The Past, Present, and Future of Supply-Chain Automation

Just in Time to Enhance 21st-Century Industry, Material-Flow, Information-Flow, Supervision and Control, and Relationship Automation Are Reaching Maturity

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In this article, we trace 20th-Century developments in the area of supply-chain automation. During the mass-production era, hard automation brought the automobile within the reach of the common man. Currently, the trend is to automate intercompany and company-to-customer relationships, also called collaboration, using the Internet. In between, several revolutions have occurred that were mainly sponsored by developments in computer and communications technologies and in intercompany and cross-country logistics. It is now possible to receive orders from a global customer and fulfill them automatically with minimal human intervention. The limiting factors, however, are the country infrastructure and the lack of trust between humans. In this article, we discuss the history of automation from the viewpoints of material-flow, information-flow, supervision and control, and relationship automation and identify future directions. The main message is that it is important to make balanced investments in all four facets of automation to maximize shareholder value.

Background

The central theme in all industrial developments during the last century has been automation. The first significant attempt was assembly-line automation for the manufacture of automobile engines by Henry

1070-9932/02/$17.00©2002IEEE

Ford in the early 1900s. Today, there are decision-support systems and communication tools available for automating marketing and sales processes, as well as the relationships with the suppliers. The motive in all these attempts is to automate processes in the supply chain, beginning with raw material procurement and ending with delivery to the end consumer, with the primary goal of serving the customer more efficiently and effectively. Thus, automation efforts that first started on the factory floor have now spread to the entire supply chain. Technology is at the root of all these developments, sometimes causing drastic disruptions in the industry and creating revolutions.

There were second- and third-order effects of the automation of supply-chain processes. For example, Henry Ford's assembly automation brought the automobile within the reach of the middle class, and this has led to the creation of shopping malls outside city limits, well-paved roads and highways, and truck transportation. A whole set of other industries sprung up and thrived. The Internet created another major shift, allowing people to shop from their homes, the need for delivery through multiple channels, and the coordination of returns. There are several different ways that one can describe the developments of the last century. Several historians and popular books have already done this [1]. Our intent is not to summarize these here, but to look at the developments in a perspective that enables us to identify future trends and research issues in this area.

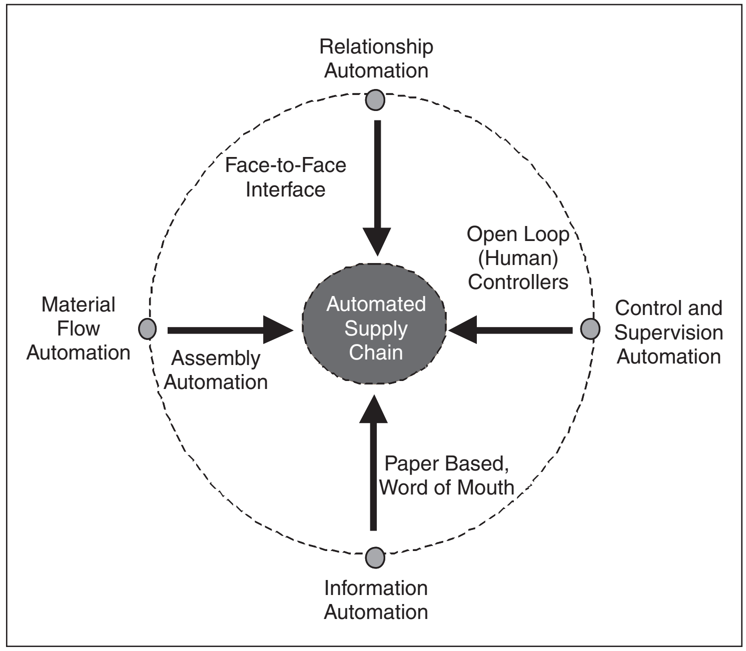

Figure 1. *Four facets of automation.*

Despite several economic and cultural changes, the main goal of manufacturing and supply-chain networks has remained the same, i.e., to procure raw materials and transform them into final products and deliver them to the global customer at the time and place specified by him or her in the presence of the other players in the market. Basically, this involves the automation of material, information, and financial flows, and relationships between businesses and customers. In a manufacturing supply-chain environment, there are several decisions to be made and facilities to be supervised and controlled. Significant efforts have also have gone into the automation of facilities such as warehouses and factory floors. Recent emphasis has been on automating and integrating intercompany material and information flows. We can classify these efforts into the following interrelated and mutually reinforcing categories

- material-flow automation
- information-flow and decision automation
- automated supervision and control
- relationship automation.

We will consider each of these separately and list the achievements during the last century. As shown in Fig. 1, material-flow automation started with assembly-line automation, information flow was by word of mouth or paper based, humans made decisions and controlled the processes, and, finally, relationships required face-to-face interactions. The main goal was to achieve a fully automated perfect supply chain, where a centralized or distributed control system embedded with decision support systems helps in the negotiation and selection of business partners and customers and generates signals that enable the automatic flow of material and information among the stake holders in the supply chain.

From the investment angle, material-flow automation requires heavy investments in warehouses, automated assembly lines, airports, seaports, transport fleets, etc. The other three types of automation require investments in information and communication technologies, business-to-business (B2B) infrastructure, content-management tools, monitoring and control equipment, and soft technologies such as databases, decision-support systems, data mining and data warehousing tools, computer-aided engineering tools, and software engineering tools. Investments in information technology (IT) could also be heavy because of rapidly changing technologies, the integration of complex software from different vendors and legacy systems, and the human-intensive nature of research and development work. Also, investments in all four facets of automation should be balanced and aligned with business strategy. For example, if a company is selling PCs directly to corporate and individual customers, it makes sense to outsource the logistics and transportation and invest in an IT infrastructure, customer-relationship management (CRM), monitoring, and assembly lines. Recent history has shown that investments in business-to-customer (B2C) infrastructure without consideration of fulfillment issues would not create value. Similarly, relationship management with their supply-chain partners is important for global players. Countries should develop supply-chain clusters, not just manufacturing facilities. The ultimate aim of these automation initiatives is to

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derive maximum value through the establishment of automated supply chains.

In this article, we discuss the recent developments in material-flow, information-flow, supervision and control, and relationship automation. Our thesis is that these facets should be looked at as integrated developments rather than isolated investments. Only then can one maximize the value that comes out of all these investments. We will also comment on the future, emphasizing the need for balanced investment in all four types of automation technologies and for aligning the investment strategy with the corporate strategy.

Material-Flow Automation

Mass Production

In 1913, Henry Ford conducted the first notable material-flow automation exercise by automating the assembly line for automobile engines. This automation is called Detroit automation or hard automation. This had tremendous impact on the economy and society at large by bringing the automobile within the reach of the middle class. The next significant technological innovation was the use of computers for controlling tool paths. This has created numerically controlled machines, material-handling robots, and automated guided vehicles. These developments have led to flexible automation and the automated factory floor. The developments of local factory computer networks linking numerically controlled (NC) machines and automated automated guided vehicles (AGV) controllers has led to the development of cell controllers and flexible manufacturing systems. After finishing processing at one machine, jobs in these systems proceed to another automatically without human intervention. There are also planning tools aiding job shop scheduling. Warehouse management systems that manage automated storage and retrieval of semi-finished and finished goods have also come into being. The lean manufacturing revolution pioneered by Toyota and followed by other Japanese car manufacturers has created another revolution. The "just-in-time" philosophy, partnerships with suppliers by sharing information, and undertaking joint product development have created success for these companies. All these developments were basically focused on the factory floor within a single company. Also, most of these developments occurred in the auto industry.

Global Manufacturing

Today, hardly a single product is manufactured by any one company or in any one country. With the globalization of manufacturing, there arose a need for moving materials, mostly semi-finished goods, in the form of subassemblies from suppliers in one country to manufacturers in another and distributors in yet another country. Domestic and international logistics became very important. A typical material and information flow between two partners is shown in Fig. 2. There were developments to fill this need from airport and seaport operators by automating loading and unloading operations and through containerization. Several countries have also created trade-free zones and technology parks. Third-party logistics providers who take responsibility for transporting material from one company to another and also maintain warehouses emerged. Transportation-management systems (TMS) and vehicle routing software that aid in efficient fleet management were developed. Track-and-trace systems help businesses track shipments and plan production schedules efficiently. Distributors and resellers are another brand of intermediaries that help in the final delivery of the product to the end consumer.

Efficient linkages between various stake holders in the supply chain, from raw material providers to the end customer, are important for reducing inventories and delay times and ultimately meeting customer demand on time, every time. One of the best practices in improving the efficiency of inbound material transfer is a supply hub that uses the concept of vendor-managed inventories. Another best practice is cross-docking, where material from the manufacturers, to the distributors, to the retailers is transferred from one truck to an-

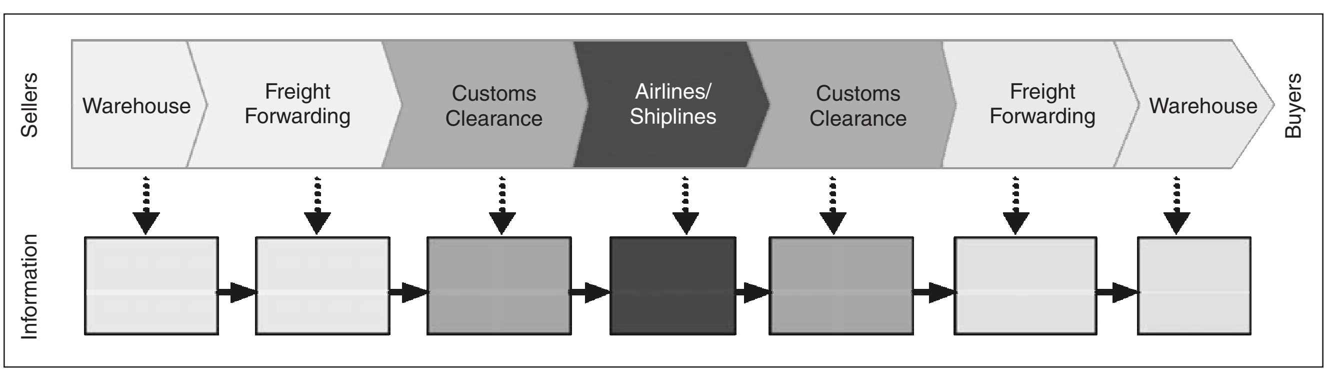

Figure 2. Material flow between two businesses.

other at the cross-docking station without the need for inventorying in warehouses. The location of supply hubs and cross-docking stations and their scheduling are issues that require attention.

The ingredients necessary for global manufacturing to succeed (such as global logistics providers and the infrastructure in terms of ports, airports, and IT bandwidth) are not uniform throughout the world. With a few exceptions, most countries do not have efficient infrastructures. In the future, global manufacturing may occur between countries that have compatible transportation and information infrastructure.

Information-Flow and Decision Automation

The Manufacturing Planning—Enterprise-Resource Planning Era

B2B is the most recent chapter in a long cycle of business automation that traces back to the 1960s. For the last four decades, virtually all IT efforts have focused on automating and improving the efficiency of individuals and operating units within the four walls of a company. A vast majority of business computing over the last several decades has been inwardly focused and accessible only by the employees of the enterprise.

The first major breakthrough in business computing occurred with the advent of the mainframe computer in the 1960s, where the focus was on automating functional processes, such as general ledger and accounting. Businesses introduced a wide range of applications, such as manufacturing planning (MRP), drafting and design [computer-aided design (CAD)], and inventory-management systems. During these early phases, neither the business units in a company (e.g., manufacturing plants, regional sales offices, corporate headquarters) nor customer and supplier relationships outside a business's four walls were automated. Employees on a divisional level could share and access information, but all external-facing communication and commerce occurred through fax and phone lines. The next stage in information-flow automation—enterprise resource planning (ERP) applications—is centered on sharing information among multiple individuals and functional areas of a company. As a result of the development of client/server architecture and relational-database-management systems, multiple users from different functional areas across the enterprise were provided real-time access to the applications developed during the preceding waves of computing, as well as a host of new applications focused on areas such as CRM and buyer/seller transactional analysis.

While these advancements allowed stakeholders within a company to gain an integrated view of the core business processes of the enterprise, information was still not shared with company's customers and suppliers. For example, individual employees from the same company could extract and share information stored on the company's financial databases or inventory-management systems, but customers and suppliers would have to access this information by using phone calls, faxes, and electronic-data interchange (EDI). With the emergence of the Internet, information sharing among partners with extranets is now seen as a source of competitive advantage.

B2B Market Places

A B2B e-Marketplace (also referred to as a trading exchange or trading community) is a trusted, Web-based intermediary that

- facilitates trading between commercial buyers and sellers (Fig. 3)
- facilitates the replacement of paper, catalog, phone, fax, and e-mail transactions in the supply chain by electronic transactions over the Internet
- provides new, collaborative mechanisms for forming and growing supply-chain relationships on the Internet
- leads to "raw-material-to-retailer" supply-chain optimization in specific vertical or horizontal markets for both indirect and direct materials.

B2B requires a major infrastructure. The range of services provided by companies include

- indirect goods procurement and workflow management
- content and catalog management
- real-time dynamic pricing and auctions
- supply-chain management tools
- collaborative product design software
- real-time logistics and fulfillment capabilities
- advanced analytic tools
- payment services.

For B2B marketplaces to be competitive, the value proposition should be to facilitate transactions from end to end, including strategic sourcing, financing, insurance, warehousing, and settlement, not just matching buyers and sellers. A far more reaching value proposition is provided by the solution provider that has the ability to monitor, integrate, and disseminate data across the supply chain to improve buying practices, optimize channel management, and improve the capacity utilization of multiple participants in the supply chain.

Supply-Chain Planning

For years, companies have relied on a range of methods to try to build more tightly integrated business processes with trading partners. The most significant method has been EDI, a standard for transmitting business documents over private or value-added networks in order to share product information, invoices, and purchase orders among business partners. EDI

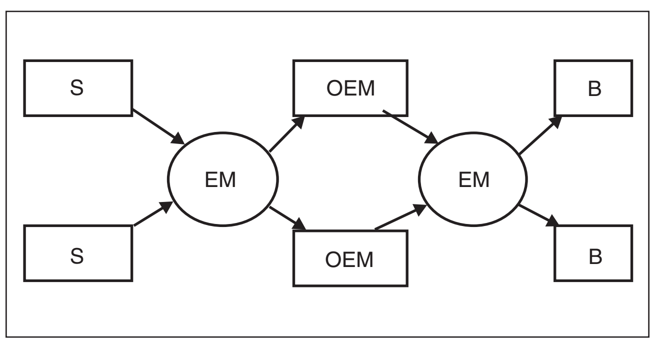

Figure 3. *Three-tier supply chain with marketplaces.*

distributes information asynchronously by way of batch transmissions, whereas real-time pricing and product information is the growing demand from businesses. The Internet has opened up possibilities for widespread, real-time sharing of information among multiple trading partners. With the Internet, market activity (the buying and selling of goods) of multiple participants and their information systems can be tied together in a real-time, globally-shared environment. The Internet is both a commerce channel and decision making platform.

Today's companies and supply chains are dynamic and heterogeneous. The Internet gives companies global visibility and information-sharing capabilities, and these are precipitating a fundamental change in supply-chain management. Static supply chains are quickly giving way to more flexible value chains composed of partners that can be assembled in real time to meet unique requirements (Fig. 4). The Internet has lowered the barriers to effective collaboration, allowing companies to easily share demand-forecast information, production-capacity requirements, manufacturing schedules, and new product designs. Transaction flows among trading partners have also been greatly facilitated, so companies can remit quote requests, purchase orders, shipment notifications, and online payments in a highly efficient and cost-effective manner. In more and more industries, it is becoming apparent that the competitive field is no longer limited to company A versus company B. The game is now supply-chain network versus supply-chain network, with an increasing reliance on collaborative relationships to create links of value. Buying, making, moving, and selling products and services are the sub-processes of supply-chain planning. Companies need superior decision-making tools and workflows that can leverage the available data, and, in real time, maximize performance of these sub-processes and the entire supply chain. Some of the processes that need support include: collaborative forecasting and planning; collaborative product-life-cycle management; supply, distribution, and production planning; procurement; transportation planning; and demand-supply matching.

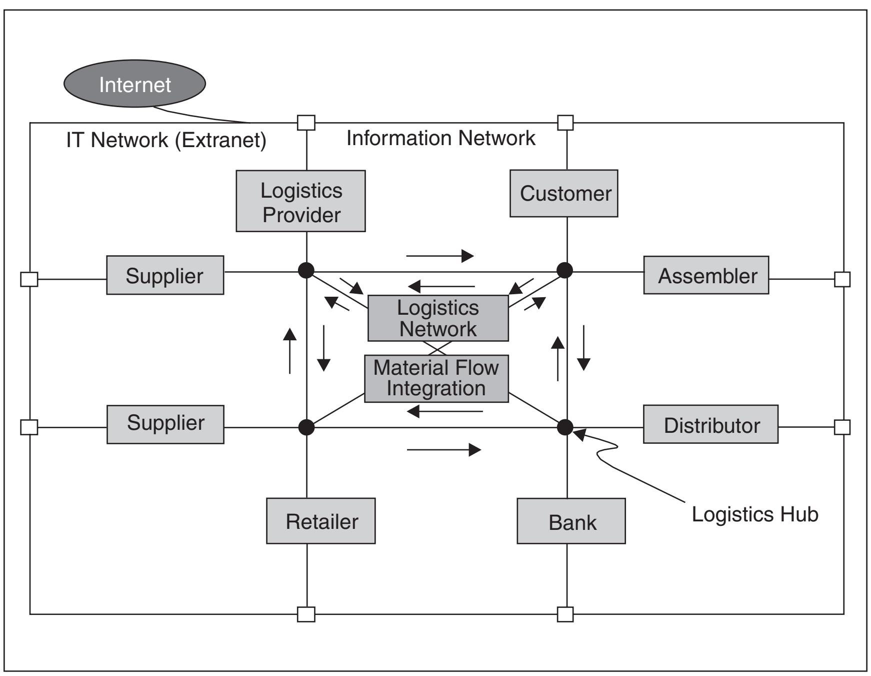

Figure 4. *Integrated supply-chain network.*

Automated Supervision and Control

This is a critical area that needs significant attention from both theoreticians and practitioners.

Factory Automation

The theory of cybernetics made possible the real-time control of individual equipment, such as the lathe, milling machine, robot, etc., using analog controllers. In the computer era, programmable controllers replaced analog control systems. With the advent of local area networks (LANs), factory-automation networks have come into being; we have cell controllers controlling multiple machines, and factory controllers controlling several such cells. It is possible to feed the raw material into a cell and get the finished product stored in an automated storage and retrieval system (ASRS), all automatically with the help of manufacturing controllers and warehouse management systems. The theory of automatic control has helped in the development of real-time control systems and supervisory-control systems. Virtually all these efforts have focused on automating and improving the efficiency of operating units within the four walls of a factory.

Automation of Other Supply-Chain Elements

The supply chain can be decomposed into horizontal processes, such as product development, customer acquisition and retention, procurement, supply chain and order delivery, etc. The corresponding sub-processes of all the stakeholders in the value chain need to be integrated without friction using IT tools, such as XML. Enterprise application integration software developed specifically for the supply chain is designed to electronically connect trading partners with a user's enterprise systems. There are several products, in the market designed to connect trading communities together. TMS software streamlines and integrates transportation operations. Warehouse-management systems (WMS) make distribution centers and warehouses run more efficiently and profitably. Advanced planning and scheduling (APS) technology helps in matching procurement and production activities more closely to actual customer demand. Advanced software now lets companies share this critical data with their supply-chain partners.

The Internet makes process integration between the decision-making systems of original equipment manufacturers (OEMs), their suppliers, and customers bidirectional and tightly integrated. Suppliers can interact dynamically and initiate actions within each other's information systems by pre-defining business rules that trigger events across systems. That means that supply chains can be fully automated from the information angle. For example, when a supplier fulfills an order, requests are automatically generated to the supplier's suppliers to replace committed stock and a ripple effect through the supply chain ensues. Less human intervention is required at each step, as decisions in inter-business processes become more automated using decision-support systems. Customers' and suppliers' computer systems can make more intelligent business decisions. For example, if one supplier's price drops below that of others, the customer's application software might automatically move that supplier up in the vendor of choice list. A customer consulting the vendor-of-choice list before ordering would see the cheaper supplier at the top of the list and place an order with that supplier rather than the others. The rapid, two-way flow of information, enables just-in-time delivery, reduces the cost per transaction, and streamlines the way resources flow through the supply chain.

Supply-chain event management involves monitoring the supply-chain process for exceptions and taking corrective actions. For example, the breakdown of a truck carrying replenishment of a critical component will have a significant effect on the production schedules of the OEM. Monitoring this event and taking appropriate corrective action, such as sending another shipment by a faster transport medium or rerouting another shipment, will need real-time decision making and access to production schedules of the OEM, shipments status, etc. Supervisory-control theory can help in developing decision-support systems for the real-time monitoring and control of supply chains.

Relationship Automation

In a supply-chain network, there are multiple players including first-, second-, and third-tier suppliers, contract manufacturers, OEMs, distributors, retailers, and so on. There is need for coordination between all these players for combined forecasting by sharing point-of-sale information, joint scheduling, and joint product development.

Automating Customer Relations

It is a challenging task to align the enterprise to meet the needs of the customer—available 24 hours a day, seven days a week via telephone, e-mail, and the Internet—and to keep accurate records of customer interactions and resolve issues quickly with care. As the range of products and services expand and customer demands increase, support systems and tools become the integrating factor in business operations. The ability of an employee or self-service option to serve the customer well depends on the speed and latency of the infrastructure moving the data to the person who needs it, the data profiling tools to understand a customer's preferences rapidly, well-constructed Web interfaces, and the ability to manage it all as if the company is aligned around delivering on *each* customer's needs. With multiple customer segments and multiple products and services, it is increasingly difficult to deliver the expertise required to keep the many promises a business makes every day. To do this and concurrently maintain competitive cost is challenging. The solution to this problem is intelligent and proactive software than can manage various interactions and follow up work items in a manner that aligns business goals and delivers on promises made, over and over again—which leads to attracting new customers and keeping them.

Automation has gradually evolved from within the four walls of the enterprise to encompass the outside world, resulting in the drive towards the automation of relationships.

The overall CRM-solutions framework includes: multimedia 24×7 customer interactions, intelligent work and customer contact routing, data mining decision making, and tracking tools that link into legacy systems. This new solutions framework creates new operational efficiencies through the alignment of front-office and back-office processes in direct support of the promises to customers and the business goals for growth, relationships, and efficiency.

Automating Supplier Relations

Partner-relationship management (PRM) uses the Internet to provide integrated solutions to the challenges of vendor/partner communication. An effective PRM system organizes leads, profiles, and documents in a central repository that can be updated and viewed in real time over the Internet. PRM systems, like extranet systems, enable the user to view information according to their specific characteristics—each user only sees information appropriate for their permission level and interests. For example, they provide resellers with instant, on-demand access to information and tools. Since resellers have self-service processes for answering their questions and doing their everyday work, the need for costly face-to-face meetings and direct mailings falls dramatically. A good PRM system allows companies to track usage and activity, giving vendors tighter control over communication.

The Future

This century has been the century of automation. All the various aspects of business activities have slowly been automated, starting with material-flow automation and followed by information-flow automation and automated supervision and control. More recently, automation has gradually evolved from within the four walls of the enterprise to encompass the outside world, resulting in the drive towards the automation of relationships. We are charting these initiatives in order to gain better insight into some of the possible technologies of tomorrow (Fig. 5). For digital products, the delivery of the product to the final customer could be trivial. Our discussion is more concerned with physical products. What about the future? The future is already here in some countries and for some products.

Design Your Supply Chain

Most current supply chains were not designed—they grew with the industry. They are complex, inefficient, and do not use the Internet, mobile communications, or other technologies. The design of supply-chain networks for a set of products and markets that includes supplier selection, information transfer between stakeholders, and monitoring and performance with minimal inventories at various stages is essential for survival. It is important to note that all four facets of automation mentioned above are important. Companies with the capability to use technology to automate relationships and produce new products will have a definite advantage over others.

Building Bridges Between Businesses

The next cycle in manufacturing automation—automating around customers and suppliers—is evolutionary and iterative in nature. Now, the Internet is both a commerce channel and decision-making platform. This shift opens up manifold possibilities for intra- and inter-supply-chain collaboration, ranging from customer-driven ordering, to collaborative design and manufacturing, to real-time pricing on the demand curve, to optimizing demand and production forecasts, to fully automated purchase orders and billing.

Is it possible to fully automate material movement from the supplier to the OEM? The answer is, "No," at least not in this decade. Shipments have to go through various agencies, airports, and seaports. The streamlined movement of material through integrated scheduling and real-time monitoring with small waiting times is what one can hope for. This can be achieved through information integration and use of decision-support systems. Basically, based on the knowledge of where and when the material is to be delivered, its current location, and the status of the logistics operators undertaking this movement, the decision-support system determines the best schedule.

Distributed Flexible Manufacturing

Manufacturing started as a local activity within a city where all activities from components manufacture to final product were performed. Examples include auto manufacturing in Detroit and Toyota cities. With global manufacturing, this scenario has changed. Now, no product is built in any one country or by any one company, with the result that inter-company logistics and collaboration became very important and critical. The Internet is used to advantage here for information transfer. But international logistics are enormously complex, requiring investments in cargo complexes and transport. This also increases the cost and time of delivery. But customers want rapid delivery of fresh products at competitive prices. Manufacturing itself is automated and commoditized. Design and partner relationship play a major role.

Given the above scenario, one trend that may occur is for manufacturing to revert back to city clusters again, but with an

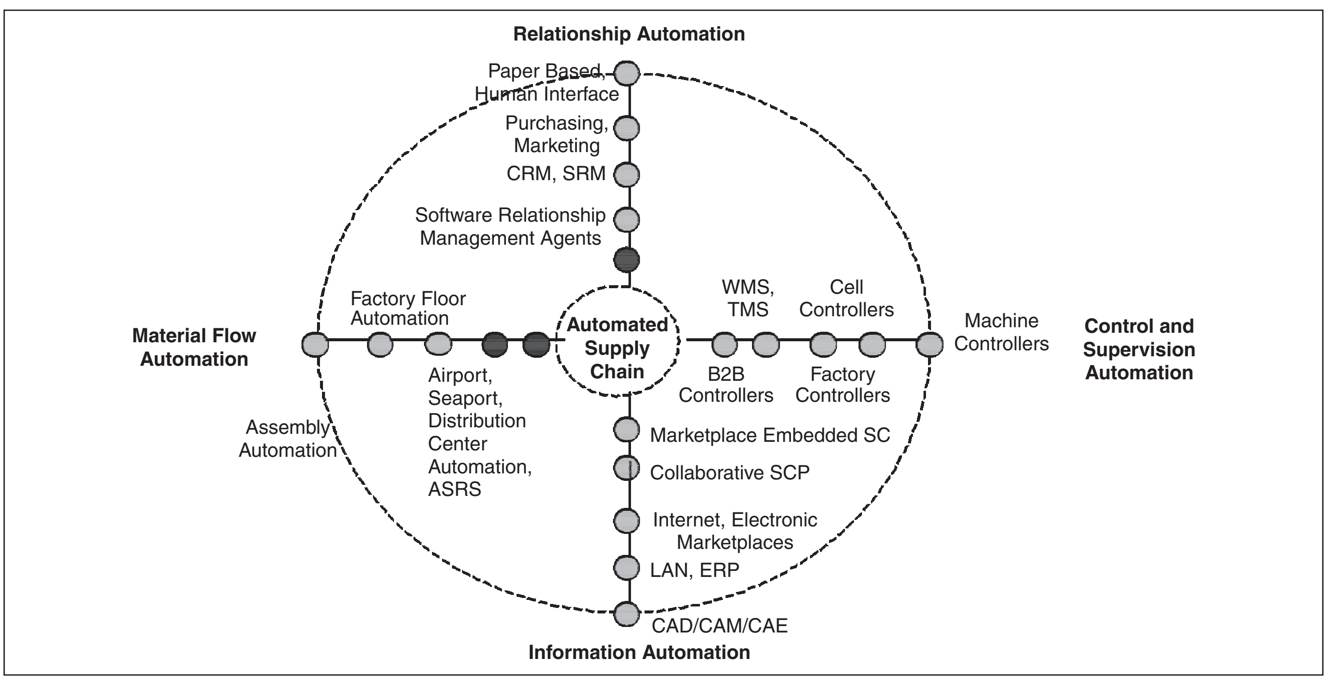

Figure 5. *Progress of automation technologies.*

important difference: the Internet will now be used for global knowledge transfer and for monitoring relationships. Products will be manufactured locally in a country or region and delivered locally. Thus, the customer will get a branded product delivered rapidly at a competitive price. We may see several regional automated supply chains collaborating on a global scale by sharing knowledge and information.

Also, there will be a big push for manufacturing plants to be more flexible. Currently, machines and layouts at each location are very specialized—they are not interchangeable. It is virtually impossible to move production from one location to another or from one company to another. There is no flexibility in terms of production because most of the plants are unique in what they produce and in terms of materials and material-handling equipment used. Manufacturing may be outsourced to third-party contractors to gain economies of scale.

Supply-Chain Performance Measurement

Although a significant amount of work was done in the supervision and control of equipment and material flow, very little attention is given to defining performance measures, measuring the performance, and improving it. Supply-chain-performance measurement provides the means by which the network can assess whether its performance has improved or degraded. The importance of using measures is to help ensure that a supply chain is competitive. There are a number of companies involved in the supply chain, and all of them should work in concert for the supply chain to do well. Ultimately, the end consumer has to be satisfied and given perfect delivery of his or her order. Perfect delivery means on-time defect-free delivery every time. Defect is a generic term that includes design defects, manufacturing defects, wrong delivery, delayed delivery, etc. A good discussion of this is available in [2].

Building the Infrastructure to Maximize Shareholder Value

Most countries do not have efficient transportation and information infrastructures. Also, not all companies (manufacturers, suppliers, distributors, logistics providers) are Internet enabled. The ingredients necessary for global manufacturing to succeed, such as global logistics providers and the infrastructure in terms of ports, airports, and IT bandwidth, are not uniform throughout the world. Thus, the future of some countries is in the past of advanced countries. There are definitive directions that one can see in terms of the future.

As described in the previous sections, the wheel of automation incorporates the four aspects of material-flow automation, information-flow automation, control-and-supervision automation, and relationship automation. The ultimate aim of these automation initiatives is to derive maximum value by establishing automated supply chains.

Automation in all its forms significantly reduces the cost of operations and, at the same time, positively impacts the revenue streams from operating a supply chain, thereby creating tremendous value. Hence, in this process of value creation, each of the four aspects of automation is a key value driver. For example, hard automation on the factory floor results in a reduced workforce and labor cost. Similarly, information automation through intranet systems and corporate LANs can result in increased employee productivity, resulting in increased output. Control-and-supervision automation results in increased asset utilization through intelligent decision-making, resulting in an increased return on assets. And, lastly, relationship automation improves customer satisfaction that, consequently, improves customer loyalty that, in turn, results in increasing revenue streams.

Companies with the capability to use technology to automate relationships and produce new products will have a definite advantage over others.

Furthermore, since these automation initiatives are closely related to the infrastructure of the enterprise, they have a multiplier effect on the value delivered to the enterprise. For example, an intimate customer relationship can provide the enterprise with opportunities for cross-selling of other goods and services and generate new revenue streams. In the same manner, investments in IT have multiple impacts, such as increased personal productivity, leading to lower manpower requirements and greater coordination between teams and employees, leading to faster time-to-market and reduced product-development time.

There is no doubt that enterprise-automation initiatives offer a great opportunity to increase the value of the enterprise. However, in order to maximize value, there has to be a systematic approach to value creation. Such a process is necessary because value can be destroyed by an inappropriate strategy just as easily it can be created by a planned investment initiative. Consider the case of the failed dot-com revolution. Companies invested too much in relationship automation by building expensive Web sites. At the same time, their material-handling processes were not automated enough to handle the orders that the relationship-management exercise was generating. Eventually, they ended up incurring significantly high material-handling costs and reduced-revenue streams from unhappy customers. A systematic approach would have ensured that they invested appropriate amounts of their investment dollars into automating their relationship, material-handling, and control-and-supervision processes. An important consideration to keep in mind when making such investments in automation initiatives is that certain investments cannot take place until previous investments are made in some prerequisite technologies and processes. For example, it is counterproductive to jump the gun and invest in global supply-chain planning software until the enterprise has global supply-chain visibility through information systems integration. Hence, it follows that in order to create value, it is important to follow a sequential investment strategy wherein each investment builds on the value created by previous investments.

Acknowledgments

The author would like to thank Prof. Peter Luh for inviting him to be a panelist at the IEEE International Conference on Robotics and Automation at the panel discussion. Also, thanks are due to Roshan S. Gaonkar for his help in figures, discussions, and critical comments.

Keywords

Automation, manufacturing, supply-chain networks, collaboration, logistics, shareholder value, supervision and control, information technology, relationship automation.

References.

[1] J.P. Womack, D.T. Jones, and D. Ross, *The Machine that Changed the World*. New York: Harper-Perennial, 1990.

[2] N. Viswanadham, *Analysis of Manufacturing Enterprises*. Norwell, MA: Kluwer, 1999.

[3] N. Viswanadham, "Manufacturing automation: The past, present and future," *The Total Enterprise Automation Conf.,* Singapore, June 2001.

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