
Vernon L. Trevathan

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Where Potential Meets Performance
25.1 Introduction

Automation does not end with equipment control; it also includes higher levels of control that manage personnel, equipment, and materials across production areas. Effectiveness in manufacturing companies is not based solely on equipment control capability. Manufacturing companies must also be efficient at coordinating and controlling personnel, materials, and equipment across different control systems in order to reach their maximum potential. This is usually accomplished using software systems and documented procedures that are collectively called the “manufacturing execution system (MES)” layer. MES defines a diverse set of functions that operate above automation control systems, reside below the level of enterprise business systems, and are local to a site or area. This chapter explains the functions of the MES layer and how these functions integrate with other corporate business systems.

The ANSI/ISA-95.00.03-2005 - Enterprise-Control System Integration, Part 3: Models of Manufacturing Operations Management standard defines 5 levels of activities in a manufacturing organization. Automation and control supports one level and MES supports a higher level, as shown in Figure 25-1.
Level 0 defines the actual physical processes.

Level 1 defines the activities involved in sensing and manipulating the physical processes. Level 1 elements are the sensors and actuators attached to the control functions in automation systems.

Level 2 defines the activities of monitoring and controlling the physical processes and in automated systems this includes equipment control and equipment monitoring. Level 2 automation and control systems have real-time responses measured in subseconds and are typically implemented on programmable logic controllers (PLC), distributed control systems (DCS), and open control systems (OCS).

Level 3 defines the activities that coordinate production resources to produce the desired end products. It includes, work-flow “control” and procedural “control” through recipe execution. Level 3 typically operates on time frames of days, shifts, hours, minutes, and seconds. Level 3 functions also include maintenance functions, quality assurance and laboratory functions, and inventory movement functions, and are collectively called Manufacturing Operations Management. Level 3 functions directly related to production are usually automated using manufacturing execution systems (MES).

Level 4 defines business-related activities that manage a manufacturing organization. Manufacturing-related activities include establishing the basic plant schedule (such as material use, delivery, and shipping), determining inventory levels, logistics “control,” and material inventory “control” (making sure materials are delivered on time to the right place for production). Level 4 is called Business Planning and Logistics. Level 4 typically operates on time frames of months, weeks, days.

Figure 25-1: Activity Hierarchy in a Manufacturing Company

<table>
<thead>
<tr>
<th>Level 0 Physical Process</th>
<th>0 - The actual production process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 Sensing and Manipulating</td>
<td>1 - Sensing the production process, manipulating the production process</td>
</tr>
<tr>
<td>Level 2 Automation and Control</td>
<td>2 - Monitoring, supervisory control and automated control of the production process</td>
</tr>
<tr>
<td>Level 3 Manufacturing Operations Management</td>
<td>3 - Work flow / recipe control to produce the desired end products. Maintaining records and optimizing the production process</td>
</tr>
<tr>
<td>Level 4 Business Planning and Logistics</td>
<td>4 - Establishing the basic plant schedule - production, material use, delivery, and shipping. Determining inventory levels</td>
</tr>
</tbody>
</table>

| Time Frame | Months, weeks, days |
| Time Frame | Days, Shifts, hours, minutes, seconds |

Time Frame | Hours, minutes, seconds, subseconds|
| Time Frame | Days, Shifts, hours, minutes, seconds |
frames of months, weeks, and days. Enterprise resource planning (ERP) logistics systems are used to automate Level 4 functions.

It is important to remember that each level has some form of control and each level has its own definition for real-time. Level 3 systems consider real-time to mean information available a few seconds after shop floor events occur. Level 4 systems consider real-time to mean logistics and material information is available daily or within a few hours after the end of a shift.

25.2 MES Integration with Business Planning and Logistics

The ANSI/ISA-95.00.01-2000 - Enterprise-Control System Integration Part 1: Models and Terminology and ANSI/ISA-95.00.02-2001 - Enterprise-Control System Integration Part 2: Object Model Attributes standards define terminology to be used for interfaces between Level 3 systems and Level 4 systems. This information is used to direct production activities and to report on production.

Formal data models for exchanged information include:

**Personnel Class, Person, and Qualification Test Information** – This is the definition of the persons and personnel classes (roles) involved in production. This information may be used to associate production with specific persons as part of a production record, or with personnel classes to allocate production costs.

**Equipment Class, Equipment, and Capability Test Information** – This is the definition of the equipment and equipment classes involved in production. This information may be used to associate production with specific equipment as part of a production record, or with equipment classes to schedule production and allocate costs.

**Material Class, Material Definition, Material Lot, Material Sublot, and QA Test Information** – This is the definition of the lots, sublots, material definitions, and material classes involved in production. This information allows Level 3 and Level 4 systems to unambiguously identify material specified in production schedules and consumed or produced in actual production.

**Process Segment Information** – This is the definition of the business views of production, based on Level 4 business processes that must send information to production, or receive information from production. Examples include: setup segments, inspection segments, production segments, and cleanup segments.

**Product Definition Information** – This is the definition of the materials, equipment, personnel, and instructions it takes to make a product. This includes the Manufacturing Bill (a subset of the Bill of Material [BOM] that contains the quantity and type of material required for producing a product). It also includes product segments, which define the routing and specific resources required at each segment of production.

**Production Capability Information** – This is the definition of the capability and capacities available from production for current and future periods of time. Capability and capacity information is required for both Level 4 scheduling and Level 3 detailed production scheduling.

**Production Schedule Information** – This specifies what products are to be made. It may include the definition of the specific personnel or roles to be used, equipment or equipment classes to be used, material lots or material classes to be produced, and material lots or material classes to be consumed for each segment of production.

**Production Performance Information** – This specifies what was actually produced. It may include the definition of the actual personnel or personnel classes used, the actual equipment or equipment classes used, the actual material lots and quantities consumed, and the actual material lots and quantities produced for each segment of production.
25.3 Level 3 Equipment Hierarchy

Figure 25-2 shows the equipment and organizational hierarchy defined in the ANSI/ISA-95.00.03-2005 - Enterprise-Control System Integration, Part 3: Models of Manufacturing Operations Management standard. Level 4 ERP Logistics systems will typically coordinate and manage the entire enterprise and sites within the enterprise, but it may also schedule to the area or work center level. Level 3 MES systems will typically coordinate and schedule areas, work centers, and work units.

The equipment hierarchy is an expansion of the equipment hierarchy defined in the ANSI/ISA-88.01-1995 batch control standard to include equipment types used in continuous production, discrete production, and inventory storage and movement. The equipment hierarchy provides a standard naming convention for the organization of equipment, automation control, and manual control.

25.4 MES and Production Operations Management

Figure 25-3 illustrates the different Level 3 production-oriented functions that take place in sites and areas. Each bubble in the figure represents a collection of activities that occur in a production facility as a production schedule is converted into actual production. It illustrates how production requirements from the business are used to coordinate and control plant floor activity. The top four arrows identify previously defined information that is exchanged with business logistics systems.

The production model is driven by production schedules developed by the business and sent to production. The production schedules are used by detailed production scheduling activities that define detailed production schedules containing production work orders. The production work orders are dispatched to work centers and work units based on time and events, the production work order is executed and data is collected in a production data collection activity. (Note: In batch systems a control recipe is the equivalent of a production work order.)

The collected data is used in production tracking activities that relate the time-series information to the work order information to generate a report on production performance and tracing and tracking.
information. The collected data and the data from tracing and tracking is used in production analysis functions to generate reports and KPIs (Key Performance Indicators). Production capability information about the current and future availability is provided to business scheduling systems by production resource management activities. Product definition information about the recipe, procedures, Bill of Material (BOM), and work routing needed for production is managed by product definition management activities.

25.5 Detailed Production Scheduling

These are the activities in a facility that take a production schedule and use information about local resources to generate a detailed production schedule. This can be an automated process, but in many plants scheduling is done manually by expert production planners or production planning staff. Automated systems are sometime referred to as plant level advanced planning and optimization systems. The key element of this activity is detailed scheduling of work assignments and material flows to a finer level of granularity than the business schedule. While Level 4 schedules may schedule work assignments to areas and work centers, detailed production scheduling will schedule work assignments to work centers and work units.

25.5.1 Production Dispatching

Once a detailed production schedule is available, that schedule is dispatched to production lines, process cells, production units, and storage zones. This can take the form of supervisors receiving daily schedules and dispatching work to technicians, or automated systems performing campaign management of batches and production runs. Production dispatching includes handling conditions not anticipated in the detailed production schedule. This may involve judgment in managing workflow and
buffers. Unanticipated conditions may have to be communicated to maintenance operations management, quality operations management, and/or inventory operations management. This is one of the core functions of an MES.

25.5.2 Production Execution Management
Production execution management activities receive the dispatched work requests and, using paper based systems, MES systems, or recipe execution systems, coordinate and control the actual work execution. This may include the execution of procedural logic in recipes and display of work flow instructions to operators. The activities include selecting, starting, and moving units of work (such as a batch or production run) through the appropriate sequence of operations to physically produce the product. The actual equipment control is part of the Level 2 functions. Production execution management is one of the core functions of an MES system, but it may also be performed by recipe or manual work flow instruction systems in DCS systems or batch execution systems. The standards for information flows from Level 3 to Level 2 are defined in the ANSI/ISA-88.01-1995, OPC, and Fieldbus standards.

