AUTO-ID TECHNOLOGY: CREATING AN INTELLIGENT INFRASTRUCTURE FOR BUSINESS†

Edmund W. Schuster‡
The Data Center
Massachusetts Institute of Technology
Cambridge, MA
www.mitdatacenter.org

†Sections of this report are based on the following two books published by the author:

Schuster, Edmund W., Stuart J. Allen. *Raising the Bar (Code): The Value of the EPCGlobal Network*. Thomson South-Western Educational Publishing, forthcoming.

Schuster, Edmund W., David L. Brock, Stuart J. Allen, Pinaki Kar, and Mark Dinning, 2005. "Enabling ERP through Auto-ID Technology." *Strategic ERP Extension and Use*. Edited by F. Robert Jacobs and Elliot Bendoly, Stanford University Press, 2005.

‡ 23 Valencia Drive
Nashua, NH 03062
603-759-5786 (c)
Edmund_w@mit.edu

About the Author

Edmund W. Schuster has held the appointment of Director, Affiliates Program in Logistics at the MIT Center for Transportation and Logistics and is currently Co-Director, Administration and Research Associate, The MIT Data Center. His interests are the application of models to logistical and planning problems experienced in industry and Auto-ID technology. Ed's most recent efforts involve building an interoperable system for mathematical models and data. He has a bachelor of science in food technology from The Ohio State University and a master in public administration from Gannon University with an emphasis in management science. Ed also attended the executive development program for physical distribution managers at the University of Tennessee and holds several professional certifications.

INTRODUCTION

Simply stated, Auto-ID technology is a means to link physical objects to the Internet using low-cost radio frequency identification (RFID) tags. To manage the large amounts of new data generated by the system, Auto-ID uses a sophisticated information technology infrastructure based on open standards. This technology lays the foundation for increases in productivity within supply chains and general commerce that will take place during the next ten years.

Auto-ID technology began in 1999 with the formation of a consortium that sponsored research at MIT. After several years of development and testing, MIT licensed Auto-ID technology to GS1, the non - profit standards organization responsible for the implementation of bar code standards during the 1970's. Since 2003, GS1 has been developing commercial application of the technology under a unit called EPCGlobal. In the years subsequent to 2003, there have been several changes to Auto-ID Release 1.0 including a rename of the information architecture to EPCGlobal Network and an increasing emphasis on something called the Electronic Product Code (EPC).

Ongoing research involving all aspects of the technology continues at Auto-ID Labs, a partnership that includes GS1, MIT, and several other universities.[1] This is an international effort to continue the technological development of common standards for Auto-ID Technology. Plans include industry specific applications research and additional testing of the technology including an industrial grade simulator for an entire supply chain to be located at MIT. The MIT Auto-ID Labs is currently under the direction of John R. Williams, Professor of Information Engineering (email jrw@mit.edu).

In many ways, the infrastructure needed to link physical objects to the Internet closely resembles that of the Internet itself. Distributed processing and open standards are the defining characteristics that combine to make Auto-ID technology operable across business and

[1] Other institutions include, the University of Cambridge (UK), the University of Adelaide (Australia), the University of St. Gallen (Switzerland), Keio University (Japan), ICU of Korea, and Fudan University (China).

international boundaries. In the future, knowledge of this infrastructure will be as common as that of microcomputers, networks and the Internet. All in business will need to know and understand at least the conceptual aspects of how Auto-ID technology works in practice.

Like the Internet, Auto-ID technology is always “on” so that a constant link exists between physical objects and the Internet. Having a seamless link to objects opens a number of possibilities for automation and ubiquitous computing. This can happen without human intervention, increasing the prospects for order of magnitude increases in future business and public sector productivity.

Auto-ID technology has potential to accomplish tasks of great value to commerce through the merging of information with physical objects such as cases or pallets of finished goods common to the consumer goods and other industries. In essence, Auto-ID technology creates an object-centric system designed to allow tasks to be performed on behalf of objects. This will serve as the base for creating the smart objects of the future, capable of independent sensing and responding within supply chains.

This article focuses on the major aspects of Auto-ID important to practitioners. Eventually, the technology will serve as the framework to sense, understand, and do within the complex supply chains of the future. Planning for the eventual implementation of Auto-ID Technology is a strategic activity for information technology professionals in anticipation of improvements that will further reduce the cost of the technology.

ADVANTAGES OF AUTO-ID TECHNOLOGY RELATIVE TO BAR CODES

Few other inventions developed during the 20th century have had as wide an impact on everyday life as the bar code [13]. First implemented in 1974, the bar code has drastically reduced the amount of labor needed to operate retail stores, improved pricing accuracy, and shortened countless checkout lines saving great amounts of time.

Beyond retail stores, bar codes have been applied in many other situations to provide important information such as the coordination of production within manufacturing plants or tracking data for overnight packages in transit. Bar codes transmit a small amount of information that identifies the manufacturer and links to a description of the object. Non-profit standards groups such as GS1 and others administer the numbering system used for the bar code ensuring a unique identification without duplication by other firms.

New research and development efforts have led to the development of the two-dimensional bar code that is able to carry more data about an object. This opens possibilities to attach important information such as billing details directly to the object as it passes through the supply chain.

A basic characteristic of bar codes is that all information travels with the object. In the case of a two-dimensional bar code, more information travels with the object as compared to a regular bar code. Though two-dimensional bar codes do provide much more information beyond product identification, all bar codes have limitations including:

- The need for a direct line of sight from the scanner to the bar code,
- The ability to read only one code at time
- Bar codes often require human intervention to capture data or to orient packages in the case of overhead bar code readers.

In addition, bar codes provide only one-way communication and seldom provide real time information or Internet connectivity to the data. There is always a chance the bar code will be missed or in other cases, read twice. As well, bar codes can be damaged or compromised in a way that makes them impossible to read. Auto-ID technology is designed to overcome all of these limitations and make it possible to automate the scanning process, providing real-time data.

THE GRADUAL MOVEMENT TO ELECTRONIC TAGS

In the last fifteen years, refinements in the design of integrated circuits along with advances in the way electronic tags are manufactured have let to a decrease in cost per unit. Though the costs are still well above bar codes, the current price of tags opens the possibility for wider application in practice.

In addition to the advances in manufacturing technology for producing the integrated circuits, there are several other important aspects worth noting that deal with the way tags are powered. Currently there are two basic types of tags used most often.

An *active* tag requires a small battery that provides electric power to continuously generate and transmit the radio frequency (RF) signal. Active tags can be read by readers (capable of receiving RF signals) located within the supply chain from a relatively long range—up to 30 meters. In general, these tags have significant amounts of memory to store information such as bill of lading details. In some cases, specialized readers called interrogators can not only read data from an active tag, but can also send signals to reprogram the tag with new information or instructions.

However, active tags have several drawbacks. Because these tags transmit signals significant distances, there is greater chance of a “frequency collision” with other electromagnetic waves such as those emitted by radios, transformers or cellular phones. This type of interference could cause the reader not to pick up the tag signal. In addition, with longer read distances, the opportunity of providing exact location information diminishes. The tiny batteries are moreover somewhat expensive, thus limiting widespread use. Common prices for active tags range from $2 or more per unit, depending on capability, memory and order size.

Beyond the expense, the other disadvantage of active tags is that the batteries sometimes wear out resulting in total loss of signal. This is disastrous if the tag fulfills a critical function such as tracking and tracing a physical object. Battery life varies a great deal depending on many different factors, so it is difficult to predict in advance when a failure might occur.

