THE “SMART” PLANT: ECONOMICS AND TECHNOLOGY

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Abstract

Advances in sensors, automation, and information technology have significantly changed the way process plants operate. High performance computing and high speed communication technology developments have been the foundation for many of these advances and advanced analytical and optimization methods based on this infrastructure can simultaneously lower costs, increase profitability and improve customer service across the supply chain. The collective changes are sometimes characterized as constituting “smart” manufacturing. They allow the plant staff to better analyze the past, assess the current state, and predict future behavior under alternative scenarios. However, the path to progress has not been smooth. There have been many false starts and many technologies with early promises unfulfilled. In this paper, we will survey the recent history of these developments. Case studies on actual implementations, recent advances in relevant technologies and probable trends in the business environment are used to forecast likely future changes in this important area of process plant operations. Some of the questions considered include: How do the fundamental process industry economic drivers guide the technology adoption? In what areas of plant operation have we seen the greatest economic impact to date and in what areas do we expect the greatest impact in the future? The technology and organizational issues that have presented barriers to implementation are also discussed.

Keywords

Manufacturing automation, Economic benefits, Advanced automation

Introduction

What is a “smart plant?” We are all aware of the extraordinary developments that have been and are occurring in the computer and communication area. Continuing decreases in the cost and size of computing elements and continuing increases in the availability of communication bandwidth are reported almost daily. Advances in software and mathematical analysis have built on these developments to significantly increase the ability to model and optimize manufacturing activities. Many new developments in process sensor and measurement devices have also appeared. These developments have lead to new methods and procedures for operating production facilities. The new procedures utilize more comprehensive and frequent measurements of the current state of the plant, increased use of models and other analytical techniques to compare what the plant is currently doing against what is expected and understand the differences, earlier detection of anomalous conditions, and tools to plan future operation with increased confidence. Collectively these advanced automation technologies have come to be known as “smart manufacturing.”

Why is “smart manufacturing” important? Computer and communication technology developments have contributed to substantial increased productivity in the manufacturing sector. The US Chemical Process Industries’ (CPI) productivity compounded at 2.5 % per year during the period 1990 to 2000 (C&EN (2001)) and certainly some of the increase is due to the increasing use of this automation technology. Of even more importance is the opportunity for increased productivity gains in the future through increased investments in this area. However, the link between technology developments and improved economic results including increased productivity is not always transparent. Many unsupportable claims on potential benefits are made.

Correspondingly, there are many technology developments that are believed to be beneficial but it is not clear how to translate this belief into realistic monetary values.

The objective of this paper is to survey recent "smart manufacturing" technology developments in the CPI and show how these developments have affected the process industries in the past and to project how they will affect them in the future. It is also intended to provide a general framework for understanding these recent technology developments and most particularly for understanding the potential economic benefits of the technology.

What are the attributes of "smart manufacturing"? They are:

- Wide availability of real time information on the current status of manufacturing and product conditions
- Comparative model-based performance analysis
- Decisions based on predictive scenarios of expected future plant and market behavior and analytical decision models

The plant systems that support these attributes are shown in the figure below. They include smart sensors, advanced equipment monitoring and diagnosis, and upper level production management and asset management systems.

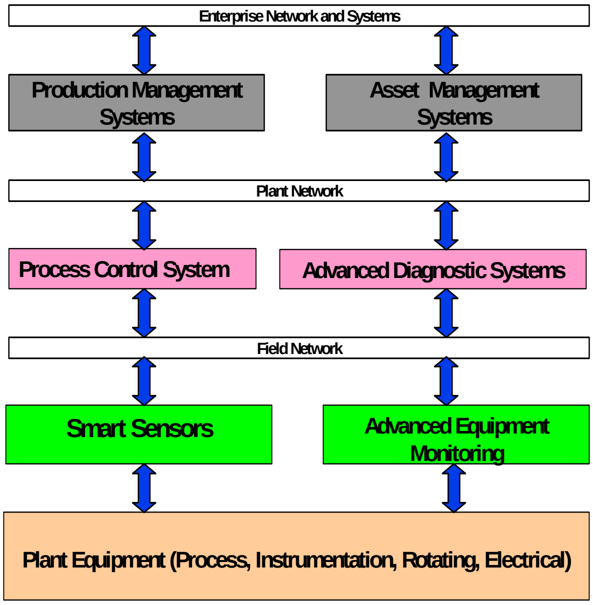

Figure 1 – Smart Manufacturing Systems

Background

The history of developments in automation and their actual application in plant production operations is explored in many sources including Feeley (1999). Early developments in controllers were first mechanical and then pneumatic in character. Controllers with electronic components began to be generally used in the 1960's with microprocessor based controllers appearing in the 1970's. Microprocessors for process control were custom devices until the 1990's when standard products began to replace them.

