor productivity (Greenspan 1999). In the early 1990s, the labor productivity growth rate averaged less than 1% annually. In 1998, that rate had grown to approximately 3%. So what has happened in this decade? In the last 10 years, information technology has enabled companies, most notably manufacturers, to change the way they do business with access to better information (often in real time) and better decision-support technologies. These changes have improved the way manufacturers respond to market wants (i.e., for products) and market demands (wants for products backed by buying power). ERP systems play a significant part in satisfying the latter by enabling better planning and execution of an integrated order fulfillment process. In short, ERP software enables these improvements by providing decision makers in an enterprise with very accurate information about the current state of the enterprise.

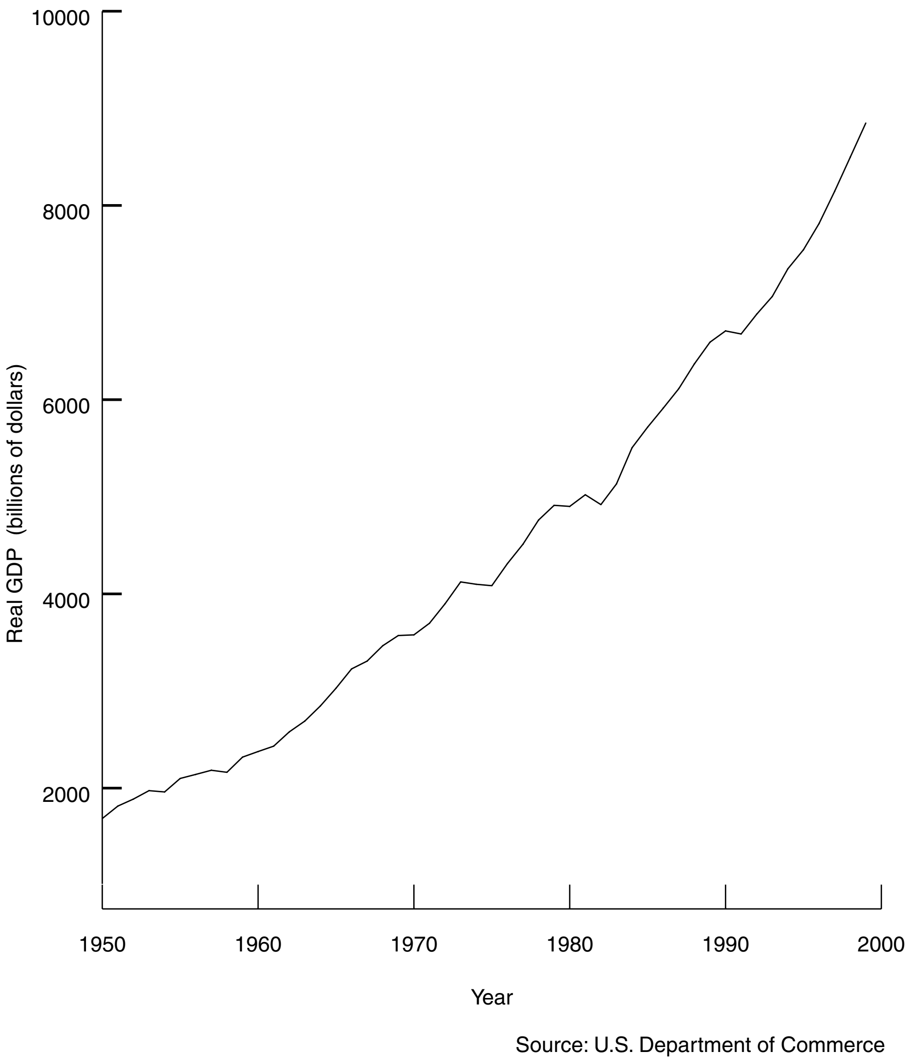

Figure 7 GDP Growth, 1950–1999.

Moreover, an increasing number of manufacturers have direct access to demand information from their customers and resource information from their suppliers. In many cases, the customer's demand information and the supplier's resource information originate in their respective ERP systems. Just as these data are more accurate for the customer/manufacturer/supplier enterprise, so too is the resulting information flowing up and down the supply chain. For the manufacturer between them, this information enables decision makers to base decisions on accurate external information, as well as accurate internal information. The following remarks by Federal Reserve Chairman Alan Greenspan perhaps best capture the essence of this phenomenon (Greenspan 1999):

> As this century comes to an end, the defining characteristic of the current wave of technology is the role of information. Prior to the advent of what has become a veritable avalanche of IT innovations, most of twentieth century business decision-making had been hampered by limited information. Owing to the paucity of timely knowledge of customers' needs and of the location of inventories and materials flows throughout complex production systems, businesses required substantial programmed redundancies to function effectively.

