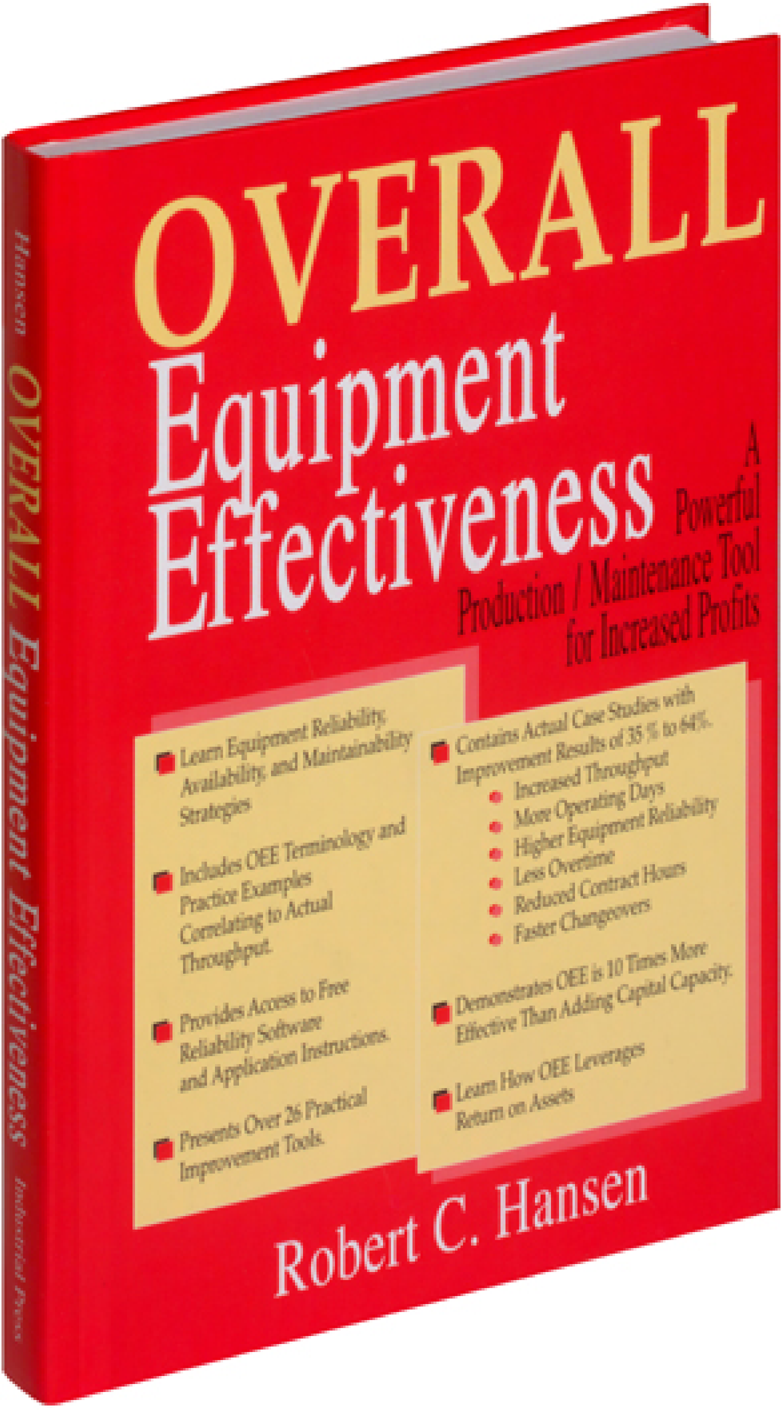
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By
Robert C. Hansen

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FOREWORD

Overall Equipment Effectiveness (OEE) began to be recognized as a fundamental method for measuring plant performance in the late 1980s and early 1990s. It was a period that saw the emergence of serious big company maintenance benchmarking, the introduction of Total Productive Maintenance (TPM) in America, and the founding of the Society for Maintenance & Reliability Professionals.

At first, OEE was closely bound to TPM and often was seen as a vague defining measurement for winning the TPM Prize. Then, as more practitioners were exposed to OEE in TPM-related articles and seminars, it was viewed as a standalone tool for measuring true performance by merging performance indicators for availability, efficiency, and quality.

OEE came to be further valued as a change agent for bringing maintenance, operations, and engineering together to address the higher-level issues of plant performance. Now, it is accepted by management consultants as a primary performance metric.

Recognizing OEE as an effective productivity management metric is one thing, using it effectively is another, as many practitioners have found out. The OEE learning curve can be steep. Bob Hansen has been there, climbed over the obstacles, and survived to develop a practical how-to approach to using OEE which he lays out in Overall Equipment Effectiveness: A Powerful Production/Maintenance Tool for Increased Profits.

I've known Bob for a number of years as a maintenance and reliability practitioner, seminar leader, and author of magazine articles. I've found his analysis of OEE and related productivity processes insightful and practical, as have members of the maintenance and reliability community. Now, he has put everything together to build this comprehensive reference.

Not only does he cover OEE, but he presents related productivity and reliability tools in a format for quick application. He provides practical tips on what to do and how to do it. As such, the book becomes a must-have desk reference for maintenance managers, production foremen, reliability engineers, manufacturing executives, and plant leadership teams.

Robert C. Baldwin, CMRP
Editor, Maintenance Technology Magazine
Barrington, IL

PREFACE

O*verall Equipment Effectiveness: A Powerful Production and Maintenance Tool for Increased Profits* brings together both the social and technical aspects of successful manufacturing and processing. I would have paid many times over to have such a book at the start of my manufacturing career. The book is a practitioner's primer; it demonstrates how to apply and improve overall equipment effectiveness at your factory or processing plant.

Picture yourself facing a majestic mountain that represents performance excellence at its peak. Every factory or processing plant represents a mountain and no two are exactly the same. In fact, each changes whenever its products, processes, materials, or people change. Achieving excellence is a continuous climb.

You have many decisions: where to start climbing the mountain, what to take with you, how to use your resources, and which tools to use to measure your progress. A wise person would first engage those who have made the climb before and learn from them what worked and what didn't work. This book lays out guidelines and strategies for a successful climb. It is not the only way to success; however, it can reveal new trails that help shorten the journey.

Every department and area where I have worked has demonstrated some level of progress over its years of operation. When significant jumps in productivity were made, I thought about the vast amount of income that could have been realized had the practices and procedures that identify and leverage the "hidden factory" been implemented years earlier.

I hope that plant and corporate managers accountable for production operations not only learn the concepts and theories but also take the responsibility to personally champion OEE. If you are not supporting reliability, then you are supporting failures.

The concept of true OEE is the most important aspect of this book. This book is worth its weight in platinum if all it does is help you discover your plant's true position relative to its current performance. This potential is determined by taking the actual quantity of good product transferred out and dividing it by the total amount that could be made in all the hours of scheduled production. This amount is what could be made without any losses due to quality, speed rate, equipment downtime, changeovers, start-ups, shutdowns, or lack of materials and supplies. If your plant is in the envious position of selling everything it can make, then your hidden factory is the difference between what good product was transferred out in the past twelve months and what could be made in 8760 hours of perfect production.

Parts of this book focus on collecting data, generating information, prioritizing, and selecting ways to significantly improve the bottom line. A major goal is to show how to identify the improvements a project should yield in financial terms, then to actually generate those results.

I have outlined a methodology that links OEE and equipment reliability improvements to bottom line increased income for operations. This methodology is a powerful tool that should assist every engineer, foreman, department head, and manager in selecting the right projects and then communicating the benefits in financial terms.

A portion of this book provides tools and techniques for examining the inherent reliability of existing or proposed equipment systems and design for reliability methodology. These include reliability block diagrams and computer simulations of modeled systems. The book refers to software that can be freely downloaded from the Internet. The examples demonstrate practical applications that investigate possible improvements. The software program can perform the vast majority of that provided by highly-priced commercial simulation software.

Another useful tool is Reliability Quantification Testing (RQT). This general tool for existing and new equipment fabrications helps quantify the actual reliability performance. It should become a mandatory tool used for accepting or commissioning equipment systems critical to your manufacturing processes. To build in reliability of proposed designs, reliability specifications and the level of testing before acceptance must become a part of the original purchase order. RQT establishes the test hours and failure frequency parameters, then generates a point estimate of actual Mean Time Between Failures for the tested system.

In addition to OEE, this book champions the theory of constraints management, quick changeovers, production–production capability balance, conditioned-based maintenance, and a maintenance strategy of short frequent linestops. Any one of these tools or techniques might leverage additional productivity out of the hidden factory at many plants worldwide and could be financially important to your company's overall business.

Several aspects of the human side of manufacturing are addressed in this book. Years of observing maintenance people doing extensive shutdown work provided insights about human energy levels and attention to details. These observations form the basis for shutdown planning guidelines. In addition, a system of ranking and compensating workers doing nonrepetitive work is provided as well as recommendations about the hiring process. One of the most important purposes of this book is to help plants avoid the pain of unplanned downsizing that results from not being as productive as they could be. Over the long term, plants can not downsize themselves to success without fundamental changes in current methodologies.

At the very least, this book is intended to motivate readers to start now on their journey up the mountain toward performance excellence. I would be delighted to receive comments and stories about the active use and application of this book's concepts in your work area.

Getting people to accept change and do things differently can be very imposing even if you know it is the right direction to go. Change often requires a leap of faith. Understanding this book will *reduce the leap of faith to a single step.* Climbing to higher levels on the mountain begins with a single step. Start Now!

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All the authors of the suggested reading materials in Appendix 1 and 8.

And, in no particular order, the people who educated me or worked directly on aspects of this book.

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CHAPTER 1

UNDERSTANDING THE POWER OF OVERALL EQUIPMENT EFFECTIVENESS (OEE)

This book is the culmination of the many years of experience I have inside a large Fortune 100 company. It is offered as a "how to improve" guide for many of the issues that exist in manufacturing work centers (factories or refineries) of all sizes and types. We will look at the key parameters for the success of manufacturing communities, then link those parameters to the financial business metrics that are vital to your company's success. We will also look at the *practical* application of theories that are commonly spoken, but seldom accepted on the factory shop floor.

Aspects of this book are appropriate for everyone involved in or supporting a manufacturing process. The book provides all work centers with techniques and measures for greater throughput that requires little or no capital spending. Over the years, I have been successful in five different types of manufacturing processes. Based on that experience, I offer recommendations regarding what does and does not work to improve productivity and reliability-maintainability in both the short term and the long term. I hope you will use this book proactively to drive improvements in your area.

1.1 Factories: Effective Producers of Good Goods

Every factory* attempts to be an effective, low-cost producer. This effort is required in today's challenging environment when customers demand quality product at the best value. Few factories attain and maintain high level productivity and low costs. Many of these use a disciplined approach to identify the best improvements to make. They use teams to eliminate the root problems that otherwise keep the factory from driving toward continuously higher levels of effectiveness. In short, they have found the power of OEE: Overall Equipment Effectiveness.[1] By recognizing the 'hidden factory' within, they have made improvements that contribute directly to the bottom line.

World-class manufacturing areas share two common characteristics. They are data driven and they are led by synergistic multi-function leadership teams. Accurately measuring and driving key success parameters contributes to higher productivity for both the area and the plant. A method called Overall Equipment Effectiveness, or OEE, can help you better understand how well a manufacturing area is performing, and identify what is limiting higher effectiveness.

Manufacturing systems are composed of equipment and machinery that combine to transform materials and sub-assemblies into products that are either parts for the next step of manufacturing or finished goods. A significant amount of capital is often invested to design, build, and implement a system so that product can be made uniformly at a high rate with minimal waste. The factory should effectively deliver the product at less cost than would be needed to produce it individually. Every business plan should include projections about the effectiveness of the proposed system and how well it will contribute to the bottom line. The company should also be aware of the degree to which it is at risk if the expected effectiveness is not attained and sustained.

Continuous and discrete processes of transforming materials and parts into products can be complex and unique; the system is often quite technical and elaborate. In many instances, a standard product is manufactured in many different formats and variations. The system, therefore, splinters into multiple processes, yet they use shared resources. Some of the cases in this book come from the author's personal experience in a set-

The word 'factory' can be replaced by 'refinery' throughout this book.

ting where over thirty process setups were used to produce variations of seventy different products from four different product families. The capital investment was well over $100 million. Thus, the operating cost to product was significant; the effectiveness of the operation had a major influence on the company's bottom line.