Computing capabilities were slower to move to field devices – primary measurements, transmitters, and valves – due to size, communication and field intrinsic safety requirements. It was only in the 1990's that significant computational capabilities came to be distributed to these components.

The pioneering advanced control technology applications were installed in the 1960's, but significant acceptance was not experienced until the 1970's and 1980's (White (1997)). This acceptance was initially concentrated in the oil refining and large volume chemicals area.

Technology Adoption

To assess the value of the technology developments it is necessary to examine the incentives for their use and the value they bring. For adoption, the technology must either provide an improvement in the overall financial performance of the plant or must solve a problem that was not adequately solved previously. There are two types of drivers for technology adoption, "technology push" and "economic pull." By "technology push" is meant that new technology creates new ways of accomplishing tasks that did not previously exist, and these new alternatives will always be attractive to some members of the user community. "Economic pull" refers to the standard economic displacement of more expensive materials and services by equivalent cheaper ones. Three major incentive areas are reviewed below – financial, safety and environmental issues, and workforce demographics.

Financial

Financial results are important and a short review of manufacturing economics is provided. The financial measure of performance that is most commonly applied to businesses, including those in the process industries, is Return on Capital Employed or ROCE. It is defined as:

$$ROCE = \frac{EBIT}{Capital\ Employed}$$

For the manufacturing segment of the process industries, the following approximations are reasonable:

*EBIT (Earnings Before Interest and Taxes) = (Product Revenue – Feed Costs – Utility Costs – Other Operating Costs) * Operating Factor – Maintenance Costs - Depreciation*

Capital Employed = Fixed Assets + Inventory + Financial Operating Capital

where the revenue and cost factors are averaged over the period of interest, normally one year, corrected to 100% operating factor.

To increase the ROCE ratio we can either increase yearly earnings or decrease the average capital employed.

Reducing inventory is an effective way of reducing capital requirements. Earnings can be increased by increasing the operating factor (for non market limited plants), by increasing product revenue and/or reducing costs.

This leads to the following operational objectives for typical process manufacturing sites:

- Produce the highest valued product mix possible
- Maximize the production from existing equipment
- Maximize the equipments' on stream operating (service) factor
- Continually reduce costs and pursue operational efficiencies
- Keep inventories as low as possible
- Minimize Health, Safety and Environmental incidents

where the last objective implicitly includes the reality that HSE issues can be governing. Note that the advanced automation systems we are reviewing affect every one of these objectives.

Where are the opportunities for increased efficiencies? The average process company spends at least 60% of total revenue on feedstocks, energy, goods and services. Energy costs are often largest component of operating costs after feedstock. There are often significant opportunities for savings in these costs through improved operation. Lost production due to unscheduled shutdowns or slowdowns averages 3 to 7% of production. Maintenance costs are the third largest cost component after feedstock and energy at 9% to 20% of the COGS (Cost of Goods Sold) but often the maintenance action is provided too early when not required and sometimes (regrettably) too late. Inventory is a significant component of working capital costs. Average industry inventory levels are (CFO, 2002); measured in days of sales:

- Pulp and Paper – 45
- Chemicals – 60
- Metals & Mining – 60

Contrast this with:

- *Dell Computer - 8*

Clearly there is room for improvement in the CPI.

There have been many documented case studies of the benefits of advanced automation to the CPI (White, 1997). The financial incentive is clear as it is in other areas of manufacturing economics.

Safety and Environmental Issues

The safety and environmental performance of the process industry is widely viewed by the public as unsatisfactory. Analysis of the cause of recent accidents and incidents indicate that many factors including design, change control, and operational issues contributed to the incidents (Duguid (2001), Belke (1999)). However, reviewing the incidents and potential amelioration indicate that improved measurements and real time analysis might well have prevented or at least substantially reduced the damage from approximately 25% to 50% of these accidents.

Environmental emissions from process plants continue to be a major problem. Although the US CPI reduced its emissions by 56.3% from 1989 to 1999 while increasing production by 33.3% (Franz, (2002a)), it still remains the largest single US manufacturing industry source of toxic emissions (Franz, 2002b). Industry along the Texas Gulf Coast, which is the world's largest single concentration of CPI sites, is under government mandates to reduce NOx emissions by a full 80% by 2007 (Sissell, 2002). Obtaining the latter goal and continuing the reduction will require many changes in plant design and operation. Improved measurements, modeling, analysis, and control are critical to the goal of reducing emissions.

Demographics

The demographics of process plant operators in North America are changing. With industry downsizing there was very limited hiring in the 80's and 90's. As a result 75% - 90% of the operators in the CPI are expected to retire in the next 10 to 15 years (Shanely, 1999). Clearly the average experience level will drop in this period. In addition, the demands for enhanced analytical skills in the job are increasing. A partial solution to this problem is again to use plant measurements, modeling and analytical techniques to automate routine decision processes or at least provide the information to make the decision process more efficient.

The general conclusion from the comments above is that there is a significant need for improved operation in the CPI and that "smart" automation technology can be a significant contributor to the improved operation.

Value Analysis Framework

Many of the developments in "smart" manufacturing involve more and better measurements of process and equipment conditions and use of models to analyze the data. Numerous claims have been and are made about the economic benefits of these individual technology developments. Normally these economic benefits are calculated by multiplying a small potential percentage improvement in performance times a large number such as product value and claiming that the result is plausibly the expected benefit. The causal map between the technology implementation and the improvement in performance is not really specified. A close review of the claims shows, however, that many developments are each claiming to achieve the same improvement. The concept of diminishing returns seems absent.

It is the assertion of this work that the value of these developments can best be understood by analyzing them in the context of the decision process in the plant. Figure 2 below presents this decision cycle. We measure a condition in the plant or detect a change of state, analyze the data to potentially spot an anomaly, predict the effect of alternative action scenarios, decide which scenario to implement, and then actually implement the scenarios.

After this, the cycle repeats. Examples of decisions made in this framework include what products to produce and when to produce them, decisions on the resources required for production including feedstocks and manpower and decisions on when to perform maintenance on a particular item of equipment.

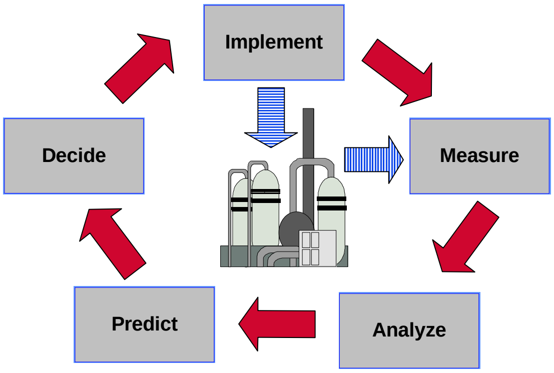

Figure 2 – Plant Decision Cycle

What are the characteristics of these components?

Measure

Modern process plants produce a lot of data. It is not unusual for a large CPI site to have 100,000 distinct measurements. If these measurements are scanned once a minute, ten gigabytes a week of data will be produced. However, the data is natively of poor quality. Instrument readings drift and noise corrupts the measurements. Even when the actual measurements are good, the statistical properties are not – the data is serially auto-correlated and cross-correlated. The important issues are timeliness of the data, its validity, and its relevance.

Analyze

Analysis in this context is obtaining the best possible estimate of the current performance of the system (plant) and its history. Generally this means processing the raw data through a model to obtain some type of performance indicator, perhaps of an individual piece of equipment or of the overall plant or site. This performance indicator is then compared against a standard. The standard could be the normal, new or clean performance of the equipment, it could be the financial budget for the plant or it could be environmental or design limits. Key issues with analysis are to detect under (or over) performance and precursors of abnormal events.