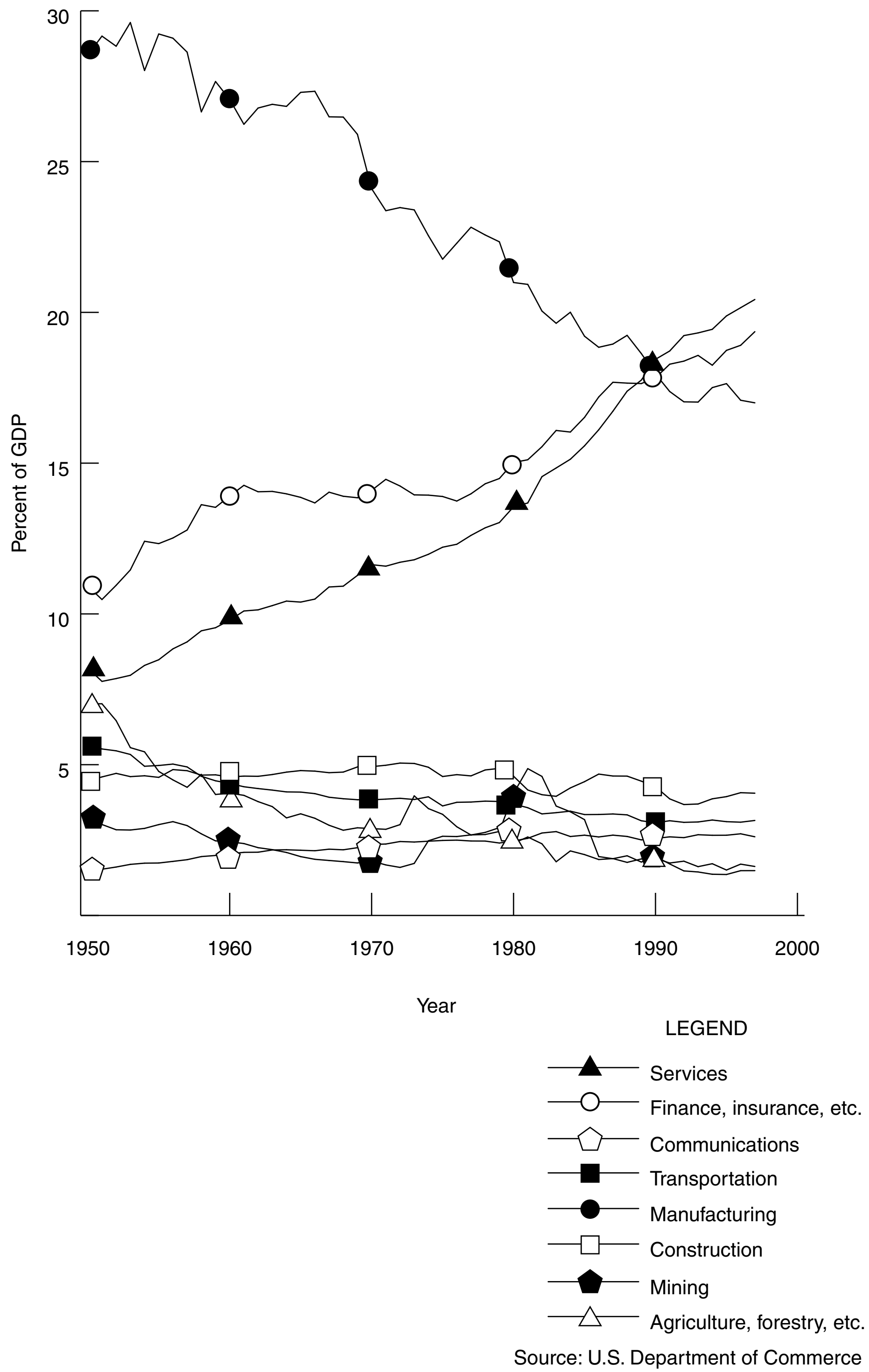

Figure 8 Gross Product Originating by Industry Share of GDP, 1950–1997.