25.5.3 Production Data Collection
Production data collection are the activities that gather, compile, and manage production data for specific units of work (batches or production runs). Manufacturing control systems generally deal with process information such as quantities (weight, units, etc.), properties (rates, temperatures, etc.), and equipment information such as controller, sensor, and actuator statuses. Collected production data includes sensor readings, equipment states, event data, operator-entered data, transaction data, operator actions, messages, calculation results from models, and other data of importance in the making of a product. The collected data is inherently time or event based, with time or event data added to give context to the collected information. This information is usually made available to various analysis activities, including product analysis, production analysis, and process analysis. Real-time data historians and automated batch record logging systems support this activity.

25.5.4 Production Tracking
The production tracking activities convert sensor and equipment data into information related to assigned work (batches and production runs), and into tracking information about equipment, material, and personnel used in production. Production tracking also merges and summarizes information that is reported back to the business activities. This is one of the core functions of an MES. When automated systems are used they usually link to data historians and batch record logging systems.

25.5.5 Production Resource Management
The resource management activities monitor the availability of personnel, material, and equipment production resources. This information is used by detailed production scheduling and business logistics planning. These activities take into account the current and future predicted availability, using information such as planned maintenance and vacation schedules, in addition to material order status and delivery dates. This activity may also include material reordering functions, such as Kanban. Kanban is a material management system used as part of just-in-time production operations where components and sub-assemblies are produced, based upon notification of demand from a subsequent operation. A Japanese word for “sign,” Kanbans are typically a re-order card or other method of triggering new production of material based on actual usage.

Resource management is usually a mixed operation, with manual work, automation, and database management. Management of the resources may include local resource reservation systems, and there may be separate reservation systems for each type of managed resource (personnel, equipment, and material). This is one of the core functions of an MES.

25.5.6 Product Definition Management
Product definition management includes activities associated with the management of product definitions. These may be recipes, work instructions, assembly instructions, standard operating procedures,
and other information used by production to make or assemble products. This is one of the core functions of an MES.

25.5.7 Production Performance Analysis
The activities associated with the analysis of production, process, and product are defined as production performance analysis. These are usually off-line activities that look for ways to improve processes through chemical or physical simulation, analysis of good and bad production runs, and analysis of delays and bottlenecks in production. Production performance analysis also includes calculating performance indicators, leading, and trailing predictors of behavior. These activities generally are major users of information collected in plant data historians. There are often separate tools for production, process, and product analysis, and the tool sets vary based on the type of production (continuous, discrete, or batch).

25.6 Other Manufacturing Activities
The above list does not define all of the activities of a production facility. There are also maintenance operations management activities, quality operations management activities, and inventory operations management activities.

Maintenance Operations Management – The activities that coordinate, direct, and track the functions that maintain the equipment, tools and related assets to ensure their availability for manufacturing.

Quality Operations Management – The activities that coordinate, direct, and track the functions that measure and report on quality. The broad scope of quality operations management includes both quality operations and the management of those operations to ensure the quality of intermediate and final products.

Inventory Operations Management – The activities that coordinate, direct, and track the functions that transfer of materials between and within work centers and manage information about material locations and statuses.

Manufacturing operations also require infrastructure activities that may be specific to manufacturing, but which are often elements also required by other parts of a manufacturing company. The infrastructure activities include:

a) Managing security within manufacturing operations
b) Managing information within manufacturing operations
c) Managing configurations within manufacturing operations
d) Managing documents within manufacturing operations
e) Managing regulatory compliance within manufacturing operations
f) Managing incidents and deviations

25.7 Level 3-4 Boundary
There are four rules which can be applied to determine if an activity should be managed as part of Level 4 or as part of Levels 3, 2, or 1. An activity should be managed at a Level 3 or below if the activity is directly involved in manufacturing, includes information about personnel, equipment, or material, and meets any of the following conditions:

a) The activity is critical to plant safety.
b) The activity is critical to plant reliability.
c) The activity is critical to plant efficiency.
d) The activity is critical to product quality.
e) The activity is critical to maintaining product or environmental regulatory compliance.

**Note:** This includes such factors as safety, environmental, and cGMP (current good manufacturing practices) compliance.

This means, in some cases, the Level 3 activities defined above may be performed as part of logistics instead of operations. Typically, this involves detailed production scheduling and production dispatching. The scope of an MES system is determined by applying the above rules to each site or area within a site.

### 25.8 References


#### 25.8.1 Practical References


### About the Author

**Dennis Brandl** is the chief consultant for BR&L Consulting, specializing in Manufacturing IT applications, including business-to-manufacturing integration, MES solutions, general, and site recipe implementations, and automation system security. He has been involved in automation system design and implementation in a wide range of applications over the past 25 years. They have included biotech, pharmaceutical, chemical plants and oil refineries, food manufacturing, consumer packaged goods, PLC-based systems, and batch control systems. He is an active member of ISA's SP95 Enterprise/Control System Integration Committee and is editor of the set of SP95 standards. He has a BS in Physics and an MS in Measurement and Control from Carnegie-Mellon University, and an MS in Computer Science from California State University.
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Maintenance, Long-Term Support and System Management

By Joseph D. Patton, Jr.

Topic Highlights

Maintenance Is Big Business
Service Technicians
Big Picture View
   No Need Is Best
   Evolution of Maintenance
Automatic Analysis of Device Performance
Production Losses from Equipment Malfunction
Performance Metrics and Benchmarks

34.1 Maintenance Is Big Business

Maintenance is a challenging mix of art and science, where both economics and emotions have roles. Please note that serviceability and supportability parallel maintainability, and maintenance and service are similar for our purposes. Maintainability (i.e., serviceability or supportability) is the discipline of designing and producing equipment so it can be maintained. Maintenance and service are performing all actions necessary to restore durable equipment to, or keep it in, specified operation condition.

The very word “durable” means the equipment is intended for long life and must therefore be maintained. For the military, a tightening budget coupled with increasing operating and support costs and a drive toward high-technology equipment, means more effort must be invested in maintaining available equipment. A similar situation is occurring in commerce and industry. It is encouraging to note business people in both civilian and government enterprises are paying more attention to life-cycle costs and are at least talking about making the investment required for front-end reliability and maintainability in order to improve system availability and reduce maintenance, repair, operating (MRO) and overall costs.

Organizations that design, produce, and support their own equipment, often on lease, have a vested interest in good maintainability. On the other hand, many companies, especially those with sophisticated high-technology products, have either gone bankrupt or sold out to a larger corporation when they became unable to maintain their creations. Then, of course, there are many organizations such as automobile service centers, TV repair shops, and most factory maintenance departments that have little, if any, say in the design of equipment they will later be called on to support. While the power of these dealers is somewhat limited by their inability to do more than refuse to carry the product line, their complaints generally result in at least modifications and improvements to the next generation of products.
Maintenance is big business. Gartner estimates hardware maintenance and support is $120B per year and growing 5.36% annually. The 10 largest petrochemical producers together spend over $15 billion annually on maintenance, which averages 4.3% of their expected replacement costs. US Bancorp estimates that spending on spare parts is $700B in the U.S.A. alone, which is 8% of gross domestic product.

### 34.2 Service Technicians

Typically, maintenance people once had extensive experience with fixing things and were oriented toward repair instead of preventive maintenance. In the past many technicians were not accustomed to using external information to guide their work. Maintenance mechanics or technicians often focused on specific equipment, usually at a single facility, which limited the broader perspective developed from working with similar situations at many other installations.

Today, service technicians are also called field engineers (FEs), customer engineers (CEs), customer service engineers (CSEs), customer service representatives (CSRs), and similar titles. This document will use the terms “technicians” or “techs.” In a sense, service technicians must “fix” both equipment and customer employees. There are many situations today where technicians can solve problems over the telephone by having a cooperative customer download a software patch or perform an adjustment. However, about half of customer calls for service result in a technician traveling to the site, and roughly half of those visits will involve at least one part replacement.

Service can be used both to protect and to promote. Protective service ensures that equipment and all company assets are well maintained and give the best performance of which they are capable. Protective maintenance goals for a technician may include the following:

- Install equipment properly
- Teach the customer how to use the equipment capability effectively
- Provide functions that customers are unable to supply themselves
- Maintain quality on installed equipment
- Gain experience on servicing needs
- Investigate customer problems and rapidly solve them to the customer’s satisfaction
- Preserve the end value of the product and extend its useful life
- Observe competitive activity
- Gain technical feedback to correct problems

Service techs are becoming company representatives who emphasize customer contact skills, instead of being solely technical experts. In addition, the business of maintenance service is becoming much more dependent on having the correct part. A concurrent trend is customer demand and service level agreements (SLAs) that require fast restoration of equipment to good operating condition. This is especially true with computer servers, communications equipment, medical scanners, sophisticated manufacturing devices, and similar equipment that affects many people or even threatens lives when it fails.

In focusing on completing a given job, most technicians prefer to take a part right away, get equipment up and running, and enter the related data later. Returning defective or excess parts may be a lower priority, and techs may cache personal supplies of parts if company supply is unreliable. However, there are many situations where on-the-site, real-time data entry and validation are vital to gaining accurate information for future improvement. As a result, a challenge of maintenance management is to develop technology that stimulates and supports maintenance realities.
34.3 Big Picture View

Enterprise asset management (EAM) is a current buzzword for the big picture. There are good software applications available to help manage MRO activities. However, most data is concentrated on a single facility and even to single points in time, rather than covering the life cycle of equipment and facilities. As Figure 34-1 illustrates, the initial cost of equipment is probably far exceeded by the cost to keep it operating and productive over its life cycle. Many maintenance events occur so infrequently in a facility that years must pass before enough data is available to determine trends and, by then, the equipment is probably obsolete or at least changed. Looking at a larger group of facilities and equipment leads to more data points and more rapid detection of trends and formation of solutions.