Predict

The next step in the decision process is to project into the future the expected behavior of the system based on the information available. In some cases this is done by simply extrapolating future behavior to be the same as current or to expect future behavior to follow the same pattern the system has exhibited in the past under similar conditions. In more complicated situations we will use an estimate of the current state, a model of the system, and assumptions about the disturbances or effects that the system will experience.

How can we improve the accuracy of the prediction? In general, it will be enhanced by having more accurate models, having a better estimate of the current state, and having more information about future disturbances. It is expected that the accuracy of the estimate will degrade the further into the future the projection occurs. This is illustrated in Figure 3 below.

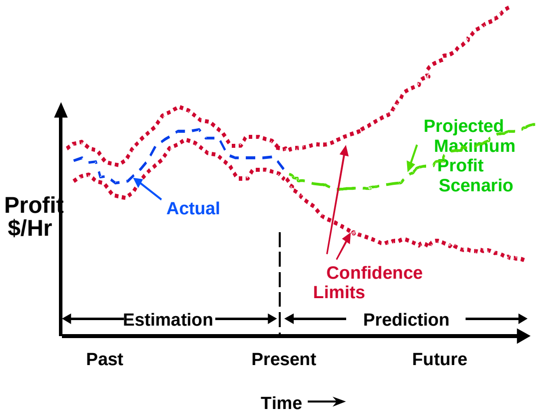

Figure 3 – Prediction versus analysis/ estimation

Decide

Ultimately it is necessary to make a decision about the action to take in the future – including no new action and no change in condition. Normally this is done by evaluating a set of feasible alternative decision sequences and then choosing one which maximizes or minimizes a combined set of objectives within the imposed set of constraints – with this evaluation and choice done within the time available. The decision is improved by increasing the set of feasible sequences considered, by better projection of the implication of the decisions into the future including risk factors, and by the factors mentioned earlier of better knowledge of the current state and more frequent evaluations. In simple terms, the earlier a problem is detected, the easier it is to solve.

Implementation

Implementation is the actual execution of the scenario chosen. It involves all of the activities required to make some change occur including most particularly inducing individuals in the plant to perform or not perform an action. One source of confusion in evaluating the benefits from technology is that only the action, the implementation, actually creates business profit or loss. Without implementation, measurement, analysis and prediction are just an exercise.

Survey of Technology Developments

The decision steps mentioned above are not obviously new and in fact have been followed in plants for many years before computers had any major impact. Those charged with decisions did the best they could at obtaining information on the state of the plant, on estimating its current performance and predicting what would happen with various decision scenarios. However, the uncertainty levels were very high and most decisions were not analytically based.

How have "smart" developments affected the decision cycle? Referring back to figure 2, we can improve the overall process by

- Knowing better what the plant is doing now – this implies more accurate measurements with less delay and more frequent measurements of previously difficult to measure conditions.
- Comparing what the plant is doing against what it is expected to do and understanding the differences – this leads to model based analysis and techniques to better comprehend the information
- Predicting better the effect of alternate decisions in the future

There are certainly dozens and perhaps even hundreds of new developments that could be discussed. In the sections below, the ones that the author views as having the most important impact on operations are presented.

Measure

<u>Smart Sensors</u> – One of the most dramatic technology developments has been in the general area of smart sensors. As microprocessors have shrunk they have been incorporated directly into basic plant equipment. In the instrumentation area this has included transmitters, valves, and primary measurement devises. These devices have become in essence small data servers. A basic transmitter a few years ago would send one 4-20 ma signal back to the control system as an indication of the measured value. Today, a modern transmitter sends back multiple readings plus at least six different alarm conditions including a self diagnosis of potential plugged leads. A standard electric motor that previously had no real time measurements now has as many as fifteen sensors providing temperatures, flux, run times, etc. that are available for recording and diagnosis. Valves now calculate and retain in local data history a current valve signature of pressure versus stem travel, compare it with the signature when the valve was installed, and provide diagnostic information or alarming on the difference. In addition to normal measurements, cheap sensors allowing thermal photographic and audiometric data monitoring on major equipment are being routinely used.

<u>Process Analyzers</u> – Procedures that could only be performed in laboratories a few years ago are now migrating to field devices. Examples include NIR (Near Infra-Red) and NMR (Nuclear Magnetic Resonance) analyses. A survey of developments is provided in Moore (1999).

<u>Communication</u> – Supporting the increases in local measurement and analytical capability has been a change from analog based communication for instrumentation to digital bus structures. These digital busses permit much more diagnostic information to be carried to the data system (Feeley, 1999). The continuing evolution in remote access through developments in the Internet are well known and will not be repeated here. What perhaps is less well known is the penetration of wireless communication into the plant environment. Remote sensors are being installed without wires on plant equipment where there is no need for two way communication and absolute reliability is not as important.

Analyze

The new developments in the measurement area plus the general increase in computer capabilities generally mean much more data is available – more than one can hope to process manually. Part of the response to this increase in data is an increase in automated analysis which takes several forms.

<u>Data Mining</u> – Data mining involves processing large databases to find undetected patterns and associations. The real time data available form the CPI presents special challenges. As mentioned earlier, it is usually corrupted by noise and non-independent, i.e. both auto-correlated and cross-correlated. However, if correlations relating to production variables can be found or if precursors to failure can be identified, the potential benefits are large. As a result, a large number of analytical tools have been developed including special linear statistical techniques such as PCA and PLS (Hawkins et al, 1999) and more general tools (Hairston et al, 1999).

<u>Model Based Performance Monitoring</u> -Generally this implies using the data in some sort of model to calculate performance measures, often called KPI's (Key Performance Indicators). These performance measures are then used to compare actual against plan or actual against original condition (Dormer, 1998). An example is the calculation of specific energy consumption, i.e. energy consumed per unit of feed or product. To accurately assess unit operation, this calculated value has to be corrected for the current feed and product types and distribution, for the current production rate, and for the run time since the last equipment maintenance. This correction can only be done via a model of process operation. Data validation and reconciliation procedures must be used to bring the input data to the standard required by the performance analysis. With the corrected KPI's, actual operation versus plan can be accurately assessed and deviations noted.

Important questions that can then be answered include:

- What is the true maximum capacity of our equipment? Today? If it was clean? If it was new?

- What really stopped us from making our production targets last month?
- How do we accurately and consistently compare performance across all of our sites?
- How do we make sure everybody is looking at the same set of numbers

One of the major uses for this technology is predictive device monitoring. Figure 4 below shows a simple example – a modern smart transmitter with automatic detection of a plugged transfer line. The standard deviation of the current measured signal is calculated and compared with the values when it was first installed. Significant reductions can indicate a problem. The objective of this example and other similar devices is to initiate alerts and corrective action based on deviations from expected behavior. Automatic notification of appropriate maintenance group when problems occur is easy to implement from such a system and benefits accrue from reduced equipment downtime.

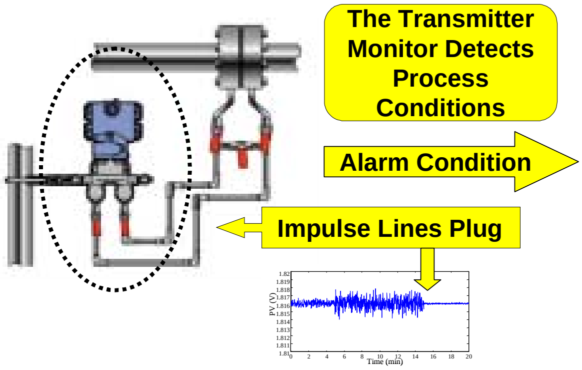

Figure 4 – Typical Smart Device

Virtual Analyzers - Virtual analyzers or soft sensors involve the use of common process measurements (temperatures, pressures, flows, etc.) to infer a difficult to measure property through the use of an empirical or semi-empirical model. This is, unfortunately, one of the development areas where the claims have outpaced reality by a large measure. However, progress has continued and there are a number of actual installations where real value is obtained (Harrod, 2001). Three key limitations that are not always recognized are:

- The estimate is only good within the data region used to train the model.
- Unsteady state process conditions will not generally yield acceptable results since the time constants in the process will normally be different for different measurements.
- Non causal models can estimate current conditions but cannot be used to predict future behavior.

Predict

Perhaps the key difference in the current CPI operation philosophy from that of previous years is the continuing evolution from reacting to a situation based on a history of performance to responding based on a more analytical prediction of performance. In this situation modeling and simulation assume a central position. The general approach is shown in figure 5 below. Historical data is used to develop a model of performance. This model is then used to predict expected future behavior based on the current and recent past data and assumptions about the future disturbances and pattern of operation. Many of the developments in advanced automation fit this pattern – multivariable control, scheduling algorithm development, etc.

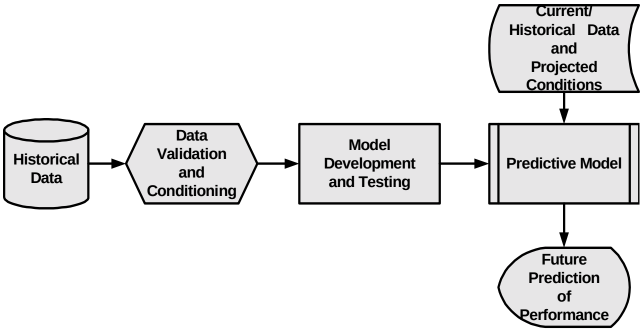

Figure 5 – Use of Predictive Models

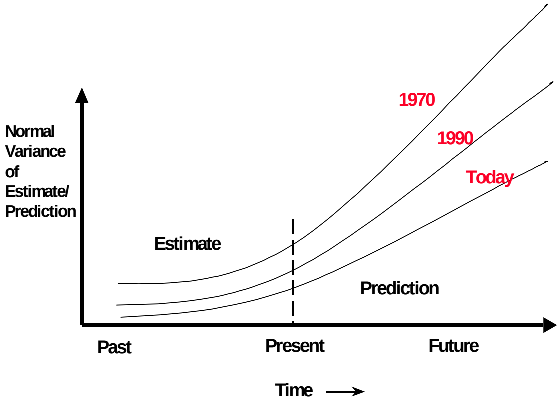

Figure 6 – Variance Evolution

Further, many of the technology developments can be categorized by their reduction in the expected error limits on estimates of current performance and predictions of future system behavior shown previously in Figure 3. The cumulative effect of these developments has been a steady reduction in the uncertainty of the planning projections as illustrated in figure 6 above. In simple terms, we are able to predict better and hence make better decisions.

Decide

As mentioned earlier, a key to good decisions is efficient evaluation of the full range of potential solutions. Clearly, the improved modeling and computational capabilities has resulted in a significant improvement in the plant staff's ability to evaluate alternatives. For example, if there was a production problem at a complex chemical site in one of a number of process units, the normal reaction in the past was to correct the problem by following the response pattern of previous similar outages. This was done not because the staff believed that it was the optimal response, but rather because the time available to respond and the available information did not support any other response. Today, it is normally possible to analyze multiple possible responses and choose one that reflects current actual demands and availabilities.

Real Time Simulation – The increased use of real time simulation as a tool for learning about complex systems such as a CPI plant is one of the most significant of the ongoing developments. This is most valuable in situations with very low tolerance for error or with very infrequent occurrences. Normal examples include training plant operators to deal with emergency situations or with plant start-up and shut-down. The key improvement obtained is a faster and safer response to these types of situations. An interesting development is the adoption of 3D virtual plant representations for this safety training. However, the use of simulation is not limited to operator training. In fact, one of the biggest areas of increased use for this technology is in overall business simulation, particularly in the logistics area.

Expert Systems – Another technology where the hype has significantly outpaced reality has been in the use of expert system technology to assist in decision making. Much has been proposed but few actual systems have been implemented. The modeling of actual decisions has proven to be more difficult in practice than anticipated. However, of perhaps more importance has been the difficulty in maintaining the expert systems current as situations in the plant change. However, work continues and there are new offerings coming such as the one in the press release below (Siemens, 2001).

> "The Industrial Solutions & Services (I&S) division of Siemens recently introduced an innovation from Siemens AG— an intelligent plant monitoring system christened "Human Interface Supervision System" (HISS) in India. HISS senses optical, acoustic and chemical impulses and combines them with analysis and reasoning to 'intelligently' diagnose and forewarn abnormal scenarios and states in industrial plants. It monitors processes around the clock and improves plant safety and availability. As an expert system, HISS finds useful application in various industries including oil & gas exploration, pipelines, chemical and petrochemical segments.
>
> HISS modules such as "HISS Watching", "HISS Listening" and "HISS Smelling" provide round-the-clock remote supervision for manned or unmanned plant locations. ……HISS actually uses human characteristics of analysis and reasoning better than humans and thus allows improvement in plant safety and superior plant availability, claims company sources."

Case Study

The CPI has always been concerned with improving the reliability of major equipment and avoiding unscheduled production slowdowns or shutdowns. As process plants get larger, the financial implications of even relatively short production outages are quite high. Reliable and efficient operation of equipment is essential for profitable production. There are several approaches to maintenance in process plants. One is to wait until the equipment breaks and then fix it if it is really important. The second, known as *preventative* maintenance, uses average times to failure for equipment and schedules maintenance before the expected failure time. However, equipment can vary widely in actual performance. Some scheduled maintenance is unnecessary and some equipment fails before its scheduled shutdown. *Predictive* maintenance attempts to find techniques to determine more precisely if equipment is underperforming or about to fail.

The performance of process equipment, such as compressors, heaters, heat exchangers and columns, often deteriorates with time due to wear and tear and fouling and this deterioration has significant economic implications. In addition, deterioration in process equipment performance in conjunction with traditional condition monitoring is often a precursor to actual equipment failure. Even when process data is monitored online, the actual equipment performance, which is not directly measurable, can be masked by changes in stream compositions, operating conditions, ambient conditions, and other normal process variations. To correct for these variations it is necessary to use rigorous engineering models of the performance and the best possible estimate of the correct values of process input data to the calculation. Figure 7 below shows the overall functioning of the system. This is discussed further in White, 2002.

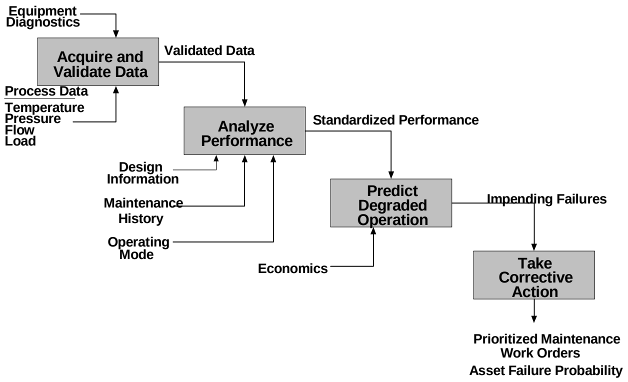

Figure 7 – Predictive Maintenance

Efficient management of plant assets reduces unplanned equipment breakdowns, improves shutdown efficiency and optimizes the maintenance budget. Important associated benefits include the opportunity to benchmark similar equipment across multiple plant sites and the ability to use centralized engineering resources to support multiple sites.

Experience with actual implementations indicates that predictive maintenance technology can result in an increase in potential plant production from existing equipment of between one and three percent due to reduced unscheduled shutdowns. A reduction in unplanned maintenance costs of ten to thirty percent is also expected. The expected incremental return on investments in this technology can be among the highest of any investments available to the plant.

Outstanding Issues

Clearly there have been many new developments in this area and many successful technology adoptions. However, there are numerous practical issues that have delayed further implementation. While technology is part of the equation, it is clear that the primary issue concerns individuals and organizations. The author’s experience is that the technology generally works – if not totally, at least partially. However, many new technology implementations fail on the human issues involved. Individuals and organizations are highly resistant to change. How to make individuals feel comfortable with the new technology and how to fit the new decision models into an organization’s existing decision and power structure are the primary open questions. While these questions may seem outside the normal range of enquiry for technologists, their answers will continue to limit the rate of progress.

Conclusion

Dramatic changes in computer and communication capabilities are occurring and will continue to have a very large impact on plant production. The trends in manufacturing financial incentives, health, safety and environmental issues, and plant operating demographics are driving many of the potential uses. Significant benefits can be obtained by taking advantages of these opportunities. Companies that are the quickest to take advantage of these opportunities will benefit the most.

In other industries developments are ongoing and perhaps illustrate the path forward. The GE appliance division is already developing refrigerators, washers, and other appliances that receive instructions and report over the web. It will not be too long until your doorbell rings and the repairman says, "I received a request from your refrigerator to come and replace the drive belt.“

Can process equipment be far behind?

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