Nearly every industry has multiple manufacturers, each competing for its share of the market. Even a company with the best product may not stay in business if its expense for getting the product to the customer is excessive. Fierce competition usually exists. Companies with the most effective factories will have the staying power to be the long-term survivors, assuming that the need for the product is continuous. This "staying power" provides a significant advantage over time. For example, in the paper clip industry, one of three U.S. manufacturers has equipment over 50 years old, still producing high quality clips[2]. Sound investments over half a century ago, and on-going maintenance, has provided a long-term business advantage to the company.

In short, factories are at the core of any manufacturing company. Staying in business requires building and maintaining effective factories.

1.2 Factory Dynamics

At any given factory, a vast number of events occur simultaneously every workday. The tasks of producing goods and maintaining equipment usually hold the central focus. However, take a moment to think about all the activities that go on and how and when they impact the manufacturing process.

Decisions made in purchasing today set in motion a timeline for each item ordered and used. How well a piece of equipment is repaired today will influence some future runtime. In the spare parts warehouse, if a bearing is accidentally dropped on the floor today, and re-shelved for later use, the piece of equipment that eventually uses it may have a shortened life. Approval or rejection of various projects can affect overall operations for years to come. Hiring and training decisions by human resources set the stage for subsequent events.

In short, all the pieces of a factory interlock. One event eventually affects all. Left on their own, all these elements can create a chaotic, reactive environment full of surprises, a home for "Murphy," the demon that brings bad luck. Actually, with all that can potentially go wrong in a factory, it is amazing that factories do as well as they do.

And yet, what makes the difference between world-class manufacturers and the rest of the pack? World-class organizations have evolved from a factory of individuals to a factory of coordinated teams working together with a common purpose. All areas have win-win relationships with their interdependent areas. They make certain that decisions are made correctly the first time. They balance production and production capability appropriately. They are in control of "the big picture;" they have engaged everyone's support in working toward a high level of excellence and sustaining that position. The bottom line: they know where they are and where they are going.

World-class companies do not create their environment overnight. They may need three to five years to achieve most of their gains. They then start a long journey of continuous improvement. Much of the work is educating all employees about doing their business with others in mind. People may still work independently, but they also understand their relationship with the whole. All employees understand the objectives and strategies of the company. I would rank 'can do' people as the most important element of the factory.

At one plant where I worked, every department had submitted its minimum operating budget for the following year. Our corporate headquarters did not accept our proposed budget. We were challenged with a goal of reducing our plant costs by an additional $12 million from the submitted budget. We held many meetings to develop a plan that could produce the results or, as an alternative, plan for inevitable downsizing. Our management team for the plant did not see how we could possibly meet the challenge. We were prepared for the worst.

Finally, one manager suggested that we turn the problem over to the plant community, offering a reward or gain-sharing plan if the plant were to meet or exceed the budget challenge. This strategy was approved and communicated to all the workers. Almost immediately, everyone in every area of the plant began to do all the little things that contributed to our beating the goal. The result was an outstanding performance for the year, surpassing the once-impossible goal by a significant amount. Everyone was amazed at how powerful this dedicated and engaged community was in making the right things happen, once a common cause was accepted.

1.3 Balancing the Business

The last section considered the big picture within the factory, the interdependence of areas and people within a plant. Similarly, the factory is one component within the overall business. It is not enough for you to understand the dynamics within your factory. You must also develop an appreciation for the importance of productivity throughout all parts of the company.

Many different components are needed to make a business successful. The dynamics of these components are often even more dramatic than the dynamics within the factory. In smaller companies, managers must often juggle many different facets of their business at once. Not only do they oversee factory operations, they are also concerned with sales and marketing, accounting and finance, and human resources for the company. Because large organizations are often organized functionally, managers often focus only on their aspect of the business. Yet within that area of focus, they are also often concerned with other areas. In all cases, you should understand how your area of responsibility fits into the larger picture.

You can develop skills and a sense of understanding about managing the overall business in many ways. Traditional academic courses in business, whether at undergraduate, graduate, or vocational schools, are a common approach. At some companies, you may be given a series of three-to-six month assignments that take you from one functional area to another. These assignments help you develop an overall understanding for the company. I encourage you to proactively seek various positions in different departments and areas your factory or different factories. Do this with the intent to learn new processes and perspectives each time too gain experience and skills. Cooperative diversity is a strength in factory teams.

Sometimes a faster way of getting exposure to a company's complex dynamics is to participate in a simulation. Many business simulations are available. Sometimes you attend a seminar away from the company. These seminars may involve groups of employees from your company or employees from many different companies. In other cases, the person running the simulation may set up an in-house program.

Decide II: A Simulation Experience

A few years ago, I participated in a helpful simulation exercise run over four days. The seminar, Decide II, was developed by Dr. Thomas Pray, Professor of Decision Science at Rochester Institute of Technology, Rochester, NY. The seminar consisted of several simulation exercises, alternating with short lectures and workshop activities. The class provided an excellent framework for cross-functional thinking and team building with several of my company associates. Among the results was a better understanding of many business reports and marketing approaches.

Within the simulation, a class of up to two dozen participants is divided into three- or four-person teams. Each team forms a company and starts with the same information and resources. All the companies make an imaginary common product and compete for the same general market. Teams must set company objectives, implement strategies, and compete against each other.

Teams select their own strategies. For example, one team may decide that its company will produce high volume/low price and pursue a large share of the market. Another team may decide to develop specialty items at high prices, securing a profitable market niche. The teams develop strategies for how their companies will manufacture and sell their products.

Decide II uses a menu-driven Visual Basic decision-support software package. Teams enter their decisions into the Decide II software. Each team then receives immediate feedback on profits, cash flow, quality, and other measures of the effectiveness of their decisions. This feedback is based not only on the decisions made by the team itself, but also on the other teams' decisions.

Over the course of the simulation, teams enter a series of eight sets of decisions, with ongoing results provided each time. Thus, the second set of decisions is based on the results and new market environment from the first set of decisions. The team's overall score is provided by the stock price, which varies relative to each company's overall health. According to Decide II, your company is rewarded for "creating economic value by ***implementing a solid and 'balanced' business plan*** that generates ***free cash*** (i.e. cash from operations), ***economic profit,*** and ***earnings from operations."***[3]

As part of the Decide II simulation, each team must make decisions covering the full range of functions, including:

- ❑ Marketing: Price, Promotion, R&D-Process, R&D-Product, Service, Customer surveys.
- ❑ Operations: Production, Labor Scheduled/Overtime, Maintenance, Material Purchases
- ❑ Finances: Capital Investment, Dividends, Securities, Market Research
- ❑ Human Resources: Headcount Plans, Training Budgets, Pay & Compensation, Employee Surveys

The simulation also works in many of the key issues facing industry today, including:

- ❑ Total Quality Management and Customer Satisfaction
- ❑ Total Quality Costs: Prevention, Appraisal and Failure costs
- ❑ Competitive Benchmarking
- ❑ Customer and Employee satisfaction surveys and impacts
- ❑ Commitment to customer service
- ❑ Headcount Planning Linked to Production and Capital Plans
- ❑ Pay and Compensation Issues
- ❑ Personnel Training and Development elements

Within each round of decision making, the teams use information from a variety of reports generated as part of the simulation, including:

- ❑ Operating Income Statements
- ❑ Balance Sheets
- ❑ Manufacturing Reports
- ❑ Total Quality Reports
- ❑ Cash Flow Reports
- ❑ Economic Forecasts
- ❑ Market Research Reports
- ❑ Stock Market Reports

Participants in the simulation quickly build an appreciation of how complex individual businesses can be. They also see the importance of balancing the use of resources, assets, information, inventories, prices, and sales in order to generate net profit. Because the simulation involves several rounds in a competitive setting, participants also see how one set of decisions affects another set of decisions and results later in the process.

For our particular team, the biggest lesson was to realize the importance of maximizing factory output without the use of overtime. That efficiency, combined with an appropriate market price, helped us develop a healthy business. In our simulation, labor was a very large part of the manufacturing cost. Therefore, minimizing overtime was of vital importance. In other settings, the primary cost may be in automating a process, with labor a minor cost factor. In this case, maximizing the equipment use, even if overtime is necessary, may well be the better choice.

The simulation reinforced the sense that the size of the opportunities for business improvement varies proportionately with the level of information sharing throughout the company. For the best decisions that lead to profitable results, decision makers in the company need information, for example, not only the cost of manufacturing each product, but also margins, compensation and reward policies.

I once worked in a factory area where assets were used to make difficult-to-manufacture products at slower speeds. The level of output ran counter to local expectations of productivity, and the morale of the workers was low. However, once the information was shared that these products provided much greater net profit than standard goods produced elsewhere, morale improved. This understanding helped the group accept the challenge of making these difficult products effectively and overall effectiveness increased. Also, the reward system for the factory could be adjusted accordingly. Remember, what is measured is extremely important. Just measuring barrels/hr or widgets/shift does not measure the business results because profit margins vary with different products.

1.4 Leadership for Teams

Effective factories usually have coordinated teams that work synergistically with a common purpose. The teams, which are from all areas of the factory, have win-win relationships with their interdependent areas and services.

According to a panel of five reliability consultants at the year 2000 annual conference of the Society of Maintenance Reliability Professionals (SMRP), successful initiatives and programs are primarily driven from the top down rather than from the bottom up. In fact when asked, the panel couldn't relate a single successful experience with a bottom up initiative unless it was first communicated to and accepted by the area leadership.

My own experience supports the concept that successful programs can be implemented at the level of the 'Champion' on down. This can be seen where successful programs develop in one work center without ever transferring to other factory areas. When the person who championed the program leaves or transfers, all too often the work center does not sustain the high performance. However, the champions are able to generate new initiatives in other areas once they establish a rapport with the new community.

Management support and area leadership significantly influences the success of initiatives. To sustain a level of excellence, the total community--management, the line organization, and support groups--has to be of one mind. High performance work groups bridge the ‘top down’ syndrome by acceptance of synergistic team leadership.

Nearly everyone comes to work with a desire to do a good job and to be part of a successful unit. Your job and the security of your business depend on strong productivity and top effectiveness. Frustration comes when priorities are not clear and reinforcement is awarded inconsistently. Thus, a single metric--measuring the community as a whole--can be powerful in bringing everyone together.

Let’s look at an example. I once facilitated a workshop activity aimed at improving the changeover time between orders for a packaging operation. This area had four similar flow-lines working around the clock seven days a week. The area had four shifts with four crews per shift, or a total of sixteen crews. Because each flow-line had two to ten changeovers per day, reducing the changeover time for the work area would greatly improve effectiveness. A workshop for developing quick changeovers using a methodology called Single Minute Exchange of Die (SMED)[4] was selected for this task. SMED or quick changeover is covered in section 8.3 of this book.

The operations manager decided to have one crew be the pilot crew that would go through the workshop and develop a best practice methodology. This approach proved to be more complex than expected. The area worked with approximately 130 different products, using 35 different processes. Many crews worked with more of one combination than another. Therefore, a typical changeover really did not exist.

In the workshop, the pilot crew categorized changeovers. They initiated improvements that reduced the majority of their changeover times by 40 percent. At the end of the pilot period they presented the results to the product line superintendent. Although they were proud to receive the superintendent's congratulations, they were shocked when he directed them to teach their methods to the other crews. They had not anticipated this directive, and felt that their reward was more work, beyond the original scope of the workshop. As a pilot crew, they synergistically made improvements, however other crews did not readily accept ‘outside’ ideas and passively committed to new methods. Thus, the improvement methods took much longer to be accepted by the other crews.