Interfacing computerized information on failure rates and repair histories with human resources (HR) information on technician skill levels and availability, pending engineering changes, procurement parts availability, production schedules, and financial impacts can greatly improve guidance to maintenance operations. Then, if we can involve all plants of a corporation, or even all similar products used by other companies, the populations become large enough to provide effective, timely information. Optimizing the three major maintenance components of people, parts, and information, shown in Figure 34-2, are all important to achieving that end.

Historically, the two main maintenance costs have been labor and materials (people and parts). Labor costs are increasing. This means organizations must give priority efforts to reducing frequency, time, and skill level and thereby the cost of labor. The costs of parts are also increasing. A specific capability probably costs less, but integrating multiple part capabilities into a single part brings high costs and more critical need for the replaceable costs. A third leg is becoming important to product development and support: information as generally provided by software on computer and communications systems. Digital electronic and optical technologies are measurably increasing equipment capabilities while reducing both costs and failure rates. Achieving that reduction is vital. Results are seen in the fact that a service technician, who a few years ago could support about 100 personal computers, can now support several thousand. Major gains can be made in relating economic improvements to maintainability efforts. Data has been gathered showing a payoff of 50:1; that is a benefit of $50 prevention value for each $1 invested in maintainability.

34.3.1 No Need Is Best

Everything will fail sometime—electrical, electronic, hydraulic, mechanical, nuclear, optical, and especially biological systems. People spend considerable effort, money, and time trying to fix things faster.
Figure 34-2: The Three Legs of Support Are People, Parts, and Information

However, the best answer is to avoid having to make a repair at all. To quote Ben Franklin, “An ounce of prevention is worth a pound of cure.” The failure-free item that never wears out has yet to be produced. Perhaps some day it will be, but meanwhile we must replace burned-out light bulbs, repair punctured car tires, overhaul jet engines, and correct elusive electronic discrepancies in computers.

A desirable long-range life-cycle objective is to achieve very low equipment failure rates and require replacement of only consumables and the parts that wear during extended use, which can be replaced on a condition-monitored predictive basis. Reliability (R) and maintainability (M) interact to form availability (A), which may be defined as the probability that equipment will be in operating condition at any point in time. Three main types of availability are inherent availability, achieved availability, and operational availability. Service management is not particularly interested in inherent availability, which assumes an ideal support environment without any preventive maintenance, logistics, or administrative downtime. In other words, inherent availability is the pure laboratory availability as viewed by design engineering. Achieved availability also assumes an ideal support environment with everything available. Operational availability is what counts in the maintenance tech’s mind, since it considers a “real world” operating environment.

The most important parameter is failure rate, as a product needs corrective action only if it fails. The main service objective for reliability is mean time between failure (MTBF), with “time” stated in the units most meaningful for the product. Those units could include:

- **Time:** hours, days, weeks, etc.
- **Distance:** miles, kilometers, knots, etc.
- **Events:** cycles, gallons, impressions, landings, etc.

It is important to realize equipment failures caused by customer use should be anticipated in the design. Coffee spilling in a keyboard, a necklace dropping into a printer, and panicked pushing of buttons by frustrated users add more calls for help. Operating concerns by inexperienced users often result in more than half the calls to a service organization. What the customer perceives as a failure may vary from technical definitions, but customer concerns must still be addressed by the business.

For operations where downtime is not critical, the need for a highly responsive maintenance organization is not critical. However, for manufacturing operations where the process performance is directly related to the performance of the automation systems, or any other part of the process, downtime can...
be directly related to the revenue-generation potential of the plant. Under these conditions, response time represents revenue to the plant itself. Thus, plants that would have revenue generation capacity of $10,000 worth of product per hour, operating in a 24-hour day, seven-day week environment, would be losing approximately $240,000 of revenue for every day that the plant is shut down. A 24-hour response time for plants of this type would be completely unsatisfactory. On the other hand, if a manufacturing plant that operates on a batch basis has no immediate need to complete the batch because of the scheduling of other products, then a 24-hour response time may be acceptable.

A typical automobile, for example, gives more utility at lower relative cost than did cars of even a few years ago; however, it must still be maintained. Cars once required frequent spark plug changes and carburetor adjustments, but fuel injection has replaced carburetion. A simple injector cleaning eliminates the several floats, valves, and gaskets of older carburetors—with fewer failures and superior performance. Computer-related failures that used to occur weekly are now reduced to units of years.

Service level agreements (SLAs) increasingly require that equipment be restored to good operation the same day service is requested, and often specify four hours, two hours, or even faster repair. Essential equipment may cause great hardship physically and financially if it is down for long periods of time.

For example, a production line of an integrated circuit fabrication facility can lose $100,000 per hour of shutdown. A magnetic resonance induction (MRI) scanner that cannot operate costs $4,000 per hour in revenue lost and even more if human life is at risk. Failure of the central computer of a metropolitan telephone system can cause an entire city to grind to a stop until it is fixed. Fortunately, reliability and the availability (uptime) of equipment are improving, which means there are fewer failures. However, when failures do occur, the support solutions are often complex.

### 34.3.2 Evolution of Maintenance

Maintenance technology has also been rapidly changing during recent years. The idea that fixed-interval preventive maintenance is right for all equipment has given way to the reliability-based methods of on-condition and condition monitoring. The process of maintenance is illustrated in Figure 34-3.

![Figure 34-3: The Branches of Modern Maintenance](image)

Many parts are now discarded rather than being maintained at organizational or even intermediate levels. The multilevel system of maintenance is evolving into a simplified system of more user participation, local first- and second-level maintenance, and backup direct from a third party or original equipment manufacturer (OEM) service organization. Expert systems and artificial intelligence are being developed to help diagnostics and to predict the need for preventive maintenance. Parts are often supplied directly from vendors at the time of need, so maintenance organizations need not invest hard money in large stocks of parts.
34.3.3 Automatic Analysis of Device Performance

There is increased focus and resource deployment to design durable products for serviceability. Durable equipment is designed and built once, but it must be maintained for years. With design cycles of six months to three years and less, and with product lives ranging from about three years for computers through 40+ years for hospital sterilizers, alarm systems, and even some airplanes, the initial investment in maintainability will either bless or haunt an organization for many years. If a company profits by servicing equipment it produced, good design will produce high return on investment in user satisfaction, repeat sales, less burden for the service force, and increased long-term profits. In many corporations, service generates as much revenue as product sales do, and the profit from service is usually greater. Products must be designed right the first time. That is where maintainability that enables condition monitoring and on-condition maintenance becomes effective.

Instruments that measure equipment characteristics are beginning to be directly connected to the maintenance computer. Microprocessors and sensors allow vibration readings, pressure differentials, temperatures, and other nondestructive test (NDT) data to be recorded and analyzed. Presently, these readings primarily activate alarm enunciators or recorders that are individually analyzed. There are, of course, automated control systems in use today that can signal the need for more careful inspection and preventive maintenance. These devices currently are certainly cost effective for high-value equipment such as turbines and compressors. Progress is being made in this area of intelligent device management so all kinds of electrical, electronic, hydraulic, mechanical, and optical equipment can “call home” if they begin to experience deficiencies. Trend analysis for condition monitoring may be assisted by computer records.

Capabilities should also be designed into computer programs to indicate any other active work orders that should be done on equipment at the same time. Modifications, for example, can be held until other work is going to be done and can be accomplished most efficiently at the same time as the equipment is down for other maintenance activities. A variation on the same theme is to ensure emergency work orders will check to see if any preventive maintenance work orders might be done at the same time. Accomplishing all work at one period of downtime is usually more effective than doing smaller tasks on several occasions.

Products that can “call home” and identify the need to replace a degrading part before failure bring major advantages to both the customer and support organization. There are, however, economic trade-offs regarding the effort involved versus the benefit to be derived. For example, the economics may not justify extensive communication connections for such devices as smart refrigerators. However, business devices that affect multiple people need intelligent device management (IDM) with remote monitoring to alert the service function to a pending need, hopefully before equipment becomes inoperable. The ability to “know before you go” is a major help for field technicians, so they have the right part and are prepared with knowledge of what to expect.

It is important to recognize the difference between Response Time and Restore Time. Response Time is the minutes from notification that service is required until a technician arrives on the scene. Restore Time adds the minutes necessary to fix the equipment. Service contracts historically specified only Response Time, but now usually specify Restore Time. Response is action. Restore is results.

The challenge is that, to restore operation, the technician often needs a specific part. Many field replaceable units (FRUs) are expensive and not often required. Therefore, unless good diagnostics identifies the need for a specific part, techs may arrive at the customer location and then determine they need a part they do not have. Diagnostics is the most time consuming portion of a service call. Technicians going to a call with a four-hour restore requirement will often consume an hour or more to complete the present assignment and travel to the new customer. Diagnostics adds even more time, so the techs could easily consume two hours of the four available before even knowing what part is needed. Acquisitioning parts quickly then becomes very important. The value of information is increasing. Information is replacing inventory. Knowing in an accurate, timely way that a part was
used allows a company to automatically initiate resupply to the authorized stocking site, even to the extent of informing the producer who will supply the warehouse with the next required part.

An organization can fix considerable equipment the next day without undue difficulty. A required part can be delivered overnight from a central warehouse that stocks at least one of every part that may be required. Overnight transportation can be provided at relatively low cost with excellent handling, so orders shipped as late as midnight in Louisville, Ky. or Memphis, Tenn. can be delivered as early as 6:00 a.m. in major metropolitan areas. Obviously those are “best case” conditions. There are many locations around the world where a technician must travel hours in desolate country to get to the broken equipment. That technician must have all necessary parts and, therefore, will take all possible parts or acquire them en route.

Service parts is a confidence business. If technicians have confidence the system will supply the parts they need, then techs will minimize their cache of service parts. If confidence is low, techs will develop their own stock of parts, will order two parts when only one is needed, and will retain intermittent problem parts.

Parts required 24/365 can be shared through either third-party logistics companies (TPLs) or intelligent lockers instead of being carried by the several individual technicians who might provide the same coverage. Handoffs from the stock-keeping facility to the courier to the technician can be facilitated by intelligent lockers. Today, most orders are transmitted to the company warehouse or TPL location that picks and packs the ordered part for shipment and notifies the courier. Then the courier must locate the technician, who often has to drop what he or she is doing, go to meet the courier, and sign for the part. Avoid arrangements that allow the courier to leave parts at a receiving dock or reception desk, because they often disappear before the technician arrives.

Intelligent lockers can facilitate the handoff procedures at both ends of the delivery process. The receiving personnel can put parts in the intelligent locker and immediately notify the courier or technician by page, cell phone, fax, e-mail, or other method that the part is ready for pick up. The receiver can then retrieve parts at his or her convenience, and the access code provides assurance that the correct person gets the part.

A single vendor can manage one-to-many intelligent lockers to provide parts to many users. For example, Granger or The Home Depot could intelligently control sales of expensive, prone-to-shrink tools and accessories by placing these items in intelligent lockers outside their stores where the ordered items can be picked up at any hour. Public mode allows many users to place their items in intelligent lockers for access by designated purchasers. Vendors could arrange space as required so a
single courier “milk run” could deliver parts for technicians from several companies to pick up when convenient. This “controlled Automat” use is sure to excite couriers themselves, as well as entrepreneurs who could use the capability around the clock for delivery of airline tickets, laptop computer drop-off and return, equipment rental and return, and many similar activities.

Installation parts for communications networks, smart buildings, security centers, and plant instrumentation are high potential items for intelligent lockers. These cabinets can be mounted on a truck, train, or plane and located at the point of temporary need. Communications can be by wired telephone or data, and wireless cell, dedicated or pager frequencies so there are few limits on locations. Installations tend to be chaotic, without configuration management, and with parts taken but not recorded. Intelligent lockers can improve these and many other control and information shortages.

Physical control is one thing, but information control is as important. Many technicians do not like to be slowed down with administration. Part numbers, usage, transfers, and similar matters may be forgotten in the rush of helping customers. Information provided automatically by the activities involving intelligent lockers should greatly improve parts tracking, reordering, return validation, configuration management, repair planning, pickup efficiency, and invoicing.

34.4 Production Losses from Equipment Malfunction

In-plant service performance is primarily directed at supporting the plant operations. As most equipment failures in a plant represent production loss, measuring the amount of loss that results from inaccurate or improper service is a key element to measuring the service operation. Because other parameters can affect production loss, only by noting the relationship of production losses caused by equipment malfunction to production losses caused by other variables, such as operator error, poor engineering, or random failures, can a true performance of the service function be assessed. By maintaining long-term records of such data, companies can visualize the success of the service department by noting the percent of the total production loss that results from inadequate or improper service. The production loss attributable to maintenance also represents a specific performance measure of the generic element of accuracy in problem definition. Effective preventive maintenance (PM) is a fundamental support for high operational availability.

PM means all actions are intended to keep durable equipment in good operating condition and to avoid failures. New technology has improved equipment quality, reliability, and dependability by fault-tolerance, redundant components, self-adjustments, and replacement of hydraulic and mechanical components with more reliable electronic and optical operations. However, many components can still wear out, corrode, become punctured, vibrate excessively, become overheated by friction or dirt, or even be damaged by humans. For these problems, a good PM program will preclude failures, enable improved uptime, and reduce expenses.

Success is often a matter of degree. Costs in terms of money and effort to be invested now must be evaluated against future gains. This means the time-value of money must be considered along with business priorities for short-term versus long-term success. Over time, the computerized maintenance management system must gather data, which must then be analyzed to assist with accurate decisions. The proper balance between preventive and corrective maintenance that will achieve minimal downtime and costs can be tenuous.

PM can prevent failures from happening at a bad time, can sense when a failure is about to occur and fix it before it causes damage, and can often preserve capital investments by keeping equipment operating for years as well as the day it was installed. Predictive maintenance is considered here to be a branch of preventive maintenance.

Inept PM, however, can cause problems. Humans are not perfect. Whenever any equipment is touched, it is exposed to potential damage. Parts costs increase if components are replaced prematurely. Unless the PM function is presented positively, customers may perceive PM activity as, “that
machine is broken again.” A PM program requires an initial investment of time, materials, people, and money. Payoff comes later. While there is little question that a good PM program will have a high return on investment, many people are reluctant to pay now if the return is not immediate. That challenge is particularly predominant in a poor economy where companies want fast return on their expenditures. PM is the epitome of, “pay me now, or pay me later.” The PM advantage is that you will pay less now to do planned work when production is not pushing, versus having very expensive emergency repairs that may be required under disruptive conditions, halting production and losing revenue. Good PM saves money over a product’s life cycle.

In addition to economics, emotions play a prominent role in preventive maintenance. It is a human reality that perceptions often receive more attention than do facts. A good computerized information system is necessary to provide the facts and interpretation that guide PM tasks and intervals. PM is a dynamic process. It must support variations in equipment, environment, materials, personnel, production schedules, use, wear, available time, and financial budgets. All these variables impact the how, when, where, and who of PM.

Technology provides the tools for us to use, and management provides the direction for their use. Both are necessary for success. These ideas are equally applicable to equipment and facility maintenance and to field service in commerce, government, military, and industry.

The foundation for preventive maintenance information is equipment records. All equipment and maintenance records should be in electronic databases. The benefits obtained from computerizing maintenance records are much greater than the relatively small cost. There should be a current data file for every significant piece of equipment, both fixed and movable.

The equipment database provides information for many purposes beyond PM and includes considerations for configuration management, documentation, employee skill requirements, energy consumption, financials, new equipment design, parts requirements, procurement, safety, and warranty recovery. Essential data items are shown in Table 34-1.

**Table 34-1: Typical Equipment Data Elements**

<table>
<thead>
<tr>
<th>Equipment Identification number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment name</td>
</tr>
<tr>
<td>Equipment product/family/group/class</td>
</tr>
<tr>
<td>Supplier(s)</td>
</tr>
<tr>
<td>OEM and supplier model numbers</td>
</tr>
<tr>
<td>Geographic location</td>
</tr>
<tr>
<td>System process location</td>
</tr>
<tr>
<td>Criticality</td>
</tr>
<tr>
<td>Responsible user</td>
</tr>
<tr>
<td>Installation date</td>
</tr>
<tr>
<td>Warranty end date</td>
</tr>
<tr>
<td>Original comprehensive cost</td>
</tr>
<tr>
<td>Current value</td>
</tr>
<tr>
<td>Safety precautions</td>
</tr>
<tr>
<td>Use per day</td>
</tr>
<tr>
<td>Use meter reading (latest plus history)</td>
</tr>
<tr>
<td>Calibration history and due dates</td>
</tr>
<tr>
<td>PM interval(s)</td>
</tr>
<tr>
<td>Last PM date and meter</td>
</tr>
<tr>
<td>Next PM due date and meter</td>
</tr>
<tr>
<td>PM average time, personnel, and parts</td>
</tr>
</tbody>
</table>
The data for new equipment should be entered into the computer database when the equipment is procured. The original purchase order and shipping documents can be the source, with other data elements added as they are fixed. It is important to remember there are three stages of configuration:

1. As designed
2. As built
3. As maintained

The *As Maintained* database is the major challenge to keep continually current. The master equipment data should be updated as an intuitive and real-time element of the maintenance system. If pieces of paper are used, they are often forgotten or damaged, and the data may not get into the single master location on the computer. Part number revisions are especially necessary so the correct part can be rapidly ordered if needed. A characteristic of good information systems is that data should only need to be entered once, and all related data fields will be automatically updated. Many maintenance applications today are Web-based so they can be accessed from anywhere a computer (or even a personal digital assistant [PDA] or enabled cell phone) can connect to the Internet.

Computers are only one component of the information system capability. Electronic PDAs, Blackberry two-way pagers, voice recognition, bar codes, and other technologies are coming to the maintenance teams, often with wireless communications. A relatively small investment in data entry technology can gain immediate reporting, faster response to discovered problems, accurate numbers gathered on the site, less travel, knowledge of what parts are in stock to repair deficiencies, and many other benefits.

It is important that the inspection or PM data be easily changeable. The computer program should accomplish as much as possible automatically. Many systems record the actual odometer reading at every fuel stop, end of shift, and other maintenance, so meter reading can be continually brought up to date. Other equipment viewed less often can have PM scheduled more on predicted dates. Meter information can be divided by the number of days to continually update the use per day, which then updates the next due date. When an inspection or PM is done and the work order closed, these data automatically revise the date last done, which in turn revises the date next due.

Companies can store preventive maintenance procedures in the computer and print them at the same time the work order is dispatched. Most computers have standard software for word processing capability that can be used to enter and revise procedures. While paperwork from a computer system should be kept to a minimum, a printed procedure checklist that the inspector can sign should help assure responsible accomplishment of tasks. Single-point control over procedures is a big help, especially on critical equipment. The risk of pulling an obsolete procedure from someone’s file drawer is greatly reduced. If all items on a procedure cannot be accomplished at one shift, the document can be passed to the next shift supervisor or held for completion until the next day. When completed, the work order would be closed out and the related information entered automatically onto history records for later analysis.

Safety inspections and legally required checks can be maintained in computer records for most organizations without any need to retain paper copies. If an organization must maintain those paper records for some legal reason, then they should be microfilmed or kept as electronic images rather than in bulky paper form.

Humans are still more effective than computers at tasks that are complex and are not repeated. Computers are a major aid to humans when tasks require accurate historical information and are frequently repeated. Computer power and intelligent software greatly enhance the ability to accurately plan, schedule, and control maintenance.
34.5 Performance Metrics and Benchmarks

The heart of any management system is establishing the objectives that must be met. Once managers
determine the objectives, then plans, budgets, and other parts of the management process can be
brought into play. Too often service management fails to take the time to establish clear objectives and
operates without a plan. As service may contribute a majority of a company’s revenues and profits,
that can be a very expensive mistake.

Objectives should be:

- Written
- Understandable
- Challenging
- Achievable
- Measurable

Each company must develop its own performance measures. Useful performance measures, often
referred to as benchmarks or key performance indicators (KPIs), include the following:

**Asset Measures—Equipment, Parts, and Tools**

A1. Support Level = \( \frac{\text{Total Quantity Issued}}{\text{Total Quantity Demanded}} \)

A2. Demand Accommodation = \( \frac{\text{SKUs (Stock-keeping Units) on Authorized Stock List (ASL)}}{\text{SKUs Demanded}} \)

A3. Demand Satisfaction = \( \frac{\text{Total Quantity of ASL Parts Issued}}{\text{Total Quantity of ASL Parts Demanded}} \)

A4. Turnover = \( \frac{\text{Quantity (or Value) Issued per Year}}{\text{Average Quantity (or Value) on Hand per Year}} \)

A5. Emergency Rate = \( \frac{\text{Quantity (or Value) Expended}}{\text{Total Quantity (or Value) Demanded}} \)

A6. Assets % = \( \frac{\text{$ Book Value of Assets}}{\text{$ Value of Work, Revenue, Total Costs, or Profits}} \)

A7. Repair Cycle = Days from failure until usable on hand. (Note that this may be divided into a)
the technician’s days to return and b) the repair time once the decision is made to repair the
defective part.)

A8. Parts per Unit Repair = \( \frac{\text{Sum of All Costs of Parts Used}}{\text{Number of Repairs}} \)

A9. Repair Cost Ratio = \( \frac{\text{Cost to Repair Defective Unit}}{\text{Cost of a New Unit}} \)

A10. No Trouble Found (NTF) = \( \frac{\text{Count of Units with No Defects Found}}{\text{Total Alleged Failures}} \)
All. Dead on Arrival (DOA) Rate = Quantity Defective for All Causes 
                                             Total Quantity Processed

**Cost Measures**

C1. Total Maintenance Costs = Sum of Labor $ + Parts $ + Travel $ + - - - + Direct $ + Indirect $ 
                                + General & Administrative (G&A) 

C2. Labor Costs = Labor Hours x Loaded Cost per Hour

C3. Parts and Materials Cost = Parts, Expendables, and Consumables Direct + Indirect Costs

C4. Production Loss (Revenue Loss) = $ Foregone Revenues and/or Cost to Obtain Substitute 
                                      Capability

C5. Actual versus Estimated = Actual $, Time, Events 
                                    Estimated $, Time, Events

C6. Revenue per Person = $ Total Revenue 
                                      Number of People

C7. Expense to Revenue Ratio = $ Expenses 
                                      $ Revenue

C8. Break-Even Quantity: Revenue = Fixed Costs + Variable Costs

C9. Return on Investment (ROI) = Net Payback 
                                      $ Invested

**Equipment Measures**

El. Availability (Uptime):

Ai (Inherent Availability) = \( \frac{MTBF \ (Mean \ Time \ Between \ Failures)}{MTBF + MTTR \ (Mean \ Time \ To \ Repair)} \)

Aa (Achieved Availability) = \( \frac{MTBM \ (Mean \ Time \ Between \ Maintenance)}{MTBM + M \ (Mean \ Maintenance \ Time)} \)

Ao (Operational Availability) = \( \frac{Uptime \ (Operational \ Time)}{Total \ Time} \)

E2. Mean Down Time (MDT) = \( \frac{Sum \ of \ All \ Down \ Time}{Number \ of \ Failure \ Occurrences} \)

E3. Mean Time Between Failures = \( \frac{Total \ Time}{Number \ of \ Failure \ Occurrences} \)

E4. Mean Time Between Maintenance = \( \frac{Total \ Time}{Total \ of \ Corrective + Preventive \ Occurrences} \)

E5. Installation Time = Hours and minutes from installation start until usable. May calculate

Mean Install Time (MIT) = \( \frac{Total \ of \ All \ Installation \ Times}{Number \ of \ Installations} \)
Preventive Measures

P1. PM Rate = \( \frac{\text{PM Events, Time}}{\text{Total Events, Time}} \)

P2. PM Completion Ratio = \( \frac{\text{PM Events Completed}}{\text{PM Events Due}} \)

P3. Mean Preventive Time = \( \frac{\text{Sum of All PM Times}}{\text{Number of PM Occurrences}} \)

P4. Minimize Total Costs = \( \text{Sum of Preventive Costs} + \text{Corrective Costs} + \text{Lost Revenue} \)

P5. Defect Detection Rate = \( \frac{\text{Total Number of Defects Reported}}{\text{Number of Inspections}} \)

Human Measures

H1. Response Time = Hours and minutes from request for assistance until expected effort is started.

H2. Restore Time = Time from notification of failure until system is operable.

H3. First Call Fix Rate = \( \frac{\text{Quantity Satisfied at First Attempt}}{\text{Total Requests}} \)

H4. Callback Rate = \( \frac{\text{Number of Repeat Attempts}}{\text{Total Attempts}} \)

H5. Attempts per Incident = \( \frac{\text{Total Attempts}}{\text{Number of Incidents}} \)

H6. Maintenance Hour per Operating Hour (MH/OH) = \( \frac{\text{Total Support Hours}}{\text{Total Equipment Operating Hours}} \)

H7. Administration and Support Ratio = \( \frac{\text{Support People Number or Costs}}{\text{Total People Number or Costs}} \)

H8. Overtime % = \( \frac{\text{Overtime Hours or Costs}}{\text{Total Labor Hours or Costs}} \)

H9. Emergency versus Planned Calls and Time = \( \frac{\text{Repair Work Number, Time, Costs}}{\text{Total Work Number, Time, Costs}} \)

H11. Backlog Days = \( \frac{\text{Demand Total Work Hours}}{\text{Supply Work Hours per Day}} \)

H12. Operational Productivity = \( \frac{\text{Utilized Time}}{\text{Total (Paid) Time}} \)

H13. Achieved Productivity = \( \frac{\text{Standard Units Output}}{\text{Total (Paid) Time}} \)

H14. Effectiveness = \( \frac{\text{Standard Units Output}}{\text{Utilized Time}} \)
Example Calculation:
The most important measure for production equipment support is operational availability, which we also term “uptime.” This is item E1 and definition AO above. This is the “real world” measure of what percent of time equipment is available for production. In the following example, we evaluate an item of automation equipment for one year, which is 365 days x 24 hours per day = 8,760 total possible “up” hours. Our equipment gets preventive maintenance for one hour every month (12 hours per year) plus additional quarterly PM of another hour each quarter (four (4) more hours per year). There was one failure that resulted in six hours of downtime. Thus, total downtime for all maintenance was 12 + 4 + 6 = 22 hours.

\[
Ao = \frac{\text{Uptime (Operational Time)}}{\text{Total Time}} = \frac{8,760 - 22}{8,760} = \frac{8,738}{8,760} = 0.9975 = 99.75\% \text{ Uptime}
\]

That would be considered acceptable performance in most operations, especially if the PM work can be done at times that will not interfere with production. The maintenance challenge is to avoid failures that adversely affect production operations.

Automation professionals should consider life cycle cost when designing or acquiring an automation system. Design guidelines for supportability include:

1. Minimize the need for maintenance by:
   - Lifetime components
   - High reliability
   - Fault tolerant design
   - Broad wear tolerances
   - Stable designs with clear yes/no indications

2. Access:
   - Openings of adequate size
   - Fasteners few and easy to operate
   - Adequate illumination
   - Work space for large hands
   - Entry without moving heavy equipment
   - Frequent maintenance areas have best access
   - Ability to work on any FRU (field replaceable unit) without disturbing others

3. Adjustments:
   - Positive success indication
   - No interaction effects
   - Factory/warranty adjustments sealed
   - Center zero and increase clockwise
   - Fine adjustments with large movements
   - Protection against accidental movement
   - Automatic compensation for drift and wear
   - Control limits
   - Issued drawings show field adjustments and tolerances
   - Routine adjustment controls and measurement points in one service area

4. Cables:
   - Fabricated in removable sections
   - Each wire identified
   - Avoids pinches, sharp bends and abrasions
   - Adequate clamping
   - Long enough to remove connected components for test
• Spare wires at least 10% of total used
• Wiring provisions for all accessories and proposed changes

5. Connectors:
• Quick disconnect
• Keyed alignment
• Spare pins
• Plugs cold, receptacles hot
• No possible misconnection
• Moisture prevention, if needed
• Spacing provided for work area and to avoid shorts
• Labeled; same color marks at related ends

6. Covers and panels:
• Sealed against foreign objects
• Independently removable with staggered hinges
• Practical material finishes and colors
• Moves considered—castors, handles, and rigidity
• Related controls together
• Withstand pushing, sitting, strapping and move stress
• Easily removed and replaced
• No protruding handles or knobs except on control panel

7. Consumables:
• Need detected before completely expended
• Automatic shutoff to avoid overflow
• Toxic exposure under thresholds

8. Diagnostics:
• Every fault detected and isolated
• Troubleshooting cannot damage
• Self-Tests preferred
• Go/no go indications
• Isolation to field replaceable unit
• Never more than two signals observed simultaneously
• Condition monitoring on all major inputs and outputs
• Ability for partial operation of critical assemblies

9. Environment—equipment protected from:
• Hot and cold temperatures
• High and low humidity
• Airborne contaminants
• Liquids
• Corrosives
• Pressure
• Electrical static, surges and transients

10. Fasteners and hardware:
• Few in number
• Single turn
• Captive
• Fit multiple common tools
• Non-clog
• Common Metric
11. Lubrication:
   • Disassembly not required
   • Need detectable before damage
   • Sealed bearings and motors

12. Operations tasks:
   • Positive feedback
   • Related controls together
   • Decisions logical
   • Self-guiding
   • Check lists built-in
   • Fail-safe

13. Packaging:
   • Stacking components avoided
   • Ease of access guides replacement need
   • Functional groups
   • Hot items high and outside near vents
   • Improper installation impossible
   • Plug-in replaceable components

14. Parts and components:
   • Labeled with part number and revision level
   • Breakable knobs and buttons replaceable separate from switch
   • Delicate parts protected
   • Stored on equipment if user replaceable
   • Standard, common, proven
   • Not vulnerable to excessive heat
   • Mean time between maintenance known
   • Wear-in/wear-out considered

15. Personnel involvement:
   • Weight for portable items 35 lb. (16 kg.) maximum
   • Lowest ability expected to do all tasks
   • Male or female
   • Clothing considered
   • Single-person tasks

16. Refurbish, rejuvenate and rebuild:
   • Materials & labels resist anticipated solvents & water
   • Drain holes
   • Configuration record easy to see and understand
   • Aluminum avoided in cosmetic areas

17. Safety:
   • Interlocks
   • Electrical shut off near equipment
   • Circuit breaker and fuses adequate
   • Protection from high voltages
   • Corners and edges round
   • Protrusions eliminated
   • Electrical grounding or double insulation
   • Warning labels
   • Hot areas shielded and labeled
   • Controls not near hazards
• Bleeder and current limiting resistors on power supplies
• Guards on moving parts
• Hot leads not exposed
• Hazardous substances not emitted
• Radiation given special considerations

18. Test points:
• Functionally grouped
• Clearly labeled
• Accessible with common test equipment
• Illuminated
• Protected from physical damage
• Close to applicable adjustment or control
• Extender boards or cables

19. Tools and test equipment:
• Standardized
• Minimum number
• Special tools built into equipment
• Metric compatible

20. Transport and storage:
• Integrated moving devices, if service needs to move
• Captive fluids and powders
• Delivery and removal methods practical
• Components with short life easily removed
• Ship ready to use

The preferred rules for modern maintenance are to regard safety as paramount, emphasize predictive prevention, repair any defect or malfunction, and, if the system works well, strive to make it work better.

34.6 References


Author’s note: With the Internet available to easily search for publications and professional societies, using a search engine with key words will be more effective than a printed list. Internet search on specific topics will be continually up-to-date, whereas materials in a book can only be current as of the time of printing. Search with words like maintenance, preventive maintenance, reliability, uptime (finds better references than does the word availability), maintainability, supportability, service management, and maintenance automation will bring forth considerable information, from which you can select what you want.
About the Author

Joseph D. Patton, Jr. is Chairman of Patton Consultants, Inc. (www.PattonConsultants.com), advisors to management on product service, logistics, and support systems. Before founding Patton Consultants in 1976, Patton was a Regular Army Officer and spent 11 years with Xerox Corp. He is author of over two hundred published articles and eight books. He earned a BS degree from the Pennsylvania State University and an MBA in marketing from the University of Rochester. He is a Registered Professional Engineer (PE) in Quality Engineering and a Fellow of both ASQ — The American Society for Quality and SOLE — The International Society of Logistics. He is a Certified Professional Logistician (CPL), Certified Quality Engineer (CQE), Certified Reliability Engineer (CRE), and a senior member of ISA.
35 Automation Benefits and Project Justifications

By Peter G. Martin

Topic Highlights
Capital Projects
Return on Investment
Net Present Value
Internal Rate of Return
Lifecycle Costs
Lifecycle Economics
Barriers to Success
Real-Time Cost Accounting

35.1 Background

When the digital computer was first introduced to process manufacturing in the late 1960s, the promise of that new technology was unbounded. Many manufacturing managers saw computer technology as the key to driving the performance of their plants to new levels, and driving real competitive advantages into their manufacturing lines. For the most part, after over 30 years of using this technology in the process industries, this vision has still not been realized.

Decisions on the initial installations of computer-based automation systems appeared to have been made on a binary basis. That is, many manufacturers just felt it was important to get the new technology installed in order to run their operations. Little consideration seems to have been given to the economic impact the system would provide. A survey of manufacturing managers indicated the primary motivators driving manufacturers to purchase automation systems include their desire to:

- Improve plant quality
- Improve safety
- Increase manufacturing flexibility
- Improve operations reliability
- Improve decision-making
- Improve regulatory compliance
- Increase product yields
- Increase productivity
- Increase production
- Reduce manufacturing costs

Although few would disagree with this list, it appears these criteria are seldom taken into consideration either during the purchase of an automation system or over the system's lifecycle. However, most of the criteria listed have a direct impact on the ongoing economic performance of the manufacturing operation.

35.2 Capital Projects

Automation systems are typically purchased from manufacturers’ capital budgets. Therefore, any discussion of the economic benefits of automation systems and technologies must be from the perspective of the capital budgeting and project process in manufacturing companies. Capital budgeting is typically a long process, often involving multiple years for each capital project. The process is initiated when a manufacturing operation identifies a need for a capital project and then develops a nomination package for the proposed project that is forwarded to corporate planners. Corporate planners evaluate all the nominated projects against qualifying criteria, as well as available capital and then select a set of nominated projects for implementation, typically for the following fiscal year. At this point, the project moves from planning to execution. A project team is convened and provides a bid package to a set of vendors who can provide the products and services necessary to satisfy the defined project requirements. The vendors are evaluated, one is selected, and the order is negotiated and purchased. The project is executed to install the system, start it up and get it operational. The system is then operated for its lifecycle and, in theory, work is done to get continuous improvement from the system.

It is interesting to note that, in the typical capital project process, automation systems vendors have little-to-no say on what the actual solution is. By the time the request for proposal (RFP) is put out for bid in Step 5 of the typical process shown in Figure 35-1, the solution has already been defined. Vendors must only respond with the lowest possible priced system that meets the solution definition. Over the past decade, as manufacturers have significantly reduced headcount in their engineering departments, this issue has begun to become very important because the vendors now may have a stronger engineering talent base than the manufacturers and may be in a better position to define performance-generating automation solutions.

Since automation systems are purchased from capital budgets, it is very important to understand capital budget economics in order to effectively analyze the economic benefits of automation systems. Figure 35-2 displays a classic lifecycle capital economic profile. The lower bar chart represents the cost of the capital project including hardware, software, engineering, installation, start-up, commissioning, operations, and maintenance.

The costs in an automation project tend to be quite high at the beginning of the lifecycle, due to the purchase of the system, engineering, installation, and startup. The costs tend to level out after startup and are largely comprised of ongoing engineering, operations, and maintenance.

Toward the end of the lifecycle, annual automation costs tend to increase, due to aged equipment, spare parts and repairs, as well as increased training levels. A review of a number of automation projects revealed that most manufacturers have a fairly good understanding of their automation costs, even if they do not have specific programs to capture them over the lifecycle of the equipment. The upper dashed line represents the economic benefit derived by the deployment of the automation system.

Notice that this value begins at start-up and is expected to continuously grow over the useful life of the automation system. The same review of the automation projects that revealed that most manufacturers have a good handle on the cost of their automation systems also revealed that almost none of
them had any understanding as to the true benefits provided by the automation. This is because the benefit line in Figure 35-2 is seldom, if ever, measured. It was determined that many engineers felt the finance people in their plants were measuring the benefit of each capital investment and were not passing that information back to engineering. The fact is the finance systems in place in most manufacturing operations cannot capture benefit information at this level of specificity. This is a huge problem when trying to assess the true economic benefit provided by automation investments.

35.3 Return on Investment

The most common way to discuss the economic benefit for any capital investment is in terms of return on investment (ROI). Basically, ROI is defined to be the cash inflows resulting from a capital investment, such as an automation system, divided by the initial investment made over a given period of time. ROI can be determined in a number of ways.

The simplest and most common approach is to evaluate the purchase price as the initial investment of the automation system against the cash inflows that result from the deployment of the system. Although the price approach is often utilized, a more complete view of ROI would be to evaluate the purchase price and all other initial (project) costs associated with the project against the accumulated cash inflows.

A more complete investment evaluation would be to evaluate the purchase price, project costs, and ongoing operational and maintenance costs against the accumulated cash inflows, but this approach is seldom if ever done. In any case, the basic evaluation approach is the same, when the accumulated cash inflows equal the purchase price or the purchase price plus initial project costs, depending on which method is utilized, 100% return on investment is achieved.
ROI is often stated in terms of time, if it takes less than one year to reach 100% return, or in terms of percentage, if it takes greater than one year to reach 100%. The time to reach 100%, ROI is often referred to as the “payback period.” Unfortunately, the point in the capital project process at which ROI is addressed is typically in Step 6 (Figure 35-1), when automation vendors are often asked to provide a projected ROI analysis with their proposals. This analysis is constructed based on what the vendor believes the unique features of their offering might be able to provide if effectively used in the manufacturing operations.

The good news for these vendors is that, after the automation systems are installed and operating, manufacturers almost never go back to check to see if the ROI projections were ever really achieved. One of the major contributing factors for not doing this analysis is the aforementioned lack of any effective way to capture the benefit side of the ROI model in an operating plant. The accounting systems in place just do not have the level of resolution necessary to systematically calculate and verify an ROI analysis of this type.

### 35.3.1 Net Present Value

An ROI analysis is quite simple, but it may also be a bit deceptive from the perspective of making a decision as to whether or not to invest in an automation project. The reason for this is, if it takes a fairly long time to get to 100% return, the amount of the investment is based on the value of the money at the time the investment is made, while the inflows will occur at a later time. From a value perspective, an expected cash inflow of a given amount at some future time is not worth the same as if that amount were paid today. Therefore, valuing future cash inflows at an equivalent amount to what they will actually be when the inflow occurs overvalues the return. The larger the amount of time that is expected to pass prior to receiving a particular cash inflow, the less it is worth in today’s currency. An ROI analysis ignores this situation. When trying to make a determination on where a company’s capital budget will be invested, a more appropriate evaluation of the worth of money over time is required.

For example, if a company has a capital budget of $1,000,000 and there are two potential projects that each would cost $1,000,000, one of which has a return of $2,000,000 over 20 years and the other
$1,500,000 over 2 years, which would be the best capital investment? The answer to this question is not obvious. A more sophisticated approach to ROI is required to effectively answer.

The Net Present Value (NPV) function is designed to address this issue. The NPV of an expected cash flow over a period of time is a function that takes the time value of money into consideration. The inputs to this function are the expected cash inflows over time, the initial investment, and the discount rate. The discount rate represents the value of a future cash inflow in today’s terms. The result of this function provides the current value of an expected time series of cash inflows minus the initial investment amount. This NPV can be compared to other potential investments to determine which potential capital investment is better for a company to make.

The equation of NPV is as follows:

\[
NPV = \sum_{t=1}^{n} \frac{(\text{Cash Inflows})^t}{(1 + \text{rate})^t} - \text{Initial Investment}
\]  

(33-1)

### 35.3.2 Internal Rate of Return

An alternative approach to conducting an NPV analysis to determine the value of a capital investment that will pay back over an extended period of time is referred to as Internal Rate of Return (IRR). IRR uses that same basic calculation approach as NPV, but the variable in the calculation is the discount rate that will result if the NPV calculation results in $0 over the selected time period. In other words, what discount rate used in an NPV calculation results in a value of $0? The higher the value of the IRR, the better the investment. Solving the following equation for IRR would result in the appropriate calculation.

\[
\sum_{t=1}^{n} \frac{(\text{Cash Inflows})^t}{(1 + \text{IRR})^t} = \text{Initial Investment}
\]  

(33-2)

Both NPV and IRR are common financial functions in standard spreadsheet packages such as Excel, as well as standard functions of financial calculators. Using a spreadsheet or financial calculator is an easy way to perform either calculation. It should be noted that, although both NPV and IRR provide a more appropriate projection of a capital project’s expected value, neither addresses the fundamental issue involved with automation projects. That is: the benefit value or cash inflows associated with an automation system are seldom, if ever, captured in a cost accounting system.

This means ROI, NPV, and IRR are not verifiable for any automation project over time. No matter which of these methods is employed to justify the automation investment during the evaluation process, it is still difficult to verify the actual value of a project after it is implemented. This issue must be addressed for automation projects to have any investment credibility at all.

Interviews with industry executives have revealed an interesting progression in credibility that has resulted from the lack of verifiability of automation investments. Thirty years ago, when management really felt they needed automation technology to compete, they readily approved capital investments; when they later inquired as to whether the ROI, NPV, or IRR were realized, the project team answered in the affirmative, and the managers believed it. Twenty years ago the managers accepted it. Ten years ago they questioned it. Today they reject it. It is becoming more essential than ever to validate the value generated by automation to regain its credibility as a value-adding technology.

### 35.4 Lifecycle Costs

The lack of an effective way to measure the benefit from automation investments has resulted in the selection criteria for automation systems being relegated to either the low price system or the lowest
lifecycle cost system. Clearly, taking a full lifecycle cost view (Figure 35-3), as compared to a price-only view, provides a much more comprehensive evaluation. But either view relegates the selection of the automation system to a cost, with no associated measurable benefit. Any offering that can be evaluated only from the perspective of cost sooner or later is categorized as a “necessary evil,” and the market moves toward commoditization. This has been the case with automation systems over the past decade.

There has been fairly significant movement toward a lifecycle cost view of automation systems, rather than a price-only view. The following model was developed to reflect this expanded view. The basic equation used for the analysis of the lifecycle cost is:

\[
LCC = \text{Price} + \text{Project Engineering} + \text{Installation} + \text{NPV(Ongoing Annual Costs)}
\]

wherein:

- \( LCC \) = Lifecycle Costs
- \( \text{Price} \) = Automation system price
- \( \text{Project Engineering} \) = Total cost to engineer the project
- \( \text{Installation} \) = Total cost to install the system (including start-up)
- \( \text{NPV} \) = The net present value function of the ongoing costs
- \( \text{Ongoing Annual Costs} \) = The annual engineering, operations, and maintenance cost of the system

The net present value function serves to calculate the time-value of money over extended periods (Figure 35-4).

It is interesting to note that the system price tends to be a reasonably small component of the overall automation system cost. In fact, studies have placed the average price at less than 35% of the total

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*Figure 35-3: Lifecycle Capital Economic Profile*
project cost, without even taking into consideration the ongoing costs. This tends to demonstrate one of the deficiencies in the price-only approach.

The expansion of economic perspective from price to lifecycle cost was a major step forward for the industry, but was still very limiting. This is the perspective of most of the industrial automation users today, since most of them still use a cost-only economic evaluation approach. If there is no economic benefit to the manufacturing operation for putting in an automation system, then automation systems are certainly not meeting management’s objectives, and probably nothing but the most rudimentary system should ever be deployed.

35.4.1 Lifecycle Economics

Many automation system users have discussed returns on their automation investments. However, calculating returns requires an accurate measure of the lifecycle benefits the manufacturing operation derives from the utilization of the automation system, not just the lifecycle costs. In interviews conducted with hundreds of manufacturing executives, it was learned none was actually measuring the benefits derived from automation. Most admitted they did not know how to get at these metrics in any reasonable way, and their current cost accounting systems did not provide the detailed economic data to be able to infer the benefit value.

A manufacturing operation sees the economic benefits from automation systems essentially in two major areas:

- First, manufacturing cost savings through such things as reduced power consumption, raw material costs, and manpower requirements
- Second, the increase in production that can be gained through better asset utilization

Of these, the only one that was regularly monitored was reduced manpower due to automation, because it is relatively easy to measure. The other elements of the benefit calculation are variables that constantly change as products are produced and are, therefore, very difficult to measure.

As the concept of automation systems’ lifecycle economic profiles started to gain recognition during the late 1990s, the author was asked to lead a session on the subject at the ISA Technical Conference...
of 1996. At that conference, and at subsequent meetings, a number of professionals from companies such as E. I. DuPont, General Foods, Eli Lilly, and Dow Chemical contributed a considerable amount of data from a number of automation projects to help build a lifecycle economic profile. A high-level view of the profile used for this exercise is shown in Figure 35-5. This profile defines the benefit as the net present value (NPV) of the annual manufacturing cost savings and the annual production increases resulting from the automation system. The net present value is a function that calculates the current value of money paid on a regular basis over a number of years. It is appropriate when trying to make an up-front decision of the best economic value among a number of possible choices that will either be generating cost or economic benefit over a period of time. An automation system does both.

Years of Expected Life (YEL) is an indicator that the NPV calculation should be done over the automation system’s expected lifecycle. This helps to determine the value of automation systems that have different expected installed lifecycles. The lifecycle cost calculation has two basic components, the project costs and the ongoing costs. The project costs can be captured in the three general categories of price, initial engineering costs and installation costs. The net present value function was also utilized for the ongoing aspect of annual engineering, operations and maintenance costs.

As part of this activity, a number of automation projects were analyzed and, from the data collected, an actual economic profile developed. Considerable data was available for the cost side of the profile, but only limited data was available to analyze the benefit side. This is not surprising in light of the lack of focus industry-wide on the benefits component of the equation.

A number of interesting results developed from the analysis of this data. First, as Figure 35-6 depicts, most of the projects for which the benefit side was measured at all showed a continuous decline in the benefit value over the system’s lifecycle. This result was shared with a number of the professionals who contributed the data. They were not overly surprised by this result. Many of the professionals attributed the continuous decline to the obsolescence of the system. This conclusion was later demonstrated to be erroneous, at best, since there are many projects that do realize continuous improvement in the economic benefit derived from the automation system. In fact, the decline seems to be more associated with the lack of measurement of the benefit side of the profile than to the reduction due to obsolescence.

One of the basic principles of process control is that if you cannot measure the controlled variable, you cannot control it. The same is true for financial variables such as lifecycle benefits. It also appears that,
if the variable is not measured, it will most probably move in the wrong direction, which is exactly what the data showed.

Another interesting aspect of the data collected was how the lifecycle cost data was actually distributed across the set of data, as shown in Figure 35-7. The price, which had traditionally been the primary economic variable in the automation system decision process, represented less than a quarter of the first five-year cost of the system. Between the initial engineering costs and the five-year lifecycle engineering costs, the engineering of the automation system accounted for 37.8% of the costs. This is considerably greater than the price of the initial system.

Perhaps the most interesting result of the analysis was found on the benefit side of the model. The benefit data collected, which was not statistically valid due to the small sample size of projects for which benefit data was available, showed the benefit to cost ratio over the first five years was 3.4:1. This means that the average ROI on automation technology for projects for which the benefit data was measured realized very strong economic returns. The analysis team did not believe the 3.4:1 ratio was representative of the average return on automation realized. In fact, the automation users who were
measuring the benefit resulting from automation were considered to be among the best performers. This would mean that the 3.4:1 ratio is a “best practices” result as compared to an average result.

When this data was shared with a larger number of automation users, the consensus seemed to be that these results were not surprising. In fact, most of those interviewed readily accepted the results. This caused us to ask why more users were not focused on the economic benefit resulting from automation. Although most of those asked did not have any solid response, an additional, more detailed analysis uncovered three practices that were significant barriers to a total lifecycle economic approach to automation.

### 35.5 Barriers to Success

The first barrier was the *replacement automation* approach to automation projects that is almost universally used. The replacement automation approach begins at most industrial plants when their capital budget is approved for an automation system upgrade. At that point, a project team is typically established to determine the specifications for the new automation system to be installed. In most of these cases the specification is developed by looking at the functionality of the currently installed system, subsequently building the new system specification around the existing system.

This leads to a request for proposal (RFP) that is provided to a number of automation suppliers for a competitive bid. Unfortunately, this RFP exactly defines the old system that is already in place. The suppliers realize that the one who will win the order is the one who meets the specification at the lowest price. Therefore, even though they may have added significant performance enhancing capabilities to their new computer-based automation systems since the old system had been installed, they propose their lowest-cost system. Typically, this means that all of the advanced capability in which the suppliers have invested is left out of the proposal. The net result is the new system being installed is an exact functional replacement for the system being replaced. Replacing old technology with new technology that does the exact same thing seldom leads to breakthrough improvement.

When this is pointed out to the user’s project team, their response is typically “don’t worry, once the new system is up and running, we will take full advantage of all of the advanced capabilities.” This is when the second barrier starts to take effect. The second barrier is the *project team approach* used on most automation projects.

Project teams of highly qualified engineers are established when capital budgets for automation projects are approved. The project team works on the project throughout the project cycle. Once the project is completed, the project team goes away. Some of the members may go on to other projects. Some may remain in the plant to manage ongoing engineering activities. But the resources required to take advantage of the advanced features of the automation system are no longer available. As a result, the “later on” when everyone was hoping to take advantage of advanced capabilities never happens. The initial benefit, if any, provided by an automation system is typically the best benefit that will be realized through the system over its lifecycle. From that point, there is a continuous degradation of benefit.

### 35.6 Real-Time Cost Accounting

The good news in all of this is that, as this continuous degradation of economic performance happens, nobody knows it. This is because, in most cases, the benefit side of the economic profile is not measured. This is the third barrier to success. Measurement systems are typically only valued if they are providing good news.

The news that might be provided by a measurement system that continuously communicates the economic benefit due to automation would probably not be very positive. But since these measurements are not being made, most manufacturers do not feel the pain of poor performance. In this case, no
news is good news. Or is it? This approach was fine when process manufacturers could not help but make significant profits no matter how good—or bad—their operations were. In today’s tough global business environment, this approach is just not acceptable.

One promising result from all of this analysis was that, when the professionals in industrial operations paid attention to the economic benefit measures, even if poorly calculated on an infrequent basis, they were able to realize phenomenal results. This implies the potential economic benefit from automation is limited by the ability to measure the benefit side of the ROI model. The implication is that, if the benefit side of the model were made measurable in a systematic and effective manner, it would uncover all kinds of untapped potential benefits from automation technologies.

The good news in this entire discussion is a number of executives in manufacturing companies have been pressing for a fundamental change in the way cost accounting systems work. This change is starting to bring visibility to the benefit of automation systems, as well as other improvement initiatives, and the automation systems are critical to the implementation of this change.

Traditional cost accounting systems have been developed to provide monthly financials for manufacturing operations at the plant level. The common accounting vehicle is the variance report, which presents cost per unit product made for each product line manufactured on a monthly basis. This information is just not sufficient to get the necessary level of visibility into plant operations.

Executives have been pushing accounting to be able to provide higher-resolution financial information from two dimensions: time and space. That is, the executives have been pushing for real-time cost data right down to the process unit level. If such data were available, the visibility into the benefit due to automation expenditures would significantly increase and true ROI calculations for any plant capital investment would become much more visible.

Accountants have been stymied as to how to generate this financial information on a real-time basis. They have not been able to determine a data source that is available at such frequencies and that will enable the calculation of the appropriate cost and profit information. Fortunately, plant engineers
have been aware of an available real-time plant database in the form of the plant instrumentation that
is already used for process monitoring and control. It has been demonstrated that this plant instru-
ment database can also be effectively used as source data for plant accounting systems enabling the
necessary real-time accounting calculations that can be used to evaluate the actual ROIs for the auto-
mation system investments.

The appropriate location for these real-time accounting calculations to be made is in the real-time
automation systems. Trying to execute them in the IT systems is very difficult to accomplish due to the
inherent design of the IT systems. Automation systems are designed to work in real time and are the
ideal location for the origination of the real-time accounting models. It is important to note that this
approach essentially dissolves the traditional separation between the IT and automation systems. The
real-time accounting models are referred to as dynamic performance measures, and although the use
of such measures is still in its infancy, the initial results have proven to be very promising.

Every process control engineer realizes that, if a variable is not measurable, it is not controllable. This
goes for physical, chemical, and financial variables. It has been nearly impossible for plant personnel to
manage the ROI of automation systems because, to this point, it has not been measured. With the
advent of dynamic performance measures, the benefit side of the ROI model is finally measurable and
available. Now, plant personnel can really work to control the ROI from automation. As this has
begun to take place, the resulting returns have been even greater than expected. Automation systems
are starting to become vehicles for performance improvement once again, rather than the “necessary evils” they had started to become.

The only true way, therefore, to prove to manufacturing management and executives that an invest-
ment they made in automation system technology has realized the economic value projected is to
have an accounting system that can measure it. For the most part, today’s accounting systems,
although providing absolutely necessary financial reporting information, are insufficient in measuring
the impact of automation system investments or almost any other investment made to improve plant
floor operations. They just do not provide the necessary data. In addition, there is no way to extract
the improvement information from the data they do provide.

Real-time cost accounting down to the process unit level, and perhaps even below that level, is
required to get the necessary measurements of improvement value. Anything short of implementing
and analyzing the real-time accounting models will not provide the necessary level of information to
credibly provide automation system payback.

It should also be noted that the development and collection of real-time accounting information is
what is required to do accurate projections of ROI and IRR for future automation projects. The projec-
tions being provided for the most part today are based on sets of unsubstantiated assumptions that are
losing credibility with manufacturing management.

A real-time accounting system provides a history of capital project economics which can be used with
a high degree of credibility to project the expected payback of proposed projects. Unfortunately, this is
a bit of a chicken-and-egg situation in that the real-time accounting systems must be installed and oper-
ating for a period of time in order to collect sufficient historical data to make reasonable projections.

The move toward real-time accounting has been very slow, but appears to be accelerating. The good
news is that initial experience has shown the economic value improvements that can be realized
through the effective application of automation technologies can be much greater than has been pro-
jected. Once this fact becomes general knowledge, the focus on value improvement through automa-
tion system technology will increase significantly, which should lead to a new era of value-based
automation.

An interesting corollary to this analysis is that traditional ROI may be a very poor measure of the value
of automation systems. The reason is that, once 100% return is reached, ROI as a measure is typically
ignored, but the automation systems keep generating economic value. It is a shame and a huge disservice to ignore the ongoing value generation incurred by automation systems once the initial project cost has been covered. With real-time accounting measures available, a better approach to the measurement of economic benefits of automation systems may be based on cash flow. The cash flow benefit from automation investment can keep accruing and improving over the life of system and the plant assets that are impacted. Viewed in this manner, the economic value of automation, effectively applied and measured, can and should be many times the original price and cost of the system. The capital cost involved in acquiring automation technology in manufacturing operations has been under such limitations in recent years that it may actually prove to be the most significant business investment a manufacturing company can make.

The potential benefits from automation are huge, but, unfortunately, have not been realized or visible to this point. Changes occurring in the way businesses measure performance may finally start to drive visibility into the value that this technology could really provide—if we just manage it and measure it in an appropriate business manner.

35.7 References


About the Author

Peter G. Martin, PhD, has more than 30 years of industry experience and education. After joining the Foxboro Company in the 1970s, Martin worked in a variety of positions in training, engineering, product planning, marketing, and strategic planning. He later became Vice President at Automation Research Corporation before returning in 1996 to the Foxboro Company (now part of Invensys Process Automation) where he currently serves as Vice President of Strategic Initiatives. Martin has BA and MS degrees in Mathematics, an MA degree in Administration and Management, and a PhD in Industrial Engineering.