> Doubling up on materials and people was essential as backup to the inevitable misjudgments of the real-time state of play in a company. Judgments were made from information that was hours, days, or even weeks old. Accordingly, production planning required adequate, but costly, inventory safety stocks, and backup teams of people to maintain quality control and for emergency response to the unanticipated and the misjudged.
>
> Large remnants of information void, of course, still persist and forecasts of future events on which all business decisions ultimately depend are still inevitably uncertain. But the recent years' remarkable surge in the availability of real-time information has enabled business management to remove large swaths of inventory safety stocks and work redundancies. . . .
>
> Moreover, information access in real-time resulting from processes such as, for example, checkout counter bar code scanning and satellite location of trucks, fostered mark reductions in delivery lead times on all sorts of goods, from books to capital equipment. This, in turn, has reduced the overall capital structure required to turn out our goods and services, and, as a consequence, has apparently added to growth of multifactor productivity, and thus to labor productivity acceleration.
>
> Intermediate production and distribution processes, so essential when information and quality control were poor, are being bypassed and eventually eliminated.

ERP systems, in part, enable those activities described by Chairman Greenspan by providing two core functions: transaction management and near-term decision support. The objective of transaction management is to track the effect of execution activities on inventories, resources, and orders, while the objective of intermediate-term decision support is to use that and other information to generate accurate plans for sourcing, production, and delivery.

3.2. ERP, Supply Chains, and Electronic Commerce

ERP systems do not provide a complete solution for supply chain management (SCM) or electronic commerce. However, especially for manufacturers, the functionality provided by ERP is a necessary (although by no means sufficient) element of both SCM and, therefore, electronic commerce. This section provides definitions of electronic commerce and SCM and explains the relationships among these concepts and ERP.

3.2.1. Electronic Commerce

Ask 10 people to define electronic commerce and you'll likely get 10 different definitions that reflect the particular biases of those asked. Recognizing the existence of these broad interpretations, this chapter uses an inclusive definition developed by the Gartner Group (Terhune 1999):

Electronic commerce is a dynamic set of technologies, integrated applications, and multi-enterprise business processes that link enterprises together.

The concept of electronic commerce centers on the use of technology, and those technologies tend to be infrastructural in nature. Some obvious current technological issues include network-related subjects (the Internet, the Web, and extranets), security, interoperability of applications software, and the exchange of application-based information within and across enterprises. These integrated applications, which collectively comprise an enterprise's electronic business or (e-business) environment, include EDI software, supply chain management, ERP, customer relationship management, and enterprise application integration software. Issues in multienterprise business processes revolve around the different interactions that occur across enterprises. Electronic commerce changes, in part or in whole, the mode of these interactions from paper and voice to networked, digital information flows. The nature of these interactions, and the relationships among trading partners in general, range from coercive to collaborative depending on the general structure and practices of a given industry, the goods and/or services produced, and the impact of information technology on the distribution channels through which those goods and services flow. Recognizing and understanding these distinctions are critical for evaluating the existing and potential impact of electronic commerce across industries.

Manufacturing industries face particular challenges in realizing the benefits of electronic commerce because of the coupling of goods and information and the coordination required across those domains. Information-intensive industries (e.g., banking, traveling, advertising, entertainment) experience the effects of electronic commerce before materials-intensive industries such as manufacturing, construction, and agriculture. In information-intensive industries, products and services lend themselves to the technology. In many of these cases, electronic commerce technology simply becomes a new distribution channel for the information product or service. The manufacturing situation is significantly more complex because it requires reconciliation of goods *and* information. The objective is not to develop new distribution channels per se (the information network does not move goods); the objective is to improve the flow of goods by using the information technology to improve the business practices. Optimizing the flow of goods through distribution channels is one particular type of electronic commerce improvement. By so doing, trading partners can root out the inefficiencies within channels and make them more adaptive to changes in the market. It is precisely those inefficiencies and adaptability that are the foci of SCM.

3.2.2. Supply Chain Management

Supply chain management is one of several electronic commerce activities. Like electronic commerce, SCM has acquired buzzword status. Nonetheless, a common understanding of SCM has emerged through the work of industry groups such as the Supply Chain Council (SCC), the Council on Logistics Management (CLM), and the APICS organization, as well as academia.

> SCM is the overall process of managing the flow of goods, services, and information among trading partners with the common goal of satisfying the end customer. Furthermore, it is a set of integrated business processes for planning, organizing, executing, and measuring procurement, production, and delivery activities both independently and collectively among trading partners.

It is important to note a critical distinction here, especially since that distinction is not explicit in the terminology. While *SCM* is often used synonymously with *supply chain integration* (SCI), the two terms have connotations of differing scopes. As stated previously, SCM focuses on planning and executing trading partner interactions of an operations nature—that is, the flow of goods in raw, intermediate, or finished form. SCI is broader; it includes planning and executing interactions of any kind among trading partners, and it refers in particular to the development of cooperating technologies, business processes, and organizational structures.

The operations-specific objectives of SCM can only be achieved with timely and accurate information about expected and real demand as well as expected and real supply. A manufacturer must analyze information on supply and demand along with information about the state of the manufacturing enterprise. With the transaction management and basic decision support capabilities described earlier, ERP provides the manufacturer with the mechanisms to monitor the current and near-term states of its enterprise. As depicted in the synchronized, multilevel, multifacility supply chain planning hierarchy of Figure 2, ERP provides the foundation for supply chain management activities. Section 1 described the various levels of the hierarchy, and Section 2 described the details of transaction management and decision support.

4. ERP CHALLENGES AND OPPORTUNITIES

While evidence suggests that ERP systems have brought about profound positive economic effects by eliminating inefficiencies, there is still room for substantial improvement. The technical challenges and opportunities for ERP systems arise from how well these systems satisfy the changing business requirements of the enterprises that use them. Case studies in the literature highlight the unresolved inflexibility of ERP systems (Davenport 1998; Kumar and Van Hillegersberg 2000). The monolithic nature of these systems often hampers, or even prevents, manufacturers from responding to changes in their markets. Those market changes relate to ERP systems in two important ways: the suitability of decision support applications to an enterprise's business environment and the degree of interoperability among applications both within and among enterprises.

These two issues lead to three specific types of activities to improving ERP interoperability: technology development, standards development, and business/technology coordination.

4.1. Research and Technology Development

4.1.1. Decision Support Algorithm Development

Manufacturing decision support systems (DSSs), especially those that aid in planning and scheduling resources and assets, owe their advancement to progress in a number of information technologies, particularly computational ones. The early versions of these applications—namely materials requirements planning (MRP) and manufacturing resource planning (MRP II)—assumed no limitations on materials, capacity, and the other variables that typically constrain manufacturing operations (e.g., on-time delivery, work-in-process, customer priority). The emergence of constraint-based computational models that represent real-world conditions has enabled manufacturers to better balance supply and demand. In spite of the improvement in DSSs, significant opportunities still exist. Different models apply to different business environments. With the rapid pace of change, the commercial viability of the Internet, and the push to "go global," there are new variables to examine and new models to develop. Instead of convergence to any single optimization function, there will likely be specialization to classes of functions. That specialization has begun as illustrated in Figure 2 and described in Section 3.2 Continued specialization (not simply customization) is likely and necessary. Those classes will account for the variety of ways that manufacturing enterprises choose to differentiate their operations from those of their competitors. While cost reduction has been the focus of the current generation of DSSs, models that also address revenue enhancement and response time are expected to be the focus of future generations.

4.1.2. Component Decomposition Analysis

As decision support technology evolves, so too does ERP system functionality. While advances in software functionality affect an enterprise's continuous IT improvement strategy, they do not comprise all of that strategy. Migration is another critical aspect of continuous IT improvement. That is, replacing and upgrading an existing system—in whole or in part—must be possible for an enterprise to move from one functional state to another. In general, ERP vendors have focused on providing functionality at the expense of replaceability and upgradability (Sprott and Wilke 1998). Consequently, lock-in effects are major concerns for manufacturing and nonmanufacturing enterprises alike.

Possessing the concepts of services and encapsulation, components are touted as the solution to this problem. A component delivers functionality to a user or another software entity through one or more well-defined interfaces. Encapsulation means that a component is a separate entity, thus making it easier with which to manage, upgrade, and communicate. Yet components alone do not guarantee interoperability, especially in complex e-business and electronic commerce environments. For ERP systems to be interoperable, there must be widespread agreement on the services that ERP applications provide and on the boundaries of encapsulation. Numerous approaches to defining services and interfaces exist, including vendor-specific conventions, intraenterprise conventions, industry-specific standards, and technology-specific standards.

These approaches all lack broad perspective and thus do not meet the challenges of enabling ERP interoperability in e-business and electronic commerce environments. To achieve interoperability with the vendor-specific conventions, a single ERP vendor must dominate not just the ERP system market but the markets of all the other systems that (need to) interoperate with ERP. Intraenterprise conventions work up to the bounds of the enterprise, as long as there are no major internal changes (such as mergers or acquisitions). The approach based on industry-specific standards fails to realize that the focal point of operations is business process and that information varies according to the characteristics of those processes. Industries obviously are defined by product, not business process, and commonality of product does not translate into commonality of business process. Operations-wise, what makes sense for one supply chain member (e.g., an original equipment manufacturer [OEM]) does not necessarily make sense for another (e.g., a lower-tier supplier). The fourth approach, technology-specific standards, tends to yield limited solutions because it focuses on syntax and not semantics. Without agreement on the meaning of the information to be exchanged and the function that the information supports, the challenges of reconciliation persist. Many technology-focused efforts fail to perform sufficient domain-specific information requirements analysis.

Because electronic commerce dramatically changes the nature of power and control in supply chains, component decomposition analysis must address the three emerging models of business-to-business (B2B) markets. The first approach is an OEM-controlled model such as those recently announced by U.S. automakers and defense contractors (Stoughton 2000). The second is supplier-controlled model such as those in metals, chemical, and paper industries. The third is an open model that allows control to be shared among all supply chain players. Many think that the open model will prevail in the long run. However, industries will not collectively reach that point at the same rate or at the same time. To realize this model, it is necessary to look beyond industry-specific exchange of operations data. It is necessary to analyze business processes and characterize them at appropriate levels of detail. These characterizations would highlight the different kinds of components and thus the information that needs to be exchanged in different scenarios.

4.2. Standards Development

Standards play an important role in achieving interoperability. With respect to ERP systems, opportunities exist for establishing standard interface specifications with other manufacturing applications.

4.2.1. ERP–PDM Interfaces

As discussed in Section 2.3.5, there is an obvious interaction point between ERP and PDM systems. Thus, there is a need for interfaces between the two systems to share separately captured engineering and sourcing specifications. In the longer run, the goal should be to have PDM systems capture all the product and process engineering specifications and to extract resource requirements information for use in ERP-supported planning activities. Conversely, sourcing information, including contract engineering services, should be captured in the ERP system. To do this, one needs seamless interactions as seen by the engineering and operations users.

4.2.2. ERP–MES Interfaces

As presented in Section 2.3.8, future ERP systems must expect to interface with such companion factory management systems in a significant number of customer facilities. There is the need to share resource planning information, resource status information, order/job/lot release, and status information. However, developing such interfaces is not a straightforward exercise. The separation of responsibilities and the information to be exchanged vary according to many factors both at the enterprise level and the plant level. Prestandardization work is necessary to identify and understand those factors.

4.2.3. Supply Chain Operations Interfaces

Supply chain information flows between the ERP systems of two trading partners have been the subject of standardization activities for 20 years, with a spate of new ones created by Internet commerce opportunities. Most of these changes concentrate on basic ordering agreement and open procurement mechanisms. Requirements analysis of this information is necessary before actual standards activities commence. As the business practices for new trading partner relationships become more stable, standards for interchanges supporting those practices will also be needed. Changes in business operations practices as well as in decision support systems have changed the information that trading partners need to exchange. This includes shared auctions, supply schedule, vendor-managed inventory, and other operational arrangements, but the most significant new area is in joint supply chain planning activities (i.e., advanced planning and scheduling).

4.3. Establishing Context, Coordination, and Coherence for Achieving Interoperability

Several developments in the past decade have combined to extend the locus of information technology from research labs to boardrooms. The commercialization of information technology, the pervasiveness of the Internet, and the relatively low barriers to market entry for new IT companies and their technologies all serve to create an environment of rapid growth and change. The ERP arena, and electronic commerce in general, suffer from a proliferation of noncooperative standards activities, each aimed at creating interoperability among a handful of manufacturers with specific software tools and business practices. There is an imperative to reduce competition among standards efforts and increase cooperation.

Understanding the complex environment that surrounds ERP and other e-business and electronic commerce applications is a critical challenge to achieving interoperability. Topsight is a requirement for meeting this challenge. The objective of topsight is to establish context, coordination, and coherence among those many activities that seek standards-based interoperability among manufacturing applications. While the hurdles that exist in the current environment are considerable, there is significant need—as well as potential benefit—for an industry-led, multidisciplinary, and perhaps government-facilitated effort to provide direction for the development and promulgation of ERP and related standards.

The notion of topsight for improving interoperability among specific applications is not new. The Black Forest Group, a diverse assembly of industry leaders, launched the Workflow Management Coalition (WfMC), which has produced a suite of specifications for improving interoperability among workflow management systems. A similar ERP-focused standards strategy effort would strive to understand better the diversity of operations and operations planning in order to improve interoperability among ERP and related systems.

For a topsight effort to succeed in an arena as broad as ERP, particularly one that is standards-based, there must be a cross-representation of consumers, complementors, incumbents, and innovators (Shapiro and Varian 1999).

As consumers of ERP systems, manufacturers and their trading partners face the risk of being stranded when their systems do not interoperate. The lack of interoperability in manufacturing supply chains can create significant costs (Brunnermeier and Martin 1999), and those costs tend to be hidden. More accurate cost structures must be developed for information goods, particularly for buy-configure-build software applications. Unlike off-the-shelf software applications, ERP systems are more like traditional assets, in the business sense, with capital costs and ongoing operational costs.

Complementors are those who sell products or services that complement ERP systems. Given the role that ERP plays in electronic commerce, this group is very large. It includes both software vendors and systems integrators and management consultants. Some of the software that complements ERP was discussed previously in Section 2.3. Others include additional categories of software necessary for achieving e-business: EDI/e-commerce, business intelligence, knowledge management, and collaboration technologies (Taylor 1999).

Incumbents are the established ERP vendors, and they make up a market that is very dynamic and diverse (Table 2). Achieving consensus of any kind with such a diverse market is a considerable challenge. To achieve ERP interoperability requires, among others, deeper understanding of common elements. That understanding can be acquired by detailed functional and information analysis of the ERP systems.

The notion of innovators in the standards process focuses on those who collectively develop new technology. While many individual technology development activities associated with ERP and electronic commerce might be considered innovative, there have been few explicit collective development

TABLE 2 The Current State of ERP Market

ERP Vendor Categories	Total Annual Revenue	Cross-Functional Scope	Manufacturing Environment Scope	Targeted Industry Scope
Tier 1 ERP Vendors	more than $2 billion	broad, manufacturing, materials, human resource, financial SCM and CRM	broad, continuous, assembly line, discrete batch, job shop, construction	broad, larger and mid-market manufacturers across numerous industries
Tier 2 ERP Vendors	between $250 million and $2 billion	moderate, but expanding beyond one or two functional areas, some adding SCM and/or CRM	variable, some support one or two manufacturing environments while others support more	moderate, larger and mid-market manufacturers across several industries
Tier 3 ERP Vendors	less than $250 million	narrow, fill void of Tier 1 and Tier 2	narrow, typically supports one type of manufacturing environment	narrow, smaller manufacturers in niche industries

efforts. Most ERP vendor partnerships tend to be confined to making existing products work together through application programmer interfaces. They generally do not involve the joint creation of new (and often complementary) technologies. The dynamics that compel banks and credit card companies to pursue smart card development do not exist in the ERP environment. However, there are others who meet this definition of innovator. Academia is one group of innovators whose relationship with ERP vendors tends not to make headlines. Still, many of the technologies in today's ERP systems have academic roots. The perspective of university researchers across numerous disciplines would add significant value to a topsight effort.

5. CONCLUSIONS

ERP is a very complex subject. It marries technology, business practices, and organizational structures. ERP systems are commercially developed software applications that integrate a vast array of activities and information necessary to support business operations and operations planning at the tactical level. ERP is software and not a business process or a set of business processes. However, as software, it enables better execution of certain processes. Although often presented as a single package, an ERP system is an envelope around numerous applications and related information. For manufacturers, those applications typically support the operations processes of materials sourcing, manufacturing planning, and product distribution. To its end users, an individual application of an ERP system may appear seamless; however, to those who procure, implement, and/or maintain ERP systems, they are complex software systems that require varying levels of customization and support both centrally and across each application. While ERP systems are commercial applications developed by individual vendors, they can hardly be considered off-the-shelf. They are part of a continuing trend of outsourcing IT solutions in which part of the solution is bought, part is configured, and part is built from scratch. Given their broad organizational and functional scope, ERP systems are unlike any other contemporary commercial manufacturing applications. They provide transaction management from both the business perspective and a database perspective. Additionally, they provide a basic level of decision support. Optionally, they enable higher levels of decision support that may be offered by ERP vendors or a third-party vendor.

This chapter presented an overview of ERP from the outside and from the inside. The outside view clarified the connection between ERP, electronic commerce, and supply chain management. The inside view describe the functional and implementation elements of ERP systems, particularly in the context of manufacturing enterprises, and identified the points at which ERP interacts with other software applications in manufacturing enterprises. Finally, we looked at open research problems surrounding ERP and identified those that are important to fitting ERP systems into current and future business processes.

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