What actions would have been better? Proactive leadership would have led to faster results. When the operations manager initiated the request for improvement, he should have confirmed the efforts were supported by the superintendent and then communicated this to all crews. The overall objective should have been outlined with the strategy of how a pilot crew would be selected from volunteers, that this crew would make recommendations for best practices, and that all crews were expected to adapt these methods into their changeovers. If the results of the improvement were visible to the crews, and a system was developed to reward the community when the average changeover improved, then the methods would have been implemented quickly. The superintendent should have invested three or four hours of proactive leadership, earning the support of all the crews. By clearly communicating the desired goal and the expectation that everyone will help implement improved work practices, proactive leadership would provide the community with a common vision. This style of leadership and communication open the way for rapid implementation and sustain improved practices.

Proactive leadership is a vital part of developing work place improvements. It can start at any level of the organization. As objectives are selected, approval should be solicited from the area leadership team to clear the way for rapid success. This book should provide the tools to generate compelling programs for higher effectiveness

1.5 Moving the Community to Improved Performance

Having an effective factory is not the only requirement of a successful business. Many other factors are also important. Which way is the economy going to move? Will the competition cut prices? Is the product in demand? Will the product evolve into another? What are the distribution channels for the product? Should the source of supply be in one place or several? World-class companies continually address these and other questions as they shape and modify their business plans.

World-class companies are known for another attribute. They are built around the concept that an effective factory producing "good goods" as needed to meet market demands is a valuable asset for any company to have. This attribute is maintained both short and long term. One of the main metrics used to identify world-class companies addresses how effectively factories run their processes when scheduled to run. OEE is designed to provide this number. Yet most factories do not compute OEE or use it to set and maintain their priorities. OEE is the product of availability (actual run time vs. scheduled time) times speed rate (actual rate vs. ideal speed rate) times quality rate (good product vs. total product). These parameters are defined in section 2.1. A second metric examines how effectively do factories run their processes relative to the total calendar time. This metric, Total Effectiveness Equipment Performance or TEEP, will be discussed in section 1.6.

All manufacturing processes have some kind of constraint. Factories often subdivide product manufacturing into several steps, using inventories or queues between steps. When factory resources are shared, or used in multiple ways, the manufacturing process grows in complexity. The constraint for one product is often different than for other products. The Constraint Management Handbook6 is a good reference for understanding and operating the vital steps of manufacturing lines and multiple product orders.

OEE should first be applied to the bottlenecks that affect throughput or any other critical and costly areas of a manufacturing line. These areas, so vital in making a plant effective, make a significant difference to the company when driven successfully. OEE is beneficial for every step of the process, however, non-bottleneck steps should be subordinated to bottleneck steps.

Effectively moving a community toward an OEE mindset starts with a company-wide education program that is driven top down. The plant management team must first identify the hierarchy of bottlenecks. Then setting expectations and communicating them to the plant employees launches the initiative for a successful change. OEE should work synergistically with the financial information for each product. When OEE is used by management as the key metric for a factory's vital points, and each person's performance appraisal is linked to improving the metric, an effective factory evolves quickly.

True OEE multiplies factors that represent availability, speed, and quality. The result can be expressed as a percentage of effectiveness that directly correlates with actual factory floor output, and can be reconciled 100 percent. This will be demonstrated in the Case Study that follows.

Understanding the correlation concept is key to having a single metric that has credibility with the production, maintenance, engineering, management, and financial areas.

OEE can be generated easily and accurately; it can quickly demonstrate the size of the hidden factory in your specific area. In turn, the plant leadership team can apply people and resources to the proper locations for the fastest improvement.

Chapter 2 will provide a practice example including recommended definitions, a sample production period, and a total range of incidents. In developing the OEE formulas, it will demonstrate that the three different approaches provide exactly the same OEE. Even areas without detailed data collection can still use the simplest method to calculate an accurate OEE.

All manufacturing areas should be able to answer the following questions for each product:

1. How many units that meet specifications were made and transferred to the next step?
2. How much time was scheduled for production of that product?
3. What is the ideal or best theoretical cycle time or throughput for units of that product? (If this were unknown, a rough approximation would be to use the speed value generated by the best 4 hours of the last 400 hours.)

With this information, the simplified calculation shown in section 2.5 can generate an accurate OEE for each product. Prorating the individual product's OEE can generate a combined OEE for the area. I recommend prorating by the percentage of production schedule time used to make specific products. Even areas with good data collection should reconcile OEE by using the simplified method. All methods should reconcile. If they do not, assume the lowest value is correct and that the other methods have overlooked an area of opportunity. Remember, true OEE directly correlates to area output.

After analyzing all major processes and important equipment systems for each plant site, summarize the results from each area as follows:

- ❑ < 65% Unacceptable. Hidden dollars are slipping away. Get help now.
- ❑ 65-75% Passable, only if quarterly trends are improving.
- ❑ 75-85% Pretty Good. However, do not stand still; continue to drive to a world-class level. (>85% for batch type processes and > 90% for continuous discrete processes. Continuous on stream process industries should have OEE values of 95% or better.)

Ron Moore of the RMGroup Inc. related to me his best OEE experience was a client with a verified on-stream OEE of 98% over a two-year period.

Using OEE metrics and establishing a disciplined equipment performance reporting system will help any manufacturing area to focus on the parameters critical to its success. Analyzing OEE categories can reveal the greatest limits to success. Forming cross-functional teams to solve these root problems will drive the greatest improvement and generate real bottom-line earnings.

The vast majority of these improvements usually come from non-capital projects. Changes to basic procedures often reduce bottlenecks. Changing supply or distribution policies can help manage bottlenecks. Significant equipment reliability improvement may result by changing maintenance methods or substituting different materials. Focused projects, such as Reliability-centered Maintenance[5], can provide major increases in uptime. Improving performance through OEE involves several steps:

1. Calculate the OEE value for current performance (see method 3 in section 2.5).
2. Use discipline and be honest with the results. Compute the financial opportunities of improved throughput (use the model provided in chapter 3). Generate a realistic business plan of closing the OEE gap to world-class levels for your type of industry. At this point, accept the assumption that improvement programs will consist primarily of education efforts and focus teams collecting/analyzing data for root causes. Minimal capital is required and existing resources are usually adequate. Training time and participative education on improvement methods contained in this book are often 90% of the investment.
3. Assuming that the size of the opportunity is significant, commit to a pro-active agenda. Define the hierarchy of critical processes and bottlenecks. Set expectations for plant goals and rewards. (This step may require changing existing measures and reward ystems.) Once the key bottlenecks are identified, they must be tackled. OEE and Constraint Management methods should work in synergy.
4. Once the goals are defined, and a plan for addressing the bottle necks is established, share this vision with the workers. Communicate the significance of the improvement and give the

community a compelling reason to make the changes. At this time, identify the reward structure.

5. Educate all members of the community about OEE measures and how to collect and reconcile the information. For example, counters, time clocks and chart recorders may be needed on key equipment systems. Reports may need to be modified to categorize downtimes. Everyone should have a major portion of their performance appraisal and compensation linked to achieving the OEE goals. By understanding the categories for data collection and how losses impact OEE, synergistic teams will form. These teams can quickly eliminate root problems. Associated departments can support additional improvements.
6. Generate the resources (e.g., money, people, time, and training) to make the changes happen. Introduce new techniques and programs, as appropriate, including condition-based, predictive maintenance and reliability programs, Total Productive Manufacturing and Best Practices techniques, Statistical Process Control, mistake proof and fail safe techniques, supplier quality requirements and follow up, and quick changeover techniques for operations and maintenance repetitive tasks.
7. Use the OEE metrics at all levels of the plant. Share the results with all parts of the plant community. With good data collection, each improvement project should demonstrate the projected increase in OEE. By frequently posting OEE metrics, any distur bances to high productivity will surface and can be quickly investigated.

A Case Study Using OEE Metrics

In 1996, I was assigned to a highly automated film finishing work center staffed with about 140 people. It was organized into high performance work teams manning four similar equipment flowlines, 7 days a week, 24 hours a day. The area was lead by a cross-functional business team and was data driven. This area finished many different sizes and formats of product and was challenged with many ‘new’ formats and products, as well as methods of operation to improve inventories. Daily meetings were held to review ongoing performance of the "factory", which included the output quantity, flow line availability, and equipment reliability expressed as an index of the four lines. Meeting the projected production schedules was critical for just-in-time delivery and avoiding overtime in related work centers.

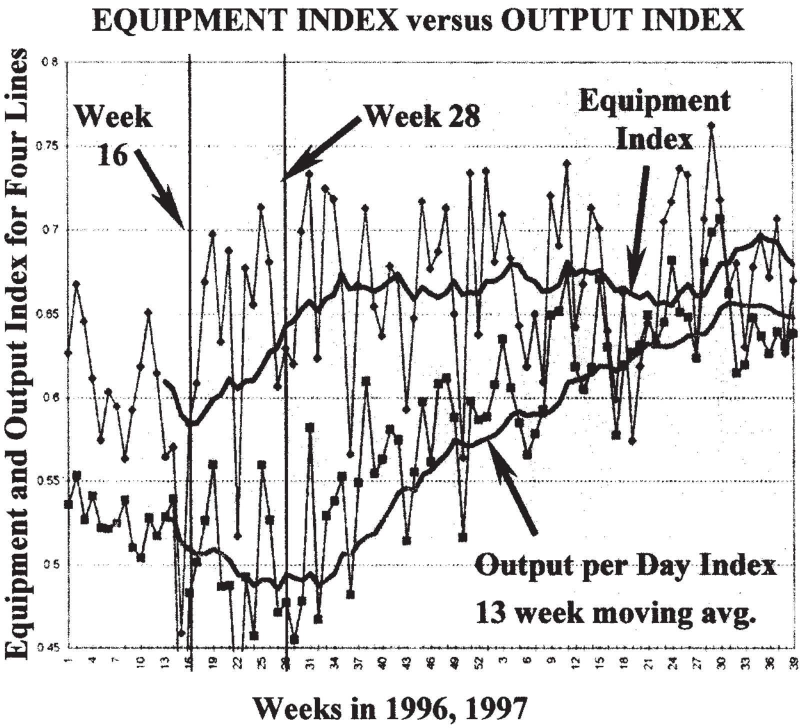

Figure 1-1 Equipment Index versus Output Index

One advantage for the area was an automated Equipment Performance System (EPS) to gather information. The EPS system provided all of the information suggested for categories to compute a detailed OEE, including frequencies of events. However, in early 1996, OEE was computed only monthly and submitted to plant management. It was not being actively used as an online guiding metric.

New levels of output had been achieved at the end of 1995 and carried into week one of 1996. See week one of figure 1-1. Output projections for 1996 were even higher. This was because prototype equipment improvement projects appeared to be successful. Early in 1996, the equipment improvement upgrades were migrated over all four flowlines.

Although the impact of shutdowns on operating schedules was minimal, the equipment changes required procedure changes and retraining for operators and mechanics.

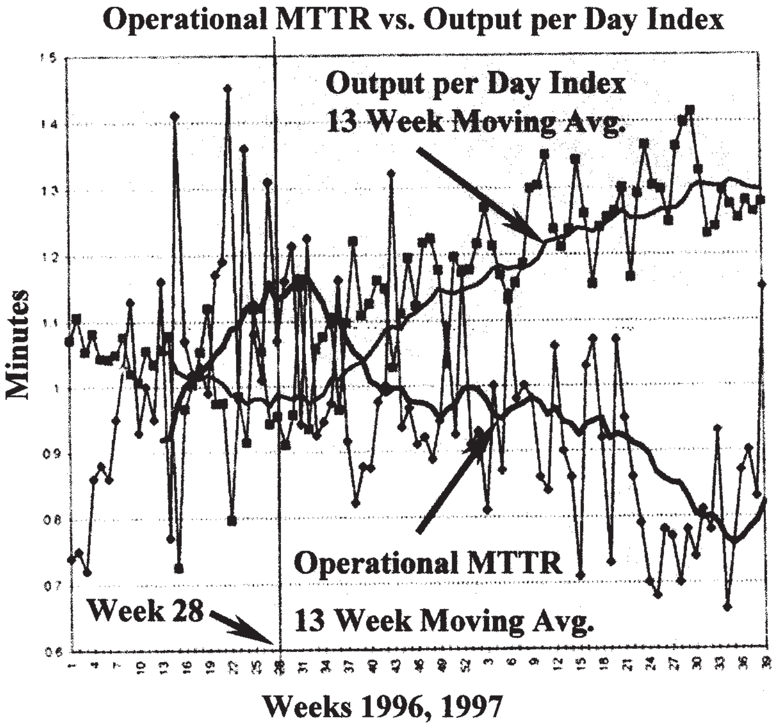

Figure 1-2 Operational MTTR

Almost from week one, 1996, the output began to decline from expected levels. The second quarter results were very serious with an under production of 10 percent. By week sixteen of 1996 the investigating team had reached a conclusion.