Given the capabilities of active tags, industry and academics undertook research to develop low cost passive tags as an alternative. With this technology, each tag does not contain a battery. Rather, the energy needed to power the tag is drawn from electromagnetic fields created by readers that also serve a dual purpose of gathering the signals emanating from the passive tags. The read distance of a passive tag is usually no more than three meters.

Since no fixed power source is required, passive tags hold a great advantage over active tags in terms of lower cost per unit. This opens the possibility for the use of passive tags in a far greater number of applications. Gradually, as costs decrease, passive tags will challenge bar codes as a means of gathering information within supply chains.

A third type, the *semi-passive* tag, is a hybrid of both active and passive tags. It has a smaller battery that is partially recharged each time the tag enters the electromagnetic field of the reader. These tags are currently under commercial development and are not widely used in industrial applications though there is promise such technology might be an important factor in the near future.

Designed to operate at low energy levels, passive tags store relatively little information. Just enough memory exists to store a serial number that can reference an IP address on the Internet. Information is stored on the Internet, not on the tag. This provides a distributed means of holding information.

Table 1 summarizes the capabilities of tags.

Table 1 - Comparison of Different Tags

	Active	Passive	Semi-Passive
Power Source	Battery	Induction from electromagnetic waves emitted by reader	Battery and Induction
Read Distance	Up to 30 meters	3 meters	Up to 30 meters
Proximity Information	Poor	Good	Poor
Frequency Collision	Hi	Medium	Hi
Information Storage	32 k or more. Read/Write	2 kb Read only	32 k or more. Read/Write
Cost/Tag	$2 - $100	25 ¢*	Under Development, Some applications

*cost is projected to decrease to 16¢ per tag given full-scale volume.

Overall, passive tags hold the promise of ubiquitous application to objects within a supply chain. However, a comprehensive information technology infrastructure must also exist to organize and communicate the data gathered from passive tags. Auto-ID provides such an infrastructure.

RFID VS AUTO-ID TECHNOLOGY

A great deal of confusion exists concerning the meaning of two terms, radio frequency identification (RFID) and Auto-ID. While RFID has been in existence for more than 50 years, Auto-ID represents a new technological development. Though both technologies share commonalities, several important differences exist.

Historically, the term RFID has applied to situations where an object identifies itself through the transmission of radio waves that are received by an antenna attached to a reader and processed into positional information.

Examples include the application of RFID tags to steamship containers and rail cars. Most of these applications involve different types of capital asset tracking and management. This type of two-way communication is tightly coupled with highly specific applications such as air traffic control, proximity warning, and shipyard management systems. Many in industry classify these applications as “closed loop” to denote that direct feedback occurs between two objects coupled by RFID types of communication. Because most of these applications are highly specialized, RFID has evolved into mostly proprietary technology characterized by closed standards.

Though RFID has offered some highly innovative applications, the technology has never achieved mass use for supply chains because the cost of electronic tags powered with tiny batteries remained relatively expensive. Manufacturing breakthroughs during the past several years that include fluidic self-assembly and vibratory manufacturing methods offer significant potential to place individual transistors onto an integrated circuit at sharply lower cost [29]. Projections show that the new generation of tags will reach a price that allows individual tagging of cases and pallets. At some time in the future, the price might be low enough to tag individual consumer goods on a large scale.

With these new manufacturing methods, production of the silicon chips needed for Auto-ID becomes a continuous manufacturing operation in contrast to the current batch method for producing the integrated circuits that make up silicone chips. This development opens the possibility of tag application to a large number of objects, such as individual cases, and pallets of merchandise within the consumer goods supply chain.

Given the scale of retail supply chains that include billions of items, industry consortiums recognized very early the need for a comprehensive information technology infrastructure to manage the large amount of data potentially available from linking objects to the Internet. With such an infrastructure, the practical possibility exists of having continuous, two-way communication with objects located anywhere within a supply chain. This *Internet of things* will create unprecedented interconnectivity, and have an important impact on the enterprise systems of the future.

The infrastructure needed to manage the Internet of things is Auto-ID technology, an intricate yet robust system that utilizes RFID. An important feature of Auto-ID technology includes open standards and protocols for both tags and readers. This means that a tag produced by one manufacturer can be read using equipment produced by a different manufacturer. This type of interoperability between tags and readers is essential for wide-scale application within supply chains.

Beyond the sophisticated information technology, Auto-ID lays the groundwork for the intelligent value chain of the future [8]. Creating "smart products" that sense and respond with the physical world requires unique identification, which is an element of Auto-ID technology. With this capability, distributed control systems can interact and give instructions to a specific object.

For example, some time in the future smart objects within the consumer goods supply chain might dynamically change price based on sensing demand and communicate this information to ERP systems without human intervention. Because it offers much more than merely identifying objects using radio communication, Auto-ID technology holds the potential to drive rapid advances in commerce by providing the infrastructure for true automation across supply chains.

APPLICATIONS

With the advantages of Auto-ID relative to bar codes, there are a number of possibilities for practical application of the technology. The foremost element of interest to practitioners is the EPC, which allows for unique identification. This is an important attribute when doing track and trace within supply chains [17] [11] [33].

However, it is also important to remember that the data generated by Auto-ID facilitates many other applications such as capacitated MRP [32], the management of service parts [16], the prevention of theft [18] and the calculation of risk (for example see [3]). Combined, these potential applications allow practitioners to consider other possibilities to improve productivity.

Given that Auto-ID offers new ways to capture data, it is natural to begin thinking about how this technology will affect the overall design and operation of Enterprise Resource Planning (ERP) systems, which are the primary computing backbone for most modern industrial organizations. At its core, ERP is essentially a large database. As increasing amounts of data become available through Auto-ID technology, the nature of ERP will change dramatically opening new possibilities to do things previously thought impossible to achieve in practice ([35].

For example, managing serial numbers for trillions of objects presents a difficult challenge for current ERP systems to handle. As a result, there will be a measured transition from lot control, currently available in some ERP systems, to serial number control enabled by new software concepts that are being developed by major ERP vendors and innovative start-up companies.

Though it is difficult to predict, practitioners should expect to see changes to ERP systems by 2008 as Auto-ID begins to reach full application in select supply chains. Several ERP vendors, such as SAP, have already introduced Auto-ID modules into their software.

HOW AUTO-ID TECHNOLOGY WORKS

In conjunction with advances by tag and equipment manufacturers, the objective of Auto-ID technology is to create infrastructure and set open standards that will make it possible for wide adoption of passive RFID technology [9] [34]. Though there have been recent changes to the technology being put forth by EPCGlobal, there are four components that originally make up Auto-ID Technology. These include:

- EPC (electronic product code)
- ONS (object naming service)
- PML (physical markup language)
- Middleware

The EPC is a numbering system that contains enough combinations to identify trillions of objects. This is necessary because the ultimate goal is to provide a structure for low cost identification at the item level, meaning every single product will have its unique code. The PML is the communication format for the data and it is based on XML (extensible markup language) that is gaining popularity in eCommerce transactions. PML represents a hierarchal data format to store information. By having a standardized means of describing physical objects and processes, PML will facilitate inter- and intra-company commercial transactions and data transfer.

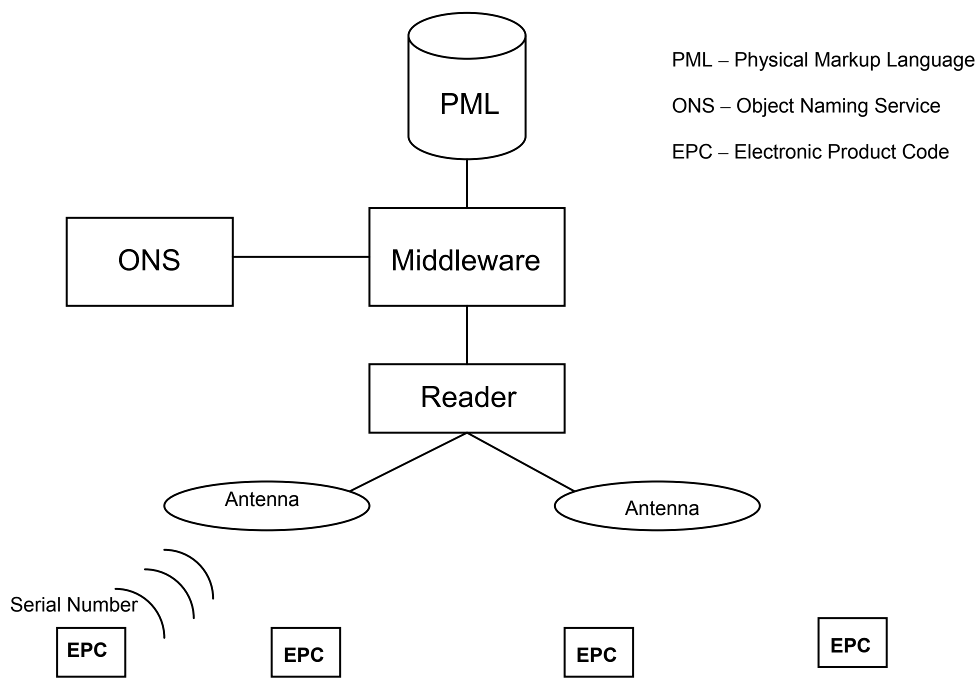
The ONS acts as a pointer to connect the EPC to the PML file stored on a network, either a local area network or over the Internet. It performs a similar function to the Domain Naming Service (DNS) of the Internet, which connects a text web address to an underlying IP address. An IP address is comprised of a 32-bit numeric address written as four numbers separated by periods, to find resources over the Internet. However, with the EPC, we start with a number and use ONS to find the product information linked to that number.

Middleware is a lower level software application that processes the data and performs error checking and de-duplication procedures in the event that more than one reader receives a signal from the same tag. It handles the scalability problem associated with the massive amount of data captured by Auto-ID. To summarize, the EPC identifies the product, PML describes the product, and ONS links them together.

To make the system work, products are tagged with passive RFID chips containing the EPC. The tags are placed on surface areas of pallets, cartons or contained within item packaging. Readers are positioned at strategic points throughout the supply chain where companies need to capture data. Readers constantly emit an electromagnetic field that is received by the tags through a small antenna. This energy activates the tag, and in turn, a signal is generated and transmitted to the reader. Through this process, readers capture the EPC and interact with a Savant to look up the information on the product using ONS.

The position of the reader receiving the EPC signal provides important information on location, and environmental conditions such as temperature, vibration and humidity, which is then linked through databases to the EPC. All this information is housed and written to corporate databases using the PML format (See figure 1 – Technology Overview).

Figure 1 – Technology Overview



This original technological architecture for Auto-ID is currently under re-design by EPCGlobal based on continued input from industry. An important barrier to greater progress in Auto-ID adoption involves basic questions of security of the ONS system. Though encryption technologies exist to protect the ONS, several leading companies have expressed a desire to communicate and transfer EPCs and associated data by using direct database-to-database communication, bypassing the need for PML and ONS. The term EPC-IS describes this new approach. While it remains unclear what structure the final architecture will take, it is clear that the basic component of Auto-ID technology, namely the EPC code, will continue as the central aspect of the system.

Given an idea of the information technology structure needed to manage the EPC code, the next section introduces issues around establishing an intelligent infrastructure for business and the impact on ERP systems.

CREATING AN INTELLIGENT INFRASTRUCTURE FOR THE ERP SYSTEMS OF THE FUTURE

Simply stated, an enterprise resource planning (ERP) system identifies and plans "the…resources needed to take, make, ship and account for customer orders [4]." To achieve these important tasks, ERP uses a variety of information technologies such as graphical user interfaces, relational databases, advanced computer languages and computer assisted software engineering tools. In essence, implementers of ERP systems seek to plan and control all the resources in a manufacturing or service-oriented company.

In many respects MRP, the subsequent development of manufacturing resource planning (MRPII), and ERP, represents increasingly sophisticated databases that over time have improved tactical and strategic business planning. Essentially, ERP serves an "uncertainty absorption [25]." It is impossible to know with certainty all future outcomes that might occur for a business. However, with enough data and proper methods of analysis, reasonable projections of future outcomes become feasible. Having data allows for the possibility of calculating risk, where several different outcomes are possible, and a probability calculated from the data can be assigned to each outcome.

The crowning achievement of ERP systems in practice is that business decision making has moved from an *uncertainty basis* where no comprehension of risk exists, to a *risk basis* where ERP serves the important function of mitigating uncertainty. The result; much more effective business decision-making based on rational analysis of data available rather than pure conjecture

With the established success of ERP, it is realistic to begin thinking about what changes in information technology will further enhance ERP, thus reducing even more uncertainty within business planning. Since ERP is at its essence a data management tool, it is reasonable that any advancement in the way that data is obtained, organized, and employed will have a significant impact on the structure of ERP software.

Auto-ID technology represents a new way to capture input data for ERP systems. The implications of Auto-ID technology affect several important areas of ERP including data interfaces, bill of material structure, accounting, the treatment of capacity in material requirements planning, and the application of mathematical models to the analysis of data. All of these are new developments that will change the nature of ERP in the years to come.

With all the advantages of Auto-ID, it is natural to begin thinking about how this new identification technology will affect the overall design and operation of ERP systems. At its core, ERP is essentially a large database. As increasing amounts of data become available through Auto-ID technology, the nature of ERP and the infrastructure needed to support the system will change dramatically opening new possibilities to do things previously thought impossible to achieve in practice.

One of the most important inputs to ERP is data about objects such as raw materials, work in process, and finished goods. The next section addresses this issue providing a blueprint for gaining the most from Auto-ID technology.

Data and ERP Systems

Since the inception of ERP, accuracy of data has been an important goal for long- term success. Early efforts focused on improving the accuracy of the bill of material (BOM), an important part of MRP. In the past, popular management programs such as Class A MRP II were important in helping practitioners get the most benefit from these systems.

With the perfection of the BOM approach, emphasis has shifted to raw data accuracy as a means of further improving the overall results of planning. Though data accuracy has been an important issue for many years, it continues to attract the interest of practitioners.

The goal of tracking items through an entire supply chain with 100% inventory accuracy remains elusive. This type of effort represents a huge challenge to current information technology infrastructures that are a critical part of ERP. In the future, automated methods of planning and control within manufacturing and service operations, and entire supply chains, will depend on accurate, real time information and unique identification of individual objects. Because manufacturing systems are in constant flux, data accuracy is not just a function of having the correct value, but of having the correct value at the correct time to reflect the proper state of the system. Accurate data that is old is of no use in a dynamic system.

Thinking beyond the utilization of real-time data, Auto-ID offers other opportunities to capture detailed data about objects within a supply chain on a scale never before experienced in commerce. However, organizing EPCs represents a challenge requiring significant changes to ERP systems.

Organizing Data from the EPC

Though it is early in the development of Auto-ID technology, it appears ERP will hold an important role in managing the EPC data needed for supply chain wide visibility. The EPC, a fundamental tenet of Auto-ID Technology, provides the capability for unique identification of trillions of objects. Unique identification on this scale results in useful information for track and trace [17] [33], and the authentication of objects located anywhere in a supply chain [18]. However, managing serial numbers for trillions of objects presents a difficult challenge for current ERP systems to handle. As a result, there will be a measured transition from lot control, currently available in some ERP systems, to serial number control enabled by new software concepts such as the Transactional Bill of Material (T-BOM).

With the T-BOM approach, serial numbers contained in the EPC are organized to provide the history of movement for an item (pedigree information), a schematic of the serial numbers for all components contained in the finished item, and a mechanism to allow a query for authentication by any party within a particular supply chain [7]. This is accomplished through sophisticated database technology that utilizes EPC information gathered from the middleware interface to Auto-ID.

The T-BOM represents a new generation of software intended to enhance system integration as Auto-ID technology begins to take hold in industry. Since current ERP systems use only lot control for tracking and tracing, it is important to add capabilities that handle EPC data so that that it can be queried and communicated as needed. Without these types of new structures to enhance ERP, there will be much less effectiveness in using data from Auto-ID technology.

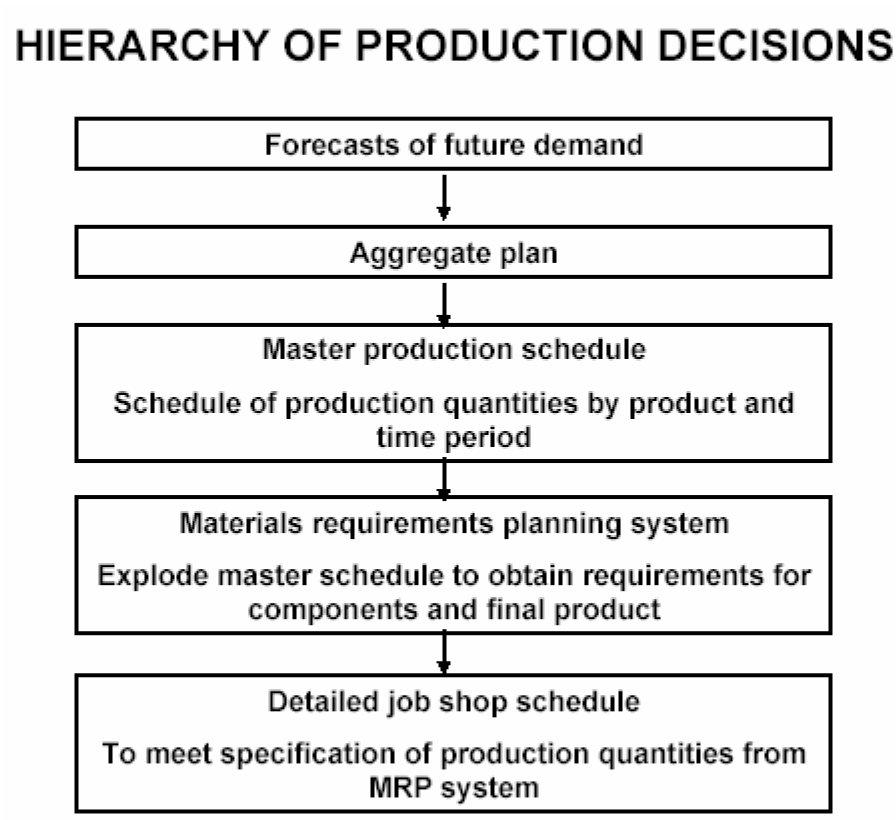
Besides tracking, tracing, and authentication, serial data on components opens new possibilities to gain insight into complex operations. There are many situations where lack of detailed information leads to ineffective supply chain management. For example, difficulties with management of versions is a common problem in the capital asset industries where service parts for long life cycle items such as aircraft frequently undergo modification and redesign midway through the life of the asset [11]. With most part numbering systems, different versions of a service part cannot be identified, inventoried, traced or tracked. In situations where there are large networks that do maintenance of deployed assets, such as airbases in support of combat aircraft, knowing the exact version of a service part in inventory is essential to providing high levels of service and readiness. In addition, the ability to track failure rates by serial number (version) is also critical to understanding overall reliability as service parts move from manufacture, to distribution and finally to installation and use [16].

There is no question that Auto-ID has great potential to provide detailed data about objects within a supply chain. The data capabilities of the technology also allow other possibilities such as a change in the algorithmic structure of ERP. The next section explores just a few of these possibilities.

Capacitated Planning and Automated Scheduling

One of the most basic processes of ERP is planning and scheduling. The following diagram provides a conceptual overview of the various planning and scheduling functions common to all ERP systems.

Figure 2 – Decision – Making in Manufacturing



Adapted from Nahmias (1993) [26]

Two aspects of Auto-ID technology have the potential to change the way that practitioners use ERP for planning and scheduling.

First, the ability to have manufacturing plant and supply chain wide visibility of objects identified with the EPC allows for large amounts of information and executable instructions to be assigned to an object. An example that has been in application for several years involves attaching an electronic tag to a component that is work in process (WIP). As the component moves through different manufacturing stages, the tagged item is scanned and instructions are downloaded from databases into computer numeric control (CNC) milling machines that automatically cut the component to exact specifications. As the component moves to the next stage of manufacturing, another scan takes place and a new set of instructions are loaded into processing machines. It is even feasible that a queue of tagged parts for an individual work center could be scanned simultaneously to identify important information for adjusting work center priorities. In this manner, detailed day-to-day shop scheduling and management of instructions become automated processes.

With this level of control, there are almost unlimited opportunities to improve information handling and automation within manufacturing plants. The opportunity also exists to increase the level of automation across entire supply chains so that a component manufactured at one plant can be transferred to another with the knowledge that all relevant information and manufacturing instructions are attached to the component and can be processed automatically. The open standards and protocols are an important feature of Auto-ID technology that allow for this type of information transfer and communication within the supply chain.

The second important aspect of Auto-ID technology that will change the way planning and scheduling is performed within ERP involves the continuous flow of data. A well designed Auto-ID system is always "on." With this improved sensing capability, critical subsystems of ERP will have accessibility to more data for scheduling calculations. Given real-time data, new possibilities exist to apply advanced algorithms such as math programming and heuristics in every practical aspect of planning and scheduling.

One of the most important goals of manufacturing is the management of capacity utilization. Several ERP subsystems are crucial in achieving this short and medium term goal. The master production schedule, the MRP system, and the detailed shop schedule all visualized in Figure 2 are the current tools within ERP to manage capacity. For many years, all of these systems assumed infinite capacity when doing planning and scheduling.

This assumption, though widely recognized as an important weakness, reflected the reality that in many cases data did not exist to support advanced finite planning and scheduling.

Planners have spent untold hours manually balancing production to meet available capacity. When the problem could not be solved manually, due dates were not met and customer service suffered.

Beginning in the mid 1980's, the advent of microcomputers resulted in the introduction of master scheduling software that accomplished capacitated planning and scheduling for end items. These software packages existed outside of ERP systems and required significant integration to achieve operability. During this time computer spreadsheets began to be used as a powerful means to build models and do finite capacity scheduling for end items [30] [1] [2] [10].

However, achieving capacitated planning and scheduling for a single level, finished good, is far easier than achieving the same task for dependent demand (MRP). In this case, the consideration of capacity constraints and cost optimization must take place through multiple levels for the BOM. Manufacturing multiple complex end items at a single facility adds to this complexity.

MRP has been singled out by managers and academics alike for the lack of consideration of capacity constraints when planning lots sizes. As Billington, et al. [6] write, "MRP systems in their basic form assume that there are no capacity constraints. That is, they perform 'infinite loading' in that any amount of production is presumed possible…"

For some types of industries, like heavy manufacturing, this limitation is an annoying inconvenience. With finished items requiring high labor inputs, the primary capacity constraint is often availability of skilled workers to do the job. If high production levels press the capacity of available trained labor, more workers can be hired or existing workers can be retrained. In other situations, such as the process industries, lack of capacitated planning and scheduling is a much more serious matter.

The process industries are asset intensive with huge investments in long lead-time equipment. In this case, adding additional capacity is not a short-term managerial prerogative so it becomes imperative to get the greatest amount of capacity utilization possible through scheduling methods that find the optimal solution and consider dynamic capacity constraints.

The lack of capacitated MRP is such a serious issue that some leading companies have declined to use MRP for planning and scheduling [39].

While the algorithms to do aspects of capacitated MRP (CMRP) are available, the drawback to implementation is partially dependent on lack of real-time data needed for a meaningful solution. To deal with dynamic demand for end items, manufacturers must account for capacity constraints at all levels of the supply chain. This ambitious goal remains elusive for most firms.

Auto-ID technology overcomes one barrier to the implementation of advanced algorithms for capacitated MRP by providing a continuous stream of data for mathematical programming models to achieve CMRP in practice. Although there are a number of complicating factors that limit the widespread use of advanced models, a major drawback appears to be schedule stability [40] because of a lack of continuous data, replanning often occurs less frequently than needed. In addition, small changes inventory and production values caused by inaccurate counts or poor execution to plan (for production and the sales forecast) also contribute to the schedule stability problem. The combination of these two factors can create large changes in out-front schedules and a great amount of instability within CMRP.

Having a continuous stream of data allows quick adjustment to variances and frequent updates. If the proper buffers exist, a stable schedule results with only minor changes occurring over the time horizon with each new planning run.

There are several documented examples of the application of CMRP in industry [31] [32]. Most notable is the work of Leachman et al. [20]. This article provides a comprehensive report on the successful application of CMRP for a semiconductor company. The approach uses large-scale linear programming (LP) to accomplish CMRP with the goal of improving on-time delivery. The authors note that before implementing the LP approach, sector-wide planning took place only once per month because of the poor quality and availability of data on demand, work in process and inventory. Essentially, planners always had incomplete information.

A large part of the project included design of databases to feed the LP planning model and the development of standard ways to represent data. In the end, the authors state that data accuracy, availability and timeliness were significant factors in the overall success of their efforts to implement CMRP as a management tool.

These are just a few examples of how Auto-ID technology will change the nature of ERP systems in practice. However, before mangers see some of these changes occurring, there remains the question of cost justifying applications of Auto-ID technology. The final section of this report provides a case study of the justification process.

BUILDING A BUSINESS CASE FOR AUTO-ID

With the current state of Auto-ID, it is feasible to do large scale tagging of objects within supply chains. This opens new possibilities for gaining real-time information, which line managers and executive's value as an important part of running a business [24]. By enabling real-time information, Auto-ID technology has the potential to improve monitoring and coordination internal and external to the firm.

Given these capabilities, companies desire to identify areas where Auto-ID technology can provide bottom line results in terms of reduced costs, better customer service, and improved profits. Building a business case for Auto-ID, given current prices for tags, readers, and IT infrastructure, is a top priority that will determine the rate of future adoption.

However, as a practical matter the calculation of costs and returns on investment (ROI) becomes difficult because many elements of Auto-ID technology fall into the category of corporate overhead. Application of tags to individual objects represents the only true variable cost. Yet even tag costs can change a great amount depending on the quantity purchased and the overall quality of the tags. Since the cost of tags should decrease within the next several years, the primary cost of Auto-ID will result from changes to information technology (IT) infrastructure.

For most firms IT infrastructure is overhead that supports many different functions. Often it is hard to assign a proper allocation of overhead that is a fair representation of the amortized asset value for specific business processes. Further, it is also difficult to identify both quantitative and qualitative benefits that arise from Auto-ID technology. With a bias toward high returns and quick paybacks on investments, there is a need to develop methods for fairly calculating the financial and qualitative impact of Auto-ID technology in practice.

The overall costs of implementing Auto-ID are substantial even by the standards of large corporations. Early projections are raising concern about the short and long-term ROI for the technology. One study shows that each of Wal-Mart's top 100 suppliers would have to spend between $13 and $23 million on Auto-ID for the technology to be fully effective [12]. Another study conducted about the same time shows that of 24 companies independently surveyed, only one indicated it anticipates getting an acceptable return on investment in less than two years [23]. With these projections, it becomes extremely important for companies to analyze the ROI of Auto-ID using proven tools established by industry leaders.

This section provides a case study and a method to evaluate the costs and benefits of Auto-ID technology based on analysis conducted by the Dell strategic supply chain group [10]. The results of the study include an initial means to evaluate Auto-ID technology that is applicable to other firms in other industries.

Before exploring ways to evaluate economic contributions, it is important to understand why the role of infrastructure is critical to the success of building an Internet of things. Infrastructure issues trace to the fundamental difference between Auto-ID and the traditional application of RFID.

Auto-ID Infrastructure

As noted, the majority of RFID applications have been proprietary. From an investment standpoint, RFID can offer acceptable financial returns for limited scope projects. In this situation, all investments associated with RFID can be easily identified.

An example is the application of active tags to railroad cars. This has been in place for more than ten years [14]. The cost of the tags and infrastructure to support these types of closed loop RFID applications are identifiable in that all computing systems are stand-alone. This makes the job of financial evaluation straightforward.

In contrast, interoperability between tags and readers characteristic of Auto-ID technology is essential for wide-scale application within supply chains, but also complicates financial justification because the system IT infrastructure becomes a significant element of corporate overhead. This overhead might not contribute directly to the benefit of companies, but rather the customers served by companies. The rollout of Auto-ID technology by Wal-Mart is an example where few manufacturers are receiving any initial benefit [5]. Since Auto-ID is a supply chain wide technology, companies should expect that "much of the value of RFID will not be generated within the four walls of the warehouse or store, but instead, will depend on close cooperation between supply chain partners [19]."

This raises some interesting questions concerning the long-term trend of supply chain integration. Historically, integration has taken the form of tightly coupled relationships with suppliers characterized by greater information sharing, improved coordination, and joint performance measures [21]. This has led to the predominance of dyadic relationships that "rarely span across more than two adjacent partners in a supply [15]."

Though these tightly coupled relationships have produced results in terms of better coordination and reduced inventory [28], there remain opportunities for multi-tier coordination to reduce the "redundancies in the supply chain that would otherwise not have been considered [15]." In this view, manufacturers, distributors, raw material suppliers, and retail outlets all work together to achieve supply chain efficiencies specifically in the areas of reduced inventory and improved customer service. Through supply chain coordination, it might be possible to reduce the impact of the bullwhip effect that often causes devastating swings in demand and inventory levels especially for suppliers located deep in the supply chain [37].

Some have even gone as far as to predict that in the future companies will not compete directly, but rather, entire supply chains will compete against each other. The theory behind this prediction is that tightly formed supply chains closely resembling a vertically integrated company will generate much greater efficiencies and lower costs as compared to tradition business organization where independence is the norm.

While this is an interesting concept, the reality of the supply chain versus supply chain competition is not straightforward. It should not be assumed that this is a universal model of future organization [27]. Suppliers seldom conduct all of their business with a single customer or belong to a single supply chain guided by a channel captain.

However, beyond the questions of supply chain to supply chain industrial organization, Auto-ID does provide the theoretical capability to gain detailed information, at the unique identification level, about multi-tiered supply chains. The most beneficial information obtained through Auto-ID technology would be real-time inventory for finished goods, work in process, and raw materials at specific locations. Assuming that Auto-ID can provide this information, there several mathematical models that could be applied to optimize an entire supply chain.

Though this has value to companies, there remains the question of who will pay for a supply chain wide infrastructure that will provide detailed inventory information. Those that benefit from improved information flows might not be the same companies that must make the investments in the infrastructure needed to produce the information. This complex issue results from the new forms of supply chain visibility at the individual end-item level that Auto-ID technology can create.

As a starting point in the analysis of Auto-ID ROI, either inside a company or within an entire supply chain, there are only two ways a new technology can create benefits; reduction of cost or increasing sales [19]. According to a recent study, Auto-ID has the potential "to reduce costs in five ways and increase sales in two [19]." Costs can be lowered through:

- Labor savings
- Reduction of theft
- Reduction of disputes with trading partners
- Reduction of excess inventory
- Reduction of spoilage/obsolescence

Sales can be increased through:

- Reduction of out-of-stocks
- Greater responsiveness to the customer

These categories of benefit creation could be individually applied anywhere within a supply chain, although there are few if any means of deciding how to divide global benefits among supply chain partners in proportion to infrastructure investment. The eventual wide-scale deployment of Auto-ID will likely depend on working out the details of how to share benefits and investments in a multi-tiered situation.

Though there are few concrete examples to demonstrate financial evaluation techniques for Auto-ID, some leading companies have undertaken early attempts to establish robust methods for financial analysis. In the absence of a universally accepted conceptual model to calculate Auto-ID ROI, the case study approach provides the best short term means to gain insight about this difficult problem.

The next section provides a brief background summary of Dell Corporation that will set the stage for a case study discussion involving the calculation of the ROI for Auto-ID based on specific business processes within the company.

The Dell Corporation

Starting with $1,000 in capitalization [38], Dell Corporation has built a computer business that has achieved $50 billion in revenue within 21 years and has a present market capitalization of $100 billion [38]. This growth has occurred without acquisitions or mergers. An important aspect of this success has been something called the direct business model, originally put into practice by Dell starting in 1984.

By bypassing the dealer channel, Dell managed to sell directly to the customer and build computers to order. This eliminated the re-sellers' markup along with the costs and risks of carrying large inventories of finished goods. The direct business model has given Dell a substantial cost advantage and the ability to obtain valuable direct information from customers [22].

In essence, the underlying key to the direct business model is Dell's insight on how to integrate different approaches such as customer focus, supplier partnerships, mass customization, and just-in-time manufacturing, into a unified whole. This insight enables "coordination across company boundaries to achieve new levels of efficiency and productivity, as well as extraordinary returns to investors [22]."

However, other attributes of the company beyond the direct business model also contribute to its success. The company has a cultural tradition that emphasizes day-to-day execution and consistency along with a strong bias toward action and decision-making based on data. There also exists a tradition of innovation in the details of daily operations. This emphasis has proven effective for Dell in terms of cost control and cash flow. In the words of the CEO Kevin Rollins, “we challenge our people to substitute ingenuity for investment [38].

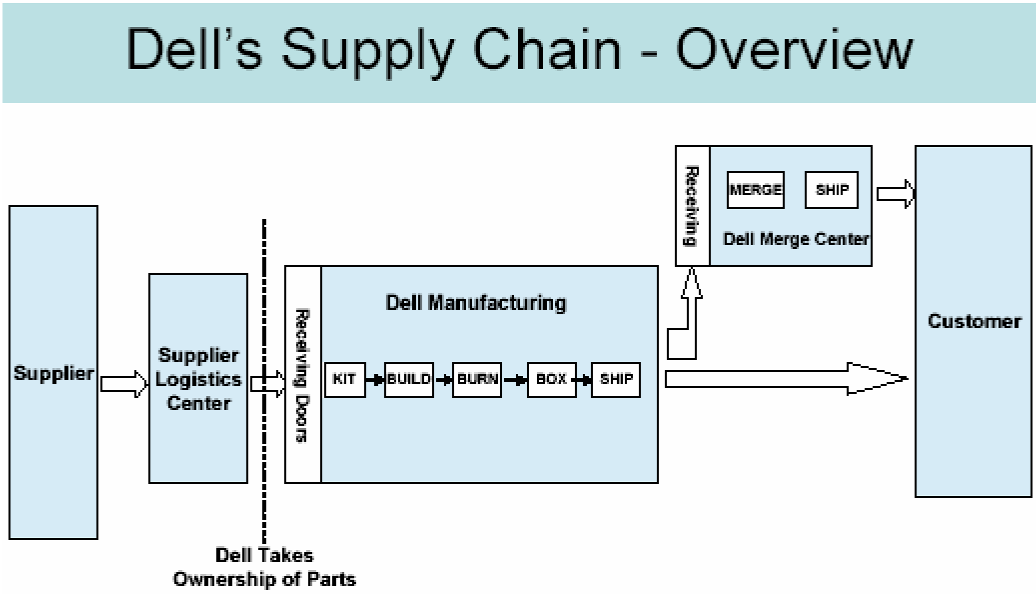
With this culture, new technologies such as Auto-ID must pass a rigorous test to win acceptance within the company. “We're very risk averse,” states Rollins [38]**.** He adds, “Occasionally our managers develop emotional connections to businesses that they really want to drive. But we make them prove the opportunity to us, and if we're not convinced, we don't move forward. We avoid areas where it's not clear we can be successful [38].” In this case, “proof” means a plausible financial analysis based on hard savings. Dell makes few decisions based on qualitative assessments or gut feel.

The Auto-ID Scorecard

The Dell supply chain is unique in that it supports an assemble to order inventory strategy that entails high though-put volume and short lead times. Previously, most assemble to order inventory strategies involved low volume and long lead times. Typical examples included the automotive industry [36].

FIGURE 15-1 shows a diagram of the Dell supply chain from beginning to end. Suppliers stock parts in logistics centers located close to Dell assembly plants. The plants assemble computers as needed to fulfill orders placed directly from customers. After assembly, the computers are shipped to the Dell Merge Center where other components, such as monitors or peripherals, are combined to form a complete order. This represents a merge in transit capability that is considered among the most advanced in American manufacturing [38]. Once all of the components are merged, the final product is shipped to customers.

Figure 3 – Dell's Supply Chain



Taking insight from various efforts to evaluate corporate balance sheets and supply chain costs [38], Dell has designed a scorecard approach for the financial analysis of Auto-ID applications within its supply chain (See FIGURE 15-2).

Figure 4 – Radio Frequency Identification Scorecard

Benefits

Characteristics of the Affected Process	**Current Situation?**
Labor Intensive Process	A
High Rate of Errors	D
Ineffective Optical Scanning	D
Benefits	**Will Imp. Allow You To?**
Reduce Labor	A
Reduce Errors	A
Reduce Inventory	D

Cost

Implementation Complexity	**Will Imp. Be?**
In a Limited Footprint	A
On a Limited Number of Products	A
Within One Company	D
Operational Expense	**Will You?**
Be Able to Share Investment Cost	A
Tag a Reusable Asset	N/A
Tag at the Pallet/Case Level	A
Avoid Item-Level Tagging	N/A

Future

Longer Term Considerations	**Does Imp. Lead To?**
A Scaleable, Repeatable Solution	A
Increased Visibility	A
Increased Velocity	A

Advantage	10
Disadvantage	4

Advantage (A) – The application of Auto-ID is an advantage over an existing business process
Disadvantage (D) – The Application of Auto-ID will not improve an existing business process

The scorecard is a simple set of critical questions designed to assess if a particular Auto-ID application is worth pursuing. In the case of Dell, each question is weighted to reflect the importance and strategic direction that management wants to promote. After completion of the scorecard for each business process, all of the scorecards are gathered together and evaluated relative to each other. This provides a simple yet effective method to screen business processes for the best candidates. Once a subset of high potential candidates are identified, detailed financial analysis is conducted. Using this approach, Dell is able to screen a number of businesses quickly, focusing only on the best candidates for detailed analysis of hard savings.

FIGURE 15-2 shows an example for a high potential Auto-ID application (Business Process A) at Dell. This simple analysis identifies the current state of a business process and the potential benefit if Auto-ID were employed. The intent is to identify situations subject to high rates of error and that are labor intensive in terms of tracking and tracing. Applying Auto-ID in these situations will give Dell a higher payback.

The example detailed in FIGURE 15-2 shows a situation where it makes sense to proceed with detailed analysis of Auto-ID. An advantage score of 10 and disadvantage score of 4 indicates application potential. Dell has applied the scorecard to the following business processes: tracking totes and trays within plant operations (assembly); tracking notebook computers from manufacture in Asia to delivery in the US; and tracking the inbound delivery of microprocessors to domestic manufacturing plants; other business processes.

In most of these cases, the score is 8 advantage, 5 disadvantage. All business processes are evaluated and ranked using the scorecard. Those processes that rank highest are selected for further analysis. There is no specific cut-off for processes selected for further analysis and processes considered inappropriate for Auto-ID. In this way, the scorecard is a relative means of evaluation.

In addition, Dell uses the scorecard to identify areas where existing data-capture technologies such as barcodes are not working to peak performance. Since bar codes represent a means of ubiquitous identification, it is likely that Auto-ID technology, which overcomes the some of the limitations of bar codes, might prove a better alternative.

One common theme from all early Auto-ID implementation efforts is that achieving an acceptable return is difficult when application occurs on a limited scale. Being a networked based technology, there is no question that the full benefit of Auto-ID will not be achieved until all firms within a supply chain implement the technology. In this regard, implementation resembles that of a ground based telephone system. A partial network of telephone lines does improve communication; however, it is only through coast-to-coast wiring of every home that the full potential of a telephone network can be realized.

The emphasis at Dell has been to identify opportunities where acceptable returns can be achieved through limited application of Auto-ID technology. This assumes that much larger benefits will probably happen through full implementation; however, a limited project offers the opportunity to become familiar with Auto-ID technology while still achieving positive financial results in practice. Smaller projects also mean less risk. In many ways, this approach resembles experimentation needed for all innovations, with each experiment being chosen based on the likelihood of financial success.

Dell examines Auto-ID justification as it does for all new types of technology. Hard savings take precedence in making investments with particular emphasis on savings in reduced labor, fewer errors, and inventory carrying cost. Though Auto-ID technology has great potential to make significant contributions in all three of these areas, partial implementation increases the difficulty in justifying leading edge applications that in the long-run will return the greatest amount of value to Dell.

A Conservative Approach

To reduce the cost of the initial implementation, Dell has taken the approach of looking for a promising subset of the supply chain for early applications within their own operations. By narrowing the scope of application, less hardware such as readers for tags is needed and there are fewer coordination problems.

In addition, it is not possible to wire an entire distribution center or factory as a starting point for Auto-ID. Rather, Dell looks for a defined location within a facility and specific individual product flows. This enables the test to be completed with the minimum of tags and readers, thus reducing the initial hardware investment. Using this approach also diminishes the impact to ongoing operations. However, care must be taken that this does not oversimplify the issues relating to Auto-ID applications between trading partners.

As a final comment, all of the scenarios examined by Dell involve tagging at the case and pallet levels. To date, there has been no analysis of tagging finished goods shipped to customers such as home or corporate users. For the realistic future, Dell will focus on Auto-ID applications that deal with supply chain issues that include suppliers and internal plant operations rather than customer applications that might involve computers or printers.

The Business Case

Once the scorecards for each process identify the best candidates for Auto-ID technology, the next step is to do the financial analysis of the benefits and costs. At Dell, all benefits must come from hard savings including reduced labor, fewer errors, and lower inventory carrying cost.

There are many important questions to ask at this stage. How many readers are needed? What are the incremental computing requirements? How are tags applied? What software will manage the data provided through Auto-ID?

Dell has concluded that although industries have focused on the price of tags as the biggest hurdle, the largest cost is in systems integration. FIGURE 15-3 shows a *mock* payback calculation for a particular business process. In this business case, the payback was about one year.

Figure 5 – Sample Auto-ID Business Case

Benefits		
Reduce Labor	80	
Reduce Errors	75	
Reduce Inventory	0	
Total Yearly Benefit	$155	
One-Time Costs		
Hardware		
Readers	5	
Application Servers	8	
Data Storage	4	
Software		
Operating System	2	
RFID and Database Software	18	
Subtotal for Hardware and Software	$37	
Installation and Integration Services	$50	
Total One-Time Costs	$87	
Recurring Costs		
Support and Maintenance (15% of Hardware and Software costs)	$5	
Number of Cases and Pallets Per Year	100	
Cost Per Tag	$0.25	
Annual Tag Costs	$25	
Total Yearly Recurring Cost	$30	
Payback Calculation		
Yearly Return @ Stabilization (Annual Benefits Less Recurring Costs)	$125	
Installation, Integration, and Stabilization Time (Years)	0.3	years
Years to Recoup One-Time Cost (One-Time Costs/Yearly Return)	0.7	years
Payback	1.0	years

Recap

Yearly Return 155 - 30 = 125

Years to Recoup One-Time Cost 87/125 = 0.7 years

Making the Decision

After completing the scorecards and business case analysis, Dell has a structured approach for going forward that involves three options.

Go

The scorecard shows an advantage and the business case has an acceptable payback period or ROI based on capital hurdle rates. In this instance, the project is implemented immediately.

Stop

The scorecard shows no advantage over existing processes in the application of Auto-ID technology. The project is stopped.

Hold

In the situation where the scorecard shows an advantage but the business case does not quite show returns that meet corporate objectives, the project is put on hold pending further developments. As costs change, it might become feasible to go forward with the project. For example, the mandates for Auto-ID technology from Wal-Mart, the Department of Defense and the Food and Drug Administration will drive greater production of tags, readers, software and systems integration. The increased volume of activity will result in economies of scale and more intense competition among vendors. In addition, technology performance will improve over time.

For most situations at Dell, Auto-ID technology currently falls into the category of hold. This is the case because the calculations for justification depend entirely on hard savings. Since Dell has already invested billions of dollars to develop business processes that are state of the art, especially in the area of minimizing inventory, it is often hard to find overwhelming savings from Auto-ID that justifies immediate implementation. However, this could all change in a relatively short period as the costs of Auto-ID technology decrease.

The greater value Auto-ID technology may be in the realm of customer service. It is very difficult to measure these benefits directly, however every business knows that when done right customer service is a factor in long-term sales growth. Being able to track and trace parts by serial number, calculate the reliability of critical components such as hard drives, and deliver service by treating each computer sale as a unique event offers great benefit to customers. This type of capability also offers differentiation from competitors who have not yet developed methods to treat each customer as a unique entity.

CONCLUSION

The underlying aspects of Auto-ID technology will form the bedrock for international commerce in the years to come. Unique identification, interoperability, standards, and automated Internet based systems to track, trace, and control physical objects all are important elements of Auto-ID technology that are moving out of the laboratory and into practical application. There will be new applications that can only be dreamed about today, and other applications that are beyond what currently can be conceptualized. Though there is a long road to full implementation of Auto-ID technology in business, the merging of data with physical objects opens so many new opportunities that it is important for all firms to plan for future operations by learning as much as possible about Auto-ID.

REFERENCES

1. Allen, Stuart J. and Edmund W. Schuster. "Practical Production Scheduling with Capacity Constraints and Dynamic Demand: Family Planning and Disaggregation." *Production and Inventory Management Journal* 35:4, 1994.

2. Allen, Stuart J., Jack L. Martin, and Edmund W. Schuster. "A Simple Method for the Multi-item, Single-level, Capacitated Scheduling Problem with Set-up Times and Costs." *Production and Inventory Management Journal* 38:4, 1997.

3. Allen, Stuart J. and Edmund W. Schuster. "Controlling the Risk for an Agricultural Harvest." *Manufacturing & Service Operations Management* 6:3, 2004.

4. *APICS Dictionary*. Published by the American Production and Inventory Control Society, Alexandria, VA, 2004.

5. Bacheldor, Beth. "RFID Investment Will Grow, But ROI Will Take Time." *InformationWeek*, May 17, 2004.

6. Billington, Peter J., John O. McClain, and L. Joseph Thomas. "Mathematical Programming Approaches To Capacity-Constrained MRP Systems: Review, Formulation and Problem Reduction." *Management Science* 29:10, 1983.

7. Bostwick, Peter. "Method and System for Creating ,Sustaining and Using a Transactional Bill of Materials (TBOM)." *U.S. Patent Office*: Washington, D.C. Patent Pending, 2004.

8. Brock, David L. "The Data Project – Technologies, Infrastructure and Standards for Distributed Interoperable Modeling and Simulation." *MIT Data Project Workshop*, 2003.

9. Dinning, Mark and Edmund W. Schuster. "Fighting Friction." *APICS – The Performance Advantage* 13:2, 2003.

10. D'Itri, Michael P., Stuart J. Allen, and Edmund W. Schuster. "Capacitated Scheduling of Multiple Products on a Single Processor with Sequence Dependencies." *Production and Inventory Management Journal* 40:5, 1999.

11. Engels Daniel W., Robin Koh, Elaine Lai, and Edmund W. Schuster. "Improving Visibility in the DOD Supply Chain." *Army Logistician* 36:3, 2004.

12. Gardner, W. David. "Analyst: Wal-Mart's RFID Suppliers Are Resisting." *TechWeb News*, Dec. 21, 2004.

13. Haberman, A.L. General Editor. 2001. *Twenty-Five Years Behind Bars*. Harvard University Press, 2001.

14. Hadow, Robert. "The Math Behind RFID in Logistics." *RFID Journal*, January 31, 2005.

15. Hoppe, Richard. "Outlining a Future of Supply Chain Management - Coordinated Supply Networks." unpublished thesis, Massachusetts Institute of Technology, 2001.

16. Kar, Pinaki, Ming Li and Edmund W. Schuster. "A Case Study of Computer Service Parts Inventory Management," Service Parts Resource Guide (1st Edition). American Production and Inventory Control Society, 2003.

17. Koh, Robin, Edmund W. Schuster, Indy Chackrabarti, and Attilio Bellman. "Securing the Pharmaceutical Supply Chain." *The MIT Auto-ID Center,* 2003.

18. Koh, Robin, Edmund W. Schuster, Nhat-So Lam and Mark Dinning. "Prediction, Detection and Proof: An Integrated Auto-ID Solution to Retail Theft." *The MIT Auto-ID Center*, 2003.

19. Laubacher, Robert, S. P. Kothari, Thomas W. Malone, Brian Subirana. "What is RFID Worth to your Company? Measuring Performance at the Activity Level." *MIT Sloan School of Management*, 2005.

20. Leachman, Robert C., Robert C. Benson, Chihwei Liu, and Dale J. Raar. "IMPReSS: An Automated Production-Planning and Delivery-Quotation System at Harris Corporation-Semiconductor Sector." *Interfaces* 26:1, 1996.

21. Lee, Hau L. "Creating Value Through Supply Chain Integration." *Supply Chain Management Review*, September 1, 2000.

22. Magretta, Joan. "The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell." *Harvard Business Review*, March-April, 1998.

23. Malykhina, Elena. "RFID's Payback Stretches Beyond 2 Years." *InformationWeek*, October 29, 2004.

24. McGee, Ken. "Give Me That Real-Time Information," *Harvard Business Review* 82:4, 2004.

25. Miles, R.H. *Macro Organizational Behavior*. Scott, Foresman and Company, 1980.

26. Nahmias, Steven. *Production and Operations Analysis*. Irwin, 1993.

27. Rice, James B. and Richard M. Hoppe. "Supply Chain vs Supply Chain: The Hype & The Reality." *Supply Chain Management Review*, September/October, 2001.

28. Sabath, Robert, Chad W. Autry, and Patricia J. Daugherty. "Automatic Replenishment Programs: The Impact of Organizational Structures." *Journal of Business Logistics* 22:1, 2001.

29. Sarma, Sanjay. "Towards the 5¢Tag." *MIT Auto-ID Center*, 2001.

30. Schuster, Edmund W. and Byron J. Finch. "A Deterministic Spreadsheet Simulation Model for Production Scheduling in a Lumpy Demand Environment." *Production and Inventory Management Journal* 31:1, 1990.

31. Schuster, E.W. and Allen, S.J. 1998. "Raw Material Management at Welch's." *Interfaces* 28:5, 1998.

32. Schuster, Edmund W., Stuart J. Allen, and Michael P. D'Itri. "Capacitated Materials Requirements Planning and its Application in the Process Industries." *Journal of Business Logistics* 21:1, 2000.

33. Schuster, Edmund W. and Robin Koh. "To Track and Trace." *APICS – The Performance Advantage* 14:2, 2004.

34. Schuster, Edmund W., Stuart J. Allen. *Raising the Bar (Code): The Value of Auto-ID Technology*. Thomson South-Western Educational Publishing, forthcoming.

35. Schuster, Edmund W., David L. Brock, Stuart J. Allen, Pinaki Kar, and Mark Dinning, 2005. "Enabling ERP through Auto-ID Technology." *Strategic ERP Extension and Use*. Edited by F. Robert Jacobs and Elliot Bendoly, Stanford University Press, 2005.

36. Sennechael, Denis and Iain MaClean. "Car Sequencing Challenge at a Nissan Plant Calls for Complex Scheduling." *APICS – The Performance Advantage*, March, 2001.

37. Simchi-Levi, David, Philip Kaminsky, and Edith Simchi-Levi. *Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies.* Irwin McGraw-Hill, 2000.

38. Stewart, Thomas A. and Louise O'Brien. "Execution Without Excuses: The HBR Interview, Michael Dell and Kevin Rollins." *Harvard Business Review*, March, 2005.

39. Taylor, S.G. and Bolander, S.F. *Process Flow Scheduling: A Scheduling Systems Framework for Flow Manufacturing*. American Production and Inventory Control Society, 1994.

40. Unahabhokha, Chatchai, Edmund W. Schuster, Stuart J. Allen. "Master Production Schedule Stability under Conditions of Finite Capacity." Working Paper, 2003.