In general, the feeling was that equipment reliability was not good. It was reported that the modifications were causing more problems, and couldn't reliably handle new products.

With this information, the technical community worked hard to make sure processes and systems were working properly. With intense focus, the equipment reliability index improved over the second quarter by approximately 10 percent. See the increase in the equipment index following week sixteen in figure 1-1 Equipment Index vs. Output per Day Index.

Yet, factory output was still going down.

A more thorough investigation followed.

In review of all parameters, the root cause was found to be operational downtime. However, a study of this category did not reveal any unique or significant single items of downtime, by machine section, crew or product.

Only after plotting Operational Mean Time To Restore (MTTR) did the understanding that the many little events, which used to take 0.8 minutes to restore, were now taking 1.1 minutes.

Over time, poor habits and interruption of concentration had diverted the attention from "making product". See figure 1-2 Operational MTTR. This underscores the importance of being able to collect time <u>and</u> frequencies of category events.

Week twenty eight of 1996 was the specific "intervention" date when the results of the detailed investigation were shared with each crew. That date is noted in figures 1-1 and 1-2.

Once the community was presented with the information and convinced that they really could influence the outcome by re-focusing their attention to detail, the output per day began to recover. In fact, output did reach the higher levels as predicted with the equipment modification project.

This understanding lead to a review of the OEE metric and revealed that existing online measures could be used to compute OEE. Online OEE does correlate very well with actual pack output for this work center. See figure 1-3 Case Study showing Actual Output and OEE Computed Output in 1997. By instituting online OEE measurement, this area has a powerful tool to monitor the on-going health of their production process.

The work center now makes OEE available each shift and plots the metric weekly. The metric is being used for a portion of everyone's annual performance rating.

1.6 Total Effectiveness Equipment Performance (TEEP)

Whereas OEE measures the effectiveness of planned production schedules, Total Effectiveness Equipment Performance (TEEP) measures the overall equipment effectiveness relative to every minute of the clock, or calendar time. In many settings, management is especially interested in how well a factory's key assets are used relative to total calendar time. TEEP is the metric that indicates opportunities that might exist between current operations and world-class levels. It reveals the hidden factory

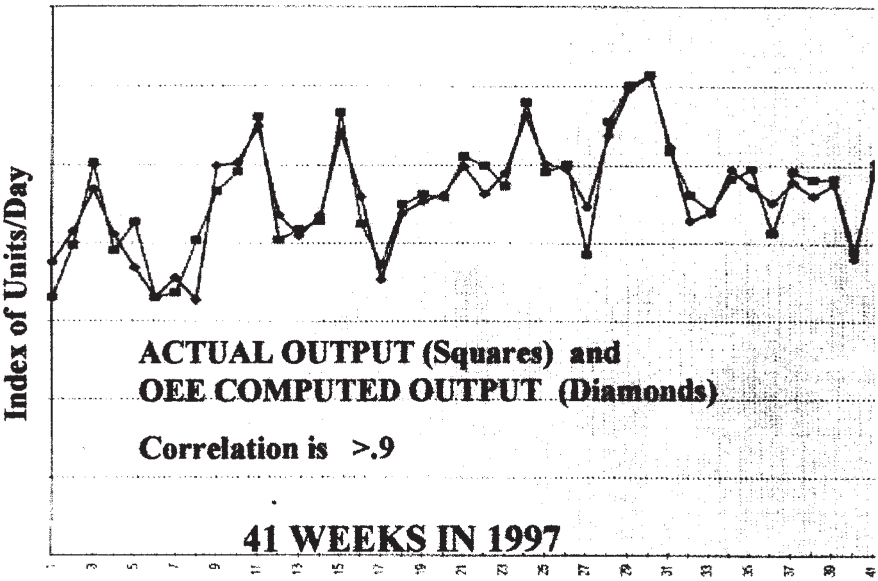

Figure 1-3 Case Study showing Actual Output and OEE Computed Output in 1997 Correlation is >.9

that can and should be leveraged to make the company more competitive. Like OEE, TEEP must be used in combination with financial information.

TEEP numbers can be used to speculate on the potential capacity of an existing plant. The last increments of reaching total capacity usually have higher unit manufacturing costs especially if labor overtime is involved. The final increments need to be evaluated from business and OEE perspectives. With focused improvement projects for OEE and TEEP which makes every hour of operation more effective, it is quite possible that future capacities with overtime will be manufactured at less than current (before OEE) standard unit costs without overtime.

The strategy at many companies is to run their factories 24/7 – 24 hours a day, 7 days a week – and to produce the maximum amount of product possible. These companies often can sell everything they can make; they may also be the lowest cost producer. In some cases, the capital investment in equipment and facilities is quite large; and using the asset around the clock maximizes return on investment. In other cases, the process is continuous and, therefore, expensive or difficult to shut down and start up. A 24/7 strategy may also be appropriate for a portion of the year to meet seasonal demands. Understanding the total size of the hidden factory becomes important. For factories that are already running 24/7, the hidden factory represents an opportunity for increased capacity.

Because TEEP categorizes all events around the clock, it is the metric that should be used when you develop a business case for more capacity or capital expansion. TEEP can be a good indicator of the capacity that is still available within an existing asset. Developing this hidden factory is beneficial because it is cost effective. Other advantages would be the hidden factory could be developed sooner. It also comes with fewer risks than new or modified equipment and systems.

According to a presentation at the 1999 Society of Maintenance Reliability Professionals conference, Rohm and Haas Corporation determined that developing hidden capacity of existing factories was ten times less expensive than building new capacity. Consider how favorable this savings is to return on assets.

Even areas that are not yet filled to capacity can benefit significantly by improving the effectiveness of non-production activities. One such benefit is the ability to respond immediately to unexpected increases in production schedules.

An important operating strategy for all companies is to maintain the balance between production and production capability over both the short and long term. Maintaining this balance helps a company sustain strong net profits on a consistent basis. To maintain this balance between production and production capability, companies must effectively manage required off-line activities; they must not delay or cancel required work. Section 6.1 provides a case study of how managing shutdown and maintenance work provided ten additional production days per year for a plant. Frequently, decisions by management to delay equipment shutdown and maintenance work in favor of generating more product for current orders, can lead to a poor performance that jeopardizes current and future orders.

OEE ignores planned downtime whereas TEEP brings into focus the necessary activities required when not planning to make product. These activities include equipment shutdowns and planned maintenance stops, experiments, new product development, meetings, training, and planning for staff needs, shift schedules, and manufacturing strategies. TEEP also records all online rework that affects the key equipment.

Companies must make good business decisions regarding how they allocate time for the various activities that impact the key assets. If all activities are highly effective, then planning and scheduling become straightforward and less reactive. Non-production tasks should take place as scheduled; they should deliver the anticipated results (expected throughput) with high reliability (quality). Opportunities to leverage part of the hidden factory can come from targeted improvements on non-production tasks. Examples include:

- ❑ Reduce planned maintenance downtime (see section 6.1 for a case study).
- ❑ Use pre-assembled equipment modules to "swap out," reducing replacement time.
- ❑ Execute only statistically designed experiments (minimize guessing).
- ❑ Staff work areas appropriately to cover lunches, breaks, week ends, and holidays.
- ❑ Train and educate workers off-line.
- ❑ Hold multiple meetings to communicate with employees before or after shifts. This avoids work stoppage for full community meetings.
- ❑ Improve reliability of delivery.
- ❑ Improve transitions to new equipment modifications (see section 9.1).

When proactive leadership drives improvements in both production and non-production activities, the increased effectiveness from the entire work community improves the bottom line. When the focus is only on production, and non-production activities are ignored or undervalued, poor work practices develop in off-line work that eventually impacts OEE.

1.7 The Bottom Line: Good Goods at Lowest Cost—Now!

The dynamics of the world, both internal and external to the factory, generate great uncertainty about what the future will be for any one course of action taken today. This uncertainty, often the source of "analysis paralysis," can cause corrective actions to be delayed day after day. Because of global competition, every company must strive to be the best it can be at delivering quality goods, on time, at attractive prices, *today.*

Highly effective factories are certainly advantageous. They increase your company's ability to leverage stronger financial benefits and sustain more favorable positions relative to its competition.

In many cases, the threat of plant shutdowns and job losses occur before the workforce accepts change. This scenario doesn't have to happen! Instead, management must determine the true size of the hidden factory and *proactively* set a course of action that leads the company to world-class numbers.

Where does this leadership start? It starts at every level of the factory. Promoting change should be like discovering gold and then communicating to the rest of the organization about the potential treasure. Once the organization grasps the size of the hidden factory, it has a compelling reason to begin its own gold rush.

For change to take place, *everyone* in the work community must recognize the consequences of the current path. Without improvement, a serious crash will happen. And in today's competitive environment, everything happens faster. *Everyone* must recognize the difference between "continuing as is" (the base case) and "what could be" if high OEE and TEEP levels existed,.

The next two chapters explain how the definitions categorize every minute of calendar time, how the three methods of computing true OEE reconcile, and how true OEE correlates to Operating Income (Earnings Before Interest and Taxes, EBIT) and Return On Assets (ROA). After understanding that that each method reconciles to the same OEE, and that the hidden factory can be identified easily, your next step is to determine the size of the opportunity for your plant or work area. Even a small increase in OEE leverages a bigger increase in net profits.

A detailed analysis will bring into focus the areas where opportunities for major improvement exist. At that point, a broad range of tools and methods can be applied to these clearly defined targets. Be creative in developing solutions. Do not limit your vision to only internal resources. Think about bringing in people from other departments and disciplines as well as outside resources. In all cases, be sure to work from good data. Verify your actions with statistically designed experiments. The most important aspect is to get started *now.* Improved benefits will only be realized after changes are implemented. Every day counts.

Companies and factories often approach new processes by identifying a pilot area. In the selected area, they test and develop methods before applying the process to other areas or plants. This approach has a number of pitfalls relative to an aggressive OEE strategy. Most change involves educating the specific work center about the metric, collecting and analyzing information, and forming cross-functional teams to work on the major limiters. The experience of the pilot group is not easily transferred to other areas. Furthermore, if the pilot area is not of key importance to the plant or overall process, it may not get the resources and attention it needs to be completely successful.

Aggressive OEE strategy should be launched in conjunction with the five steps of constraint management methodology described by Eliyahu Goldratt in Critical Chain[7].

1. The strategy should be implemented as a plant or factory objective using the prioritized list of bottleneck assets (Identify).
2. The strategy should focus the resources and the initial program on the top ranked bottleneck (Exploit).
3. All other areas of the plant should not only be informed of the key equipment OEE goals. They should also be supportive of the prioritized list and serve the key assets accordingly (Subordinate).
4. The selected bottleneck area should incorporate all necessary changes for high OEE (Elevate).
5. When this area is successful, the next prioritized key asset should implement the new methods, insuring that the greatest benefits are achieved quickly (Go Back).

Many companies have achieved tremendous improvement by launching such a strategy, including Reynolds Metals Company, as outlined in the June 1998 issue of Reliability magazine[8]. Reynolds Metals embraced a new process it called "Total Productive Manufacturing." This process refocused its manufacturing at the plant level, from "Mission/ Vision" all the way to best practices on the shop floor. Measuring its own progress was a vital part of the process of change. The backbone of these measures was OEE improvement.

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CHAPTER 2

LEARNING THE BASICS OF OEE METRICS

2.1 Definitions of OEE Categories

This chapter introduces definitions of OEE categories, a sample production report, summary results with OEE calculations, and a reconciliation of the various OEE results and losses. The categories that follow are suggested as a basic set for nearly every key manufacturing area. The purpose of the categories is to provide enough detail to focus priorities and reveal areas of major opportunity. All events must be categorized without using categories such as "miscellaneous" or "other." At the same time, the categories should not be so detailed that they are overwhelmed by too much incremental information. Larger processes should accumulate information for each key step.

The categories should allow the company to identify its opportunities in a reasonable time frame. They should also form the baseline for detailed analysis. Using common categories enables a company to benchmark similar areas both internally and externally. To be successful at benchmarking, all events must be categorized; total reconciliation is then supported and credibility is maintained. More discussion on benchmarking can be found in section 8.10.

A sample product report of the important categories follows in section 2.3. This report, which covers a production period of 40 hours, looks at a full range of problems and includes a log sheet that categorizes the various events. A suggested report is attached along with the TPM (Nakajima) OEE formulas[1] and three methods of computing OEE. Regardless of the approach used, the OEE and various Loss percentages should total 100 percent.

Key Definitions:

- ❑ Asset Utilization. The percent of Total (calendar) Time that the equipment runs.
- ❑ Downtime (DT). All Unplanned Machine downtime events should be categorized into the following categories:
- ❑ DT Technical. Downtime due to any equipment failures affecting the machine or process, including periphery equipment, (utilities, sprinklers, doors, humidifiers etc.), equipment failure due to maintenance errors, and equipment-caused dirt or scratches.
- ❑ DT Operational. Downtime caused by not following procedures, operating outside of specifications, operator error, etc.
- ❑ DT Quality. Downtime caused by nonconforming supplies and raw materials, process control problems, unplanned testing, non-manufacturable product, and dirt from the product or process.
- ❑ Excluded Time. This is (normally) planned time not scheduled for production. This would be scheduled maintenance downtimes (preventative maintenance and shutdowns planned at least a week in advance), scheduled meetings, experiment time (if the product is not going to be sold), planned training (if no product is made), Headroom time such as Holidays/Sundays/weekends, and "no product scheduled". It should also <u>include unplanned time</u> when completing orders early due to good performance. Good performance should not be detrimental to OEE.
- ❑ Ideal Cycle Time or Theoretical Rate. Also called Ideal Speed Rate. The best rate of speed or cycle time for key equipment or the flow line bottleneck, given a size and format of product. For example, key equipment or a flow line bottleneck is designed and accredited for 17 sec cycle time, or 3.53 units/min for a certain size. This rate should then be used for all products of that size and format. If a slower rate is used for difficult product within that

family of products, then the reduction in OEE should be noted in the Comments column. In this way, any loss due to non-manu facturable product can be recognized and communicated. (This step is important for pricing products properly). If the equipment system is not the bottleneck of the product flow, then the ideal speed rate should be defined as the desired rate to feed the bottleneck. OEE is then measured against desired speed with the understanding that the maximum speed factor is 1.0. (Overspeed should be used only for scheduled make up situations, and noted in the remarks so that inventory balancing can be reconciled.)

- ❑ Loading Time. Also called Scheduled Time or Planned Production Time. The time that normal operations intend to make production. It includes all events that are common to meeting delivery schedules, such as product changeovers or transitions, set ups, information downloads, all production run time, and unplanned stoppages for equipment, people, quality, and testing.
- ❑ Overall Equipment Effectiveness (OEE). How effectively (makes good product at rated speed) the process runs when it is scheduled to run, see section 2.5 for the formula.
- ❑ Operating Time. Also called Runtime or Uptime. The portion of loading time when the system is actually making product.
- ❑ Quality Rate. The number of good units divided by the total units produced. The rate can be measured by items, square feet, cubic feet, gallons, barrels, etc.
- ❑ Quantity of Good Product. Product that conforms to specifications. This count should not include volume that is on hold or may be condemned. Product that is transferred and later found to be No Good (NG) should be included under Waste (see below). However, if the loss is due to a specific root cause, then that loss should be noted in the comments under Waste. (See the example in the report, figure 2-5).
- ❑ Speed Loss. The percent reduction of OEE due to running the equipment slower than Ideal Rate for the size and format or product family. It represents the difference between the *theoretical* time for the rate or cycle and the actual time used to make the product.
- ❑ Stop Time (ST) can be Planned or Unplanned.

- ST Operational. Planned stop time. It includes operational actions such as product changeovers and size changes, as well as standard testing, planned material loading, and required documentation.
- ST Induced. Unplanned stop time when the line is down due to external (non-machine) reasons such as lack of materials and supplies, lack of people, lack of information, and unplanned meetings.
- Theoretical Rate. See Ideal Cycle Time.
- Theoretical Run Time. This is the minimum amount of time to produce the amount of good product. It is equal to the amount of good product divided by the ideal cycle time.
- Total Effective Equipment Performance (TEEP). The percent of Total (calendar) Time the equipment runs at ideal speed making good product.
- Total Time. Every minute of the clock. For a year, this measure is total calendar time (60 min $\times$ 24 hr $\times$ 365 days); sometimes called Calendar Time.
- Waste. The total waste rate of the normal process. This should include structural waste, incident waste, testing waste, and recall waste. Unplanned waste that is generated while running the equipment should be captured here with a reference to the root cause of the incident. (Note: Companies often exclude structural waste to avoid visibly acknowledging its existence.)

2.2 Data Collection Review

Data collection and analysis for OEE is sometimes thought of as good in theory but not in practice. The arguments against it use excuses such as "We have too many different products" and "Our process is changed for different style outputs." In these situations, the best approach is to step back and review the boundaries of the system. Start where materials are input into a systematic flow with an expected product or subassembly for the next factory step. This transformation step is often linked with others in a series of steps that have few if any fixed buffers. The process has an expected flow or cycle time.

OEE is appropriately applied to bottlenecks, critical process areas, and high expense areas. An appropriate test is to ask, "If the effectiveness of this transformation step is improved, will the bottom line be significantly impacted?' If the answer is yes, then putting effort into generating true OEE and driving improvement is worthwhile.

As an example, I once observed a work center that successfully used OEE on the shop floor as follows. The company was highly automated; it used shop floor computers to gather much of its information. Its Equipment Performance System (EPS) collected not only the various downtime causes and frequencies, but also run time and speed monitoring. From this database, the company could easily compute OEE for each product.

Essentially, the company picked a standard process that represented its most common product. This product-process format was used as the benchmark for OEE. Because the format was used so routinely, significant production history was available. Furthermore, the product was manufactured on all of the work center's different equipment flowlines. Next, the work center defined how other formats and sizes with the same product should compare with the benchmark process. This comparison generated an OEE coefficient. The comparison was repeated for different product families and formats as well as for different process setups. The information gathered was valuable when communicating with superintendents and plant managers about capability questions and the impacts of different product mixes. It also provided the yardstick for shop floor crews to use when examining their real time productivity on shifts.

This plant had the advantage of having automatic data monitoring and information feedback for nearly all the products it produced. However, at the very minimum, plants can simply gather the information for each product run, usually manually from cycle counters, run hour clocks and other measuring devices. Simple chart recorders can be extremely valuable because the frequencies and duration of events can be easily captured and analyzed.

Figure 2-1 provides a form that lists the minimum information that should be gathered.

This information collected for each product run can quickly form the database to begin examining OEE and to start driving productivity improvements. For example, comparing start/stop time vs. run time measures efficiency, start/stop cycle time vs. run time measures speed information, and units vs. transferred output measures quality. Comparing input materials vs. units produced captures waste and inventory information. Comments from the crew leader help cross-functional teams work

Product ID __________ Crew ID __________ Date ___________

Format _____________ Lot # _____________ Machine # ______

Scheduled Production Time _______________

Actual Start Time _________________ Actual Finish Time ________________

Beginning Cycle Counter #_____________ Ending Cycle Counter # _____________

Beginning Run Hr. Clock ______________ Ending Run Hr. Clock ______________

Input Material, Quantity _________ Units Produced __________

Number of Good Units Transferred ____________

Crew Notes (DT problems and frequencies, Quality, issues, ST Operational, ST Induced, Set point changes and actions). Mark up and attach process uptime chart recorder output to this report.

____
____
____
____
____
____

Use back of form for notes on Functional Failures, Equipment failures, Technical notes.

Figure 2-1 Example Run Order Report Form

on root cause elimination of limiting problems. One goal is to understand the actual functions that have failed, as well as the actual equipment and technical problems. Another goal is to reconcile the actual output with the computed OEE, confirming that true OEE is being captured.

A decision must be made about how to handle re-work. In many processes, manufactured items cannot be transferred or shipped with out being re-worked first. (In such cases, the first effort of bottleneck has failed. OEE for that manufacturing time is zero.) Re-work efforts can fall into the following three categories.

1. The re-work can be completed off-line using non-critical equipment. It may even simply involve re-packaging and can be completed manually. In either case, the rework does not impact the bottleneck system. It becomes a manufacturing cost decision. OEE of the bottleneck does not change. However, the measure for factory units produced should note how much re-work was finally transferred so that reconciliation between OEE and first pass yield can be determined.
2. The re-work can be completed online at a time when the equipment was not originally scheduled for production, perhaps on weekends or overtime. As with the first category, this work essentially is completed with off-line equipment and, again, it becomes a manufacturing cost decision. As before, the first pass yield number needs to be identified. This type of action should be identified when examining the TEEP metric; it involves activity on a key asset that would have conflicted with regular production had it been scheduled.
3. The re-work must be completed online, competing with regular production time. In this case, the re-work material should be looked at as new input material. The time, speed, and quality factors should compute into the current OEE. A note needs to be made so that the incoming inventory is adjusted appropriately now that waste has been turned into good units.

Consider the following example:

Assume that 100 percent OEE (running at ideal speed with no downtime and no quality losses) for a production area is 100 units per hour. Normal production has been running at 75 percent OEE (75 units per hour).

During week 1, the work area ran production for 168 hrs and produced at a normal rate for 160 of those hours. However, during 8 of those hours, the product was placed in the wrong colored boxes, creating 800 units of re-work. In sum, for 8 hrs, OEE is zero and for the remaining 160 hrs OEE is 75 percent. The week's report would indicated an OEE for the area of 71.4 percent, calculated as follows:

$$\frac{(160 \times 0.75) + (8 \times 0)}{168} \times 100 = 71.4 \text{ percent}$$

During Week 2, a holiday week, the area worked 144 hours including the re-work. The equipment ran normally. However, the 800 re-work units had to be manually fed into the system. The time for this re-work took 12 hrs, resulting in only 780 good units. Because 780 units in 12 hours averages 65 units per hour, the equivalent OEE is 65 percent for those 12 hours. The rest of the production for the remaining 132 hrs was at a normal OEE rate of 75 percent. The week's report would indicate be 132 hrs at 75 percent and 12 hrs at 65 percent, yielding an OEE of 74.2 percent.

$$\frac{(12 \times\ 0.65) + (132 \times\ 0.75)}{144} \times 100 = 74.2 \text{ percent}$$

The overall OEE for the two week period is 160 +132, or 294 hrs, at 0.75 percent, 8 hrs at 0 percent and 12 hrs at 65 percent. This yields a combined OEE of 72.7 percent.

$$\frac{(292 \times\ 0.75) + (8 \times\ 0) + 12 \times\ 0.65}{312} \times 100 = 72.7 \text{ percent}$$

In general, good data collection is a key requirement for successful OEE strategy. The success of any factory is greatly affected by how effectively accurate information is collected and analyzed.

2.3 Practice Production Report

The spreadsheet in figure 2-2 follows and provides a sample 40-hour production report. It includes many different types of interruptions that illustrate the different OEE categories. Assume this area has a normal waste rate of 3.5 percent and that it produces finished units at the rate of 4 per minute (ideal or theoretical rate). Each column of the spreadsheet represents 10 minutes of calendar time.

Each event is identified with a letter and a brief description. The height of each shaded area represents the rate at which units are being produced, with each row representing 2 units per minute. Thus, an area 2 rows high has an expected rate of 4 units per minute. By summing the shaded areas of production, the number of units produced can be determined (see section 2.5). The units produced for the experiment represented by the block following letter W are excluded from this number.

The analysis that follows computes OEE and TEEP for the specific 40-hour time period in the spreadsheet. Do not confuse the production report for a weekly report. (If the 40 hours did represent the planned production schedule for a week, OEE would remain the same, but TEEP would be computed on the basis of 168 hours.)

2.4 Summarizing the Production Report

Figure 2-3 provides a table that can be used to summarize the basic information from the production report in section 2.3. You may use this table to practice classifying the events with the definition categories from section 2.1. (I recommend that you complete the practice summary before continuing through this chapter.) This exercise is typical of the information gathering and analysis that should be part of your daily routine.

A completed summary of the basic information is also provided in figure 2-4 so that you can compare your selections with mine. Your summary sheet may be laid out differently and may contain different abbreviations for the descriptions and categories, but the basic information should be similar. Note not only the duration of events but also the frequency. The frequencies will help provide reliability analysis; they will help you identify and eliminate problems.

The summary sheet does not list the actual chronology of events, only a generic sequence. The actual chronology would be useful and should be considered for capture as well. I have been in problem solving sessions where we needed to know not only the sequence of products/processes, but also the length of each run and the specific raw material lots associated with each order. At times it can be advantageous to coordinate the crew leaders' notes and remarks into the summary sheet so that their unique observations are directly visible with the corresponding order. However, for our immediate purpose – understanding how OEE can be derived and computed – the basic sheet is sufficient.

When you summarize date data, you should also consider boundary parameters. Setting boundaries at finished orders usually helps keep production events intact. Sometimes the summary will be by shift or by daily shift break (e.g., start of A shift) to keep crew information intact. Sometimes monthly or quarterly financial breaks may be mandated, even though they may fall awkwardly in the schedule. I recommend using completed orders or process changes. These will provide the data that is easiest to use for driving OEE improvement.

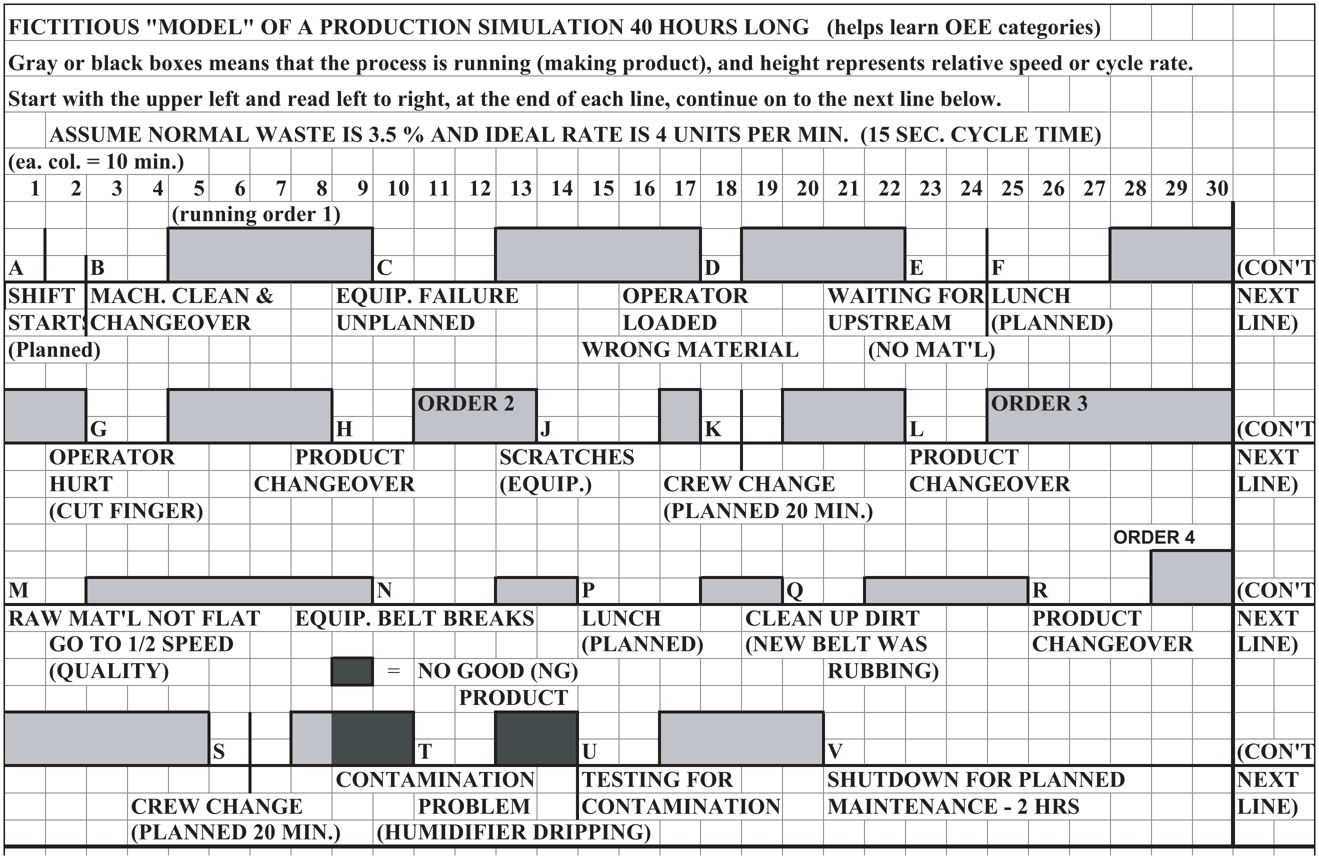


Figure 2-2 Sample Record of a 40 hr Production Run

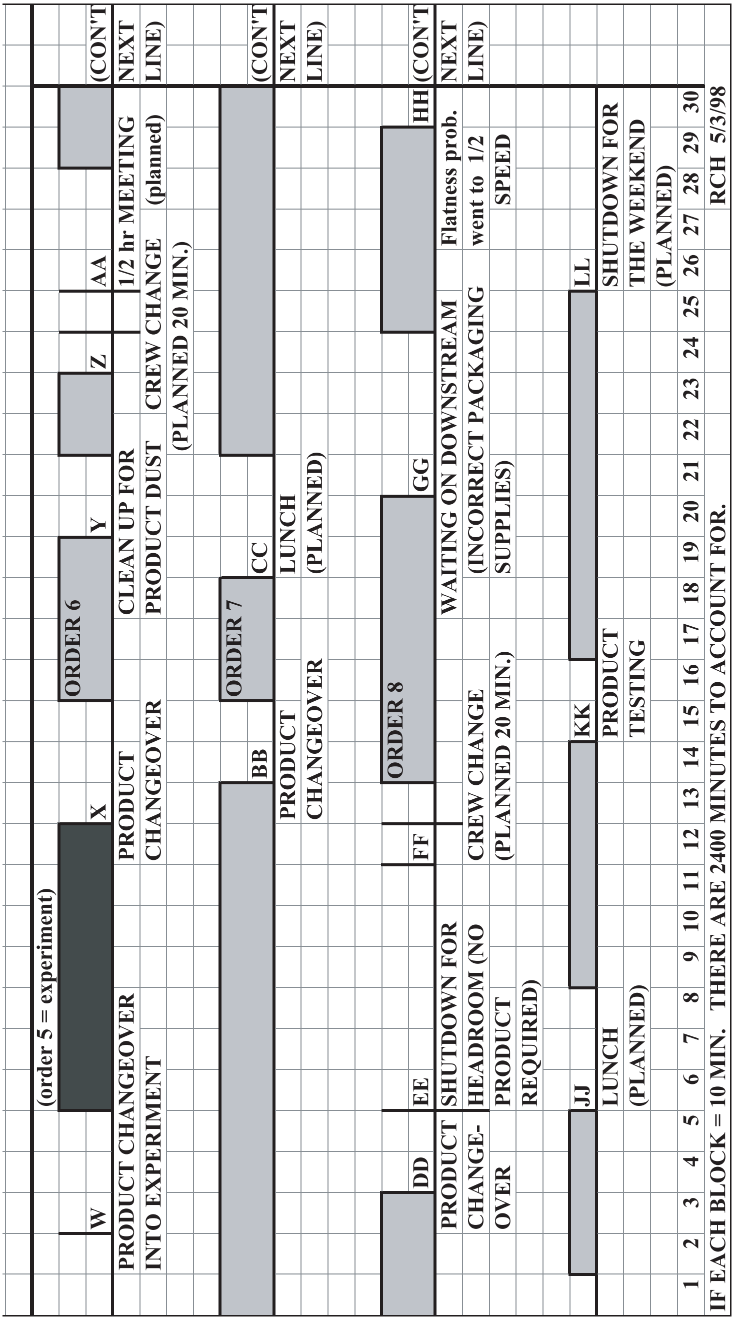


Figure 2-2 Sample Record of a 40 hr Production Run continued.

2.5 OEE and TEEP Formulas and Results

This section begins by listing formulas that are important for computing OEE. The language originally used by Nakajima1 appears in italic. All three methods used to compute OEE are derived from the Nakajima formulas. All three provide the same OEE values.

Even the simplest of the methods, the third one, gives a true measure of the hidden factory. The inputs for this simple method are scheduled time, quantity of good units, and ideal rate – easily reconciled with actual factory records that are usually available on a regular basis. Remember that the ideal rate for the plant bottleneck will be the highest accredited rate for the specific process being run. The ideal rate for non-bottleneck areas is discussed in the definition of ideal cycle time in section 2.1. In such cases, the speed factor should be limited to 1.0 (if rate is higher than ideal) with proper notification for inventory control.

The nomenclature in italics and basic formulas are stated in "Introduction to TPM" by S. Nakajima[1].

1. *Loading Time = Total Time – All Planned Downtime* (Excluded Time)
   = Schedule Time

2. *Operating Time = Loading Time – (Non-operating Time)*
   = Run Time = Uptime = Equipment making product time

3. *Operating Time = Loading Time – (All Downtime + All Stop Time)*

4. $$\textit{Availability} = \frac{\textit{Operating Time}}{\textit{Loading Time}} = \frac{\text{Runtime}}{\text{Scheduled Time}} = \frac{\text{Scheduled Time - }(\Sigma\text{ DT} + \Sigma\text{ST})}{\text{Scheduled Time}}$$

5. Availability = Loading Time - (Σ DT + Σ ST) Loading Time

6. Actual Cycle Time = Runtime Actual Amount Produced

7. Theoretical Cycle Time = Ideal Speed (Equipment Capacity as Designed)
   = Highest Accredited Speed Rate (If higher than design rate, see definitions in section 2.1)

8. $$\text{Operating Speed Rate} = \frac{\text{Theoretical Cycle Time}}{\text{Actual CycleTime}}$$

OEE AND TEEP DISCUSSION SHEET (refer to production simulation example)
DT=DOWNTIME unplanned (could be TECHNICAL, OPERATIONS, OR QUALITY)
ST=STOP TIME (could be planned OPERATIONS i.e. changeovers, planned mtgs, etc.
or INDUCED (unplanned external to the machine events, lack of mat'l, people or info.)

DOWN ITEM	MIN.	DESCRIPTION	CATEGORY	
				SUMMARY OF CATEGORIES
				TOTAL CLOCK TIME = MIN.
				EXCLUDED TIME= MIN.
				RUN TIME @ 100% = MIN.
				RUN TIME @ _______ % MIN.
				ST OPERATIONS = _______ min. ____ freq.
				ST INDUCED = _______ min. ____ freq.
				DT TECHNICAL = _______ min. ____ freq.
				DT OPERATIONS = _______ min. ____ freq.
				DT QUALITY = _______ min. ____ freq.
				TOTAL ST & DT = _______ min. ____ freq.
				ASSUME NORMAL WASTE @ _____ %
				Sp. Rate = _____ / min.
				THIS INFORMATION WILL BE USED FOR O.E.E. & T.E.E.P. IN THE FORMULAS THAT FOLLOW.
RUN TIME=				

Figure 2-3 Downtime Report Form for figure 2-2

9. *Operating Speed Rate* = $\dfrac{\text{Total Amount} \times \text{Theoretical Cycle Time}}{\text{Operating Time}}$

10. *Net Operating Rate* = $\dfrac{\textit{Actual Processing Time}}{\textit{Operating Time}}$

(Note: This equals 1.0 by definition)

11. *Net Operating Time* = $\dfrac{\text{Processed Amount} \times \text{Actual Cycle Time}}{\text{Operating Time}}$

12. *Performance Efficiency = Net Operating Rate × Operating Speed Rate*

13. *Performance Efficiency* = 1.0 × Operating Speed Rate

14. *Performance Efficiency* = $\dfrac{\textit{Processed Amount} \times \textit{Theoretical Cycle Time}}{\textit{Operating Time}}$

15. *OEE = Availability × Performance Efficiency × Quality Rate*

16. OEE = $\dfrac{\text{Runtime}}{\text{Scheduled Time}}$ × Operating Speed Rate × Quality Rate

17. Asset Utilization = $\dfrac{\text{Operating Time}}{\text{Total Time}} = \dfrac{\text{Runtime}}{\text{Total Time}}$

18. Total Effective Equipment Performance (TEEP) =
Asset Utilization × Speed Rate × Quality Rate

19. TEEP = $\dfrac{\text{Theoretical Runtime}}{\text{Calendar Time}}$

Figure 2-4, the completed summary sheet from section 2.4, provides input values for the three methods used to compute the following OEE values. The basic information from the practice production report (section 2.3) is used each time.

Total Time = 240 blocks × 10 min/block = 2400 min

Ideal (Theoretical) Rate = 4 units/min (15 sec cycle time)

Assume a 3.5 percent waste or 96.5 percent yield for normal production activity.

OEE AND TEEP DISCUSSION SHEET (refer to production simulation example)				
DT=DOWNTIME unplanned (could be TECHNICAL, OPERATIONS, OR QUALITY)				
ST=STOP TIME (could be planned OPERATIONS i.e. changeovers, planned mtgs, etc.				
or INDUCED (unplanned external to the machine events, lack of mat'l, people or info.)				
				RCH 2/4/98
DOWN ITEM	MIN.	DESCRIPTION	CATEGORY	
A	10	SHIFT STARTS	EXCLUDED	
B	30	MACH. CLEAN AND C/O	ST OPERATIONS	SUMMARY OF
C	30	EQUIP. FAILURE	DT TECHNICAL	CATEGORIES
D	10	WRONG MATERIAL LOADED	DT OPERATIONS	TOTAL CLOCK TIME =
E	20	WAITING FOR RAW MAT'L	ST INDUCED	2400 MIN.
F	30	LUNCH--NO RELIEF PLANNED	EXCLUDED	EXCLUDED TIME=
G	20	OPERATOR HURT	DT OPERATIONS	570 MIN.
H	20	PRODUCT CHANGEOVER	ST OPERATIONS	
J	30	SCRATCHES--EQUIP. CAUSED	DT TECHNICAL	RUN TIME @ 100% =
K	20	CREW CHANGE (PLANNED)	EXCLUDED	1000 MIN. (INCLUDES
L	20	PRODUCT CHANGEOVER	ST OPERATIONS	40 MIN. FOR WASTE
M	20	FLATNESS PROBLEM	DT QUALITY	RUN TIME @ 50% =
N	30	EQUIP. BELT BREAKS	DT TECHNICAL	340 MIN.
P	30	LUNCH--NO RELIEF PLANNED	EXCLUDED	
Q	20	DIRT CLEAN UP (EQUIP.)	DT TECHNICAL	ST OPERATIONS =
R	30	PRODUCT CHANGEOVER	ST OPERATIONS	170 min. 7 freq.
S	20	CREW CHANGE (PLANNED)	EXCLUDED	ST INDUCED =
T	20	CONTAMIN. (EQUIP. CAUSED)	DT TECHNICAL	60 min. 2 freq.
U	20	TESTING DUE TO INCIDENT 'T'	DT TECHNICAL	
V	120	PLANNED SHUTDOWN	EXCLUDED	DT TECHNICAL =
W	30	CHANGEOVER INTO EXPER.	EXCLUDED	150 min. 6 freq.
X	30	PRODUCT CHANGEOVER	ST OPERATIONS	DT OPERATIONS =
Y	20	CLEAN UP DUE TO PRODUCT	DT QUALITY	30 min. 2 freq.
Z	20	CREW CHANGE (PLANNED)	EXCLUDED	DT QUALITY =
AA	30	MEETING PLANNED & SCHED.	EXCLUDED	80 min. 4 freq.
BB	20	PRODUCT CHANGEOVER	ST OPERATIONS	TOTAL ST & DT =
CC	30	LUNCH--NO RELIEF PLANNED	EXCLUDED	490 min. 21 freq.
DD	20	PRODUCT CHANGEOVER	ST OPERATIONS	
EE	60	SHUT DOWN FOR NO SCHED.	EXCLUDED	ASSUME NORMAL
FF	20	CREW CHANGE (PLANNED)	EXCLUDED	WASTE @ 3.50%
GG	40	NO PACKAGING SUPPLIES	ST INDUCED	AND 4 UNITS/MIN.
HH	20	FLATNESS PROBLEM	DT QUALITY	
JJ	30	LUNCH--NO RELIEF PLANNED	EXCLUDED	THIS INFORMATION
KK	20	PRODUCT TESTING (QUALITY)	DT QUALITY	WILL BE USED FOR
LL	50	WEEK END SHUTDOWN	EXCLUDED	O.E.E. & T.E.E.P.
EXP. TIME	70	TOTAL EXPERIMENT TIME	EXCLUDED	IN THE FORMULAS
1/2 SPEED	340	TOTAL TIME AT 1/2 SPEED	(SPEED LOSS)	THAT FOLLOW.
RUN TIME=	340	min. @ 1/2 RATE & 1000 min. @ FULL RATE (incl. 40 min. of waste time)		

Figure 2-4 Completed Downtime Report for figure 2-2

Then, Actual Units Produced =

$$(1000 \text{ min} \times \frac{4 \text{ units}}{1 \text{ min}}) + (340 \text{ min} \times \frac{2 \text{ units}}{1 \text{ min}}) = 4680 \text{ units}$$

Given that 160 units were contaminated and, therefore, designated as No Good (NG),

Number of Good Units Produced = $(4680 - 160) \times 0.965 = 4362$ Good Units

$$\text{Quality Rate} = \frac{\text{Good Units}}{\text{Total Units}} = \frac{4362}{4680} = 0.932$$

Method 1: OEE Using Nakajima Formulas

Loading Time = Total Time – Excluded Time =2400 min – 570 min = 1830 min

$$\text{Availability} = \frac{\text{Loading Time - }(\Sigma \text{ DT} + \Sigma \text{ ST})}{\text{Loading Time}}$$

$$= \frac{1830 \text{ min - } (490 \text{ min})}{1830 \text{ min}} = 0.7322 = 73.22 \text{ percent}$$

From above, Total Units Produced = 4680

$$\text{Actual Cycle Time} = \frac{\text{Runtime}}{\text{Actual Amount Produced}}$$

$$= \frac{(1000 \text{ min} + 340 \text{ min}) \times 60 \text{ sec/min}}{4680} = 17.18 \text{ sec}$$

$$\text{Operating Speed Rate} = \frac{\text{Theoretical Cycle Time}}{\text{Actual Cycle Time}} = \frac{15 \text{ sec}}{17.18 \text{ sec}} = 0.873$$

Performance Efficiency = 1 × Operating Speed Rate = 1 × 0.873 = 0.873

OEE = Availability × Performance Efficiency × Quality Rate
= 73.2 percent × 0.873 × 0.932 = 59.6 percent

Note: Nakajima doesn't calculate TEEP

Method 2: OEE Using Event Time Records

Scheduled Time = Total Time - Excluded Time =
2400 - 570 = 1830 min - Runtime = 1000 + 340 = 1340 min

$$\text{Operating Speed Rate} = \frac{(1000 \text{ min.} \times 1.0) + (340 \text{ min.} \times 0.5)}{1340} = \frac{1170}{1340} = 0.873$$

$$\text{Availability} = \frac{\text{Runtime}}{\text{Scheduled Time}} = \frac{1340}{1830} = 0.732 = 73.2 \text{ percent}$$

$$\begin{aligned}\text{OEE} &= \text{Availability} \times \text{Speed Rate} \times \text{Quality Rate} \\ &= 73.2 \text{ percent} \times 0.873 \times 0.932 = 59.6 \text{ percent}\end{aligned}$$

$$\text{Asset Utilization} = \frac{\text{Runtime}}{\text{TotalTime}} = \frac{1340}{2400} = 0.558 = 55.8 \text{ percent}$$

$$\begin{aligned}\text{TEEP} &= \text{Asset Utilization} \times \text{Speed Rate} \times \text{Quality Rate} \\ &= 55.8 \text{ percent} \times 0.873 \times 0.932 = 45.4 \text{ percent}\end{aligned}$$

Method 3: OEE Based On Good Units Transferred

Accurate OEE can be determined by multiplying Theoretical Cycle Time, Number of Good Units, and Schedule Time. An event time record is not required, except for detailing profitable OEE opportunities. Recall from above that 4362 Good Units were produced and should be equal to the amount of product transferred. If all product is transferred without reduction for off specification units in your area, then modify the transferred amount by historical quality levels. Theoretical Cycle Time is known to be 4 units/min, and Scheduled Time is 1830 min., a known production value.

$$\text{Theoretical Runtime} = \frac{4362 \text{ units}}{4 \text{ units/min}} = 1090.5 \text{ min}$$

$$\text{OEE} = \frac{\text{Theoretical Run Time}}{\text{Scheduled Time}} = \frac{1090.5}{1830} = 0.5959 = 59.6 \text{ percent}$$

This result is exactly the same as that reached by methods 1 and 2.

$$\text{Total Effective Equipment Performance} = \frac{\text{Theoretical Runtime}}{\text{Total Time}} = \frac{1090.5}{2400}$$

= 0.4544 = 45.5 percent, the same result as with method 2.

This section is key to understanding the factors used to compute OEE. It demonstrates that true OEE can be found by several approaches. Furthermore, it reconciles with plant output as seen in the next section.

2.6 Reconciliation and Loss Analysis

Once OEE is calculated, the various losses are computed from the summary sheet information. Analyzing these losses will help you identify areas that have major opportunity for improving OEE. Obviously, improvement in any area will help OEE. However, the greatest opportunities for OEE improvement are those areas with large losses.

OEE is not the only factor behind company productivity. Therefore, the different potential programs must be ranked for their overall benefit. For example, some industries may have specific quality or financial considerations that must be incorporated into their lists of priorities. All programs should not only be evaluated for their anticipated benefits, but also be congruent with the goals of the company. When completed, they should be measured for evidence of their success. Evaluating the trends of most key parameters will usually identify the impact of a program before and after its completion. Chapter 5 discusses a value fulcrum, a concept that can help rank nearly equal projects on a reactive to proactive scale.

When setting goals, you should link throughput improvement with desired progress of other parameters. Take this step when you initially assess the current baselines of all parameters. It often takes creativity to define the relationship between parameters. However, by clearly communicating the desired outcomes, the priorities are understood and supported by the entire community. I recommend that you focus on no more than three key projects at a time and complete them as quickly as possible. Do not let your resources be diffused on a multitude of jobs. Good progress will occur if you select and eliminate the right limiters.

In general, the loss analysis step is a point where synergy between OEE and other key parameters occurs. During this step, the detailed equipment performance records will help identify significant root cause limiters. Cross-functional teams properly trained in objective problem solving and focused on the areas of large losses often make breakthrough gains in OEE improvement. Detailed observations that are provided by an effective equipment performance system database will be of assistance. Once the key root cause limiters are identified and eliminated, significant improvement in performance will occur.

Section 2.1 identified several types of loss that together equal total loss. These are waste loss, speed loss, ST (stop time) operational loss, ST induced loss, and DT (downtime) loss. Examine the example that has been used throughout this section. Note that 4680 units were produced and 4362 units were good units. The difference in these numbers (318 units) is the quality loss and the theoretical factory time to produce these units is the lost time due to quality. Also, 340 minutes were used in operating at 1/2 rate (2 units/min) which results in1/2 of this time (170 minutes) as 100 percent speed loss. Therefore the losses are as follows:

$$\text{Theoretical factory time lost to quality} = \frac{318 \text{ units}}{4 \text{ units/minute}} = 79.5 \text{ minutes}$$

$$\text{Waste Loss} = \frac{\text{Waste Time}}{\text{Scheduled Time}} = \frac{79.5 \text{ minutes}}{1830 \text{ minutes}} = 0.043 = 4.3 \text{ percent}$$

$$\text{Speed Loss} = \frac{\text{Speed Loss Time}}{\text{Scheduled Time}} = \frac{170 \text{ minutes}}{1830 \text{ minutes}} = 0.093 = 9.3 \text{ percent}$$

$$\text{ST Operational Loss} = \frac{\text{ST Operations}}{\text{Scheduled Time}} = \frac{170 \text{ minutes}}{1830 \text{ minutes}} = 0.093 = 9.3 \text{ percent}$$

$$\text{ST Induced Loss} = \frac{\text{ST Induced}}{\text{Scheduled Time}} = \frac{60 \text{ minutes}}{1830 \text{ minutes}} = 0.033 = 3.3 \text{ percent}$$

$$\text{DT Loss} = \frac{\text{DT Technical} + \text{DT Operations} + \text{DT Quality}}{\text{Scheduled Time}} = \frac{(150 + 30 + 80)}{1830}$$
$$= 0.142 = 14.2 \text{ percent}$$

$$\text{Total Loss} = (4.3 + 9.3 + 9.3 + 3.3 + 14.2) = 40.4 \text{ percent}$$

Recall from the previous section that OEE = 59.6 percent. Therefore,

Total Loss + OEE = 40.4 percent + 59.6 percent = 100 percent

The reconciliation is complete.

This reconciliation step should be completed on a routine basis. If the OEE values do not correlate with factory output, then the lowest value should be assumed until the discrepancy is resolved. It takes discipline to correctly collect data and to confirm that the database is correct. But this discipline is necessary to be sure everyone is working with good information.

A sample report follows (see figure 2-5). The values are filled in for the results of the practice example. This type of form is useful when you are looking at similar process systems and developing areas for best practices. It is also useful for demonstrating improvement over time for the same equipment system.

The report displays various losses and OEE, showing that they can be reconciled to 100 percent. Also, the input for simple computation of OEE is available and can be used to confirm that true OEE is provided. If this format is used for monthly reports, the various OEE values can then be properly weighted relative to Scheduled Time to determine OEE for the quarter or year. You may also want to incorporate the number of frequencies of each category into the report. This information is necessary and valuable in computing reliability parameters.

Reference:

1. Nakajima, Seiichi. Introduction to TPM: Total Productive Maintenance. Cambridge, Massachusetts: Productivity Press, 1988.

OEE REPORT FOR ____________ DATE: ____________ INFORMATION PERIOD = ____________

REPORTED BY =

PLANT & EQUIP.	SCHED. TIME	# GOOD UNITS	EXPECT. CYCLE T.	O.E.E. %	% ST OPER.	% ST INDUCED	% DT T, O, & Q	% LOSS WASTE	% LOSS SPEED	COMMENTS
OEE EXAMPLE	1830 min	4362	4 /min	59.6	9.3	3.3	14.2	4.4	9.3	40 min. of contamination NG is
										in WASTE, not DT Technical

Figure 2-5 Sample Report Form

CHAPTER 3

FINANCIAL ASPECTS OF OEE

Many manufacturing organizations have trouble accurately measuring the financial benefits of proposed improvement projects. Important projects are often overlooked or not properly prioritized relative to average projects. As a result, a manufacturing area can get mired in driving false improvement projects, never making significant gains in reliability and productivity. Furthermore, financial accounting methods used by factories vary widely leading to more confusion in identifying meaningful projects.

Financial statements are the scorecards used to communicate and benchmark a company's business. Understanding the link between OEE and financial statements is of paramount importance in ranking reliability and improvement projects.

It is beyond the scope of this book to cover financial accounting methods. However, the book uses a generic simplified approach that can fit most specific cases and give you a relevant first look at financial benefits. In the end, you should enlist the assistance of your company's financial analyst to help you measure your OEE improvement projects using a method similar to the one presented here. With your analyst's help, you will know the financial impact of the best projects and can convey the information to your company's decision-makers in terms they understand and fully support.

Remember that OEE strategy is to be applied to your factory's bottlenecks as well as other key areas that are either high cost or critical to the factory operation. By focusing on bottlenecks at key stages in the factory, OEE is a true measure of factory output. After identifying constraints, the next step is to exploit the resource. Your test question should be, "If good improvement occurred in this area, will a major impact occur with the factory's overall improvement goals?" If your answer is yes, then you are working on the right areas. In turn, if you are successful, you will significantly impact the bottom line.

To help understand how OEE impacts manufacturing’s contribution to the bottom line (operating income before interest expenses and taxes), we can look at a hypothetical factory in three different situations. In section 3.1, a base case establishes the current situation. Section 3.2 considers the same factory with an improved OEE, making the same amount of product. Section 3.3 then looks at the same factory with an improved OEE, but selling all it can produce. This analysis will demonstrate how even small increases in OEE can leverage into big increases in the bottom line. In sections 3.4 – 3.6, we will use a similar approach to review the impact on another key financial parameter, Return On Assets (ROA) sometimes called the ‘productivity ratio’.

3.1 Case A: Base Case

Cost is often the major focus of manufacturing operations, and bottom line income is the key measure for factories. You would generally think that these two factors would always be in line with each other. However, I have seen situations in which factory costs were reduced, yet operating income went down. Cost optimization of a local area was detrimental to the factory as a whole. Maintenance budgets were slashed and mechanic overtime was eliminated. When problems occurred on off shifts, equipment stayed down until regular day shift. Maintenance labor expense was reduced but the factory bottleneck was starved as a result.

In most cases, however, factory effectiveness correlates very well with operating income. The following example fits the majority of cases where the financial aspects of a company are major critical goals.

Suppose a factory called R.C. Hansen’s Factory receives raw materials and semi-assembled parts, then provides finished products that are sold for a net price of $100 each. Assume the factory process is a set of transformation steps in series, similar to a long assembly line with minimum or zero buffers between steps.

Assumptions: During the year, the factory manufactured full out, operating around the clock, 320 of 365 days (7680 scheduled hrs). The other 45 days were used for experiments, shutdowns and planned maintenance days, holidays, training days and headroom allowance. Headroom allowance is where an annual production plan purposely reserves manufacturing capacity for risk management (uncertainty). This can be in the form of unanticipated new orders (positive) or a buffer to accommodate unusual OEE losses (negative). Note that headroom is part of excluded time and addressed when computing Total Effective Equipment Performance (TEEP). It is addressed in OEE only when it is "cashed" and re-identified as planned production time.

For the base case, the factory manufactured 1 million units. The product mix and output schedules were relatively constant over the year. The units were sold for a net price of $100 each. Therefore, Net Sales = 1,000,000 x $100 = $100 million

Before jumping into the financial breakout, we will use the following definitions for this chapter.

"Direct material includes all of the important materials or component parts that physically comprise the product. Examples are sheets of steel, electric motors, and microprocessors. Incidental material items-such as glue and fasteners-are considered indirect materials and are included in factory overhead. Supply items-such as cleaning supplies and lubricants-are considered factory supplies and are included in factory overhead.

Direct labor includes the salary and wage costs of factory employees who work directly on the product. Machine operators, assemblers, and painters are examples of such workers. The salary and wage costs of factory employees who work indirectly on the product-such as supervisors, inspector, material handlers and maintenance workers are considered indirect labor costs and are included in factory overhead.

Factory overhead, sometimes called manufacturing overhead or factory burden, includes all other manufacturing cost not included in direct materials or direct labor. Examples of items included in factory overhead are indirect material, factory supplies used, indirect labor, factory payroll taxes and fringe benefits, factory utilities (natural gas and electricity), factory building and equipment costs (insurance, property taxes, repairs and maintenance and depreciation), and other factory costs." [1]

With these definitions, assume the following breakout of the financial figures: Categories and proportions are similar to page 928 of the reference book. (figures in millions)

Net sales			$100
Less			
Direct Materials used		$25	
Direct Labor		24	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplied	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	
Operating Expenses			
Selling Expenses		16	
Administration Expenses		8	
Operating Income: Earnings Before Interest and Taxes (EBIT)		9	

Of the categories above, Direct Materials and Direct Labor vary almost directly with the amount of product made for sale. If productivity improvements are made but the same amount of product is produced, the Direct Labor expense will vary with the productivity improvement. Usually these expenses vary with scheduled operating days and are the direct labor number of the financial breakout. However, with fewer operating days, Sunday overtime is often the first reduction target that could increase the rate of expense reduction for direct labor.

In our case, the small amount of process materials and utility costs collected in the Factory Overhead will be considered negligible when examining costs that vary with sales. If these expenses are significant in your situation, you will need to proportion the variable amount in these categories similar to the approach used in sections 3.2 and 3.3.

Suppose that using the methodology outlined in chapter 2 to study the factory bottleneck, we find a combined OEE of 60 percent, (assume Availability = 65 percent, Speed Factor = 0.97, and Quality Factor = 0.95. OEE = 65 percent × 0.97 × 0.95 = 60.0 percent).

Now you can examine the value of improved OEE for your factory, answering the question "What could have been?" You should begin to see the linkage between changes in OEE and operating income before interest and taxes at your factory.

Given this approach, let us now compute the combined Ideal Speed Rate for the base case. The Ideal Speed Rate (R) for our current factory process is obviously influenced by the specific product and process mix. We will assume the same mix for the two scenarios that follow.

From section 2.5, OEE computation method #3, we know that

$$\text{OEE} = \frac{\text{Theoretical Runtime}}{\text{Scheduled Time}}$$

and

$$\text{Theoretical Runtime} = \frac{\text{Number of Good Units Made}}{\text{Ideal Speed Rate}}$$

We also know OEE (60 percent or 0.6), Number of Good Units Made (1,000,000), and Scheduled Time (7680 hr). Therefore, we can solve for Ideal Speed Rate, R. Substituting terms, and we have

$$R = \frac{\text{Number of Good Units Made}}{\text{Scheduled Time} \times \text{OEE}} = \frac{(1{,}000{,}000 \text{ units})}{7680 \text{ hr} \times 0.6} = \frac{217.0 \text{ units}}{1 \text{ hr}}$$

This single measure for Ideal Speed Rate combines the various ideal rates for the product mix. Recall that the product mix and schedules have been assumed to be relatively constant for the past 12 months and for the near future. Any difference in the financials will be the direct result due to OEE improvement.

Various "what if" scenarios could be reviewed. Two important financial investigations would be "What if we had achieved higher OEE and 1. Produced the same volume as the Base Case or 2. Operated the same number of days and sold everything we could make?"

Recognize that we operated full out in the Base Case and marketing and sales are constrained until the factory increases annual capacity. Without specific cause and effect projects, demonstrating higher capacity may take several years. With well documented, targeted OEE projects and using this metric real-time (at least daily), you can statistically demonstrate higher capability in a short time frame.

When increased sales are uncertain, I have often had long discussions with financial analysts over what value to assign improvement projects for developing higher capability that only provides for potential future sales. Future sales are uncertain and may not develop for a year or more. Without the capability, increased sales would require future (significant) investment. With the capability, sales can be generated with minor expense increases, which will be demonstrated with question 2.

The answer is left up to you, but it must be somewhere in between question 1 and question 2. Depending on time, if only one third of the sales develop, it may double the business case addressed in question 1.

3.2 Case B: Same Output, Improved OEE

Case B provides the same scenario as Case A, except OEE improves from 60 percent to 66 percent (OEE = 66 percent: Availability 71.6 percent × Speed Factor 0.97 × Quality Factor 0.95 = 66.0 percent). For this example, we have made gains only in availability perhaps resulting from reliability projects or faster changeovers. A discussion on project value for improved availability, is presented in section 5.1 and encourages the elimination of unplanned downtime. Equipment reliability projects such as Reliability Centered Maintenance[2] or condition monitoring practices focused on bottlenecks may contribute to increased availability. They can be reviewed and presented using these examples.

In Cases B and C, the increase in OEE of 6 percentage points represents a 10 percent improvement:

$$\frac{66}{60} = 1.10$$

As in the base case, the factory makes 1 million units and sells them for a net price of $100 each. Given OEE (66 percent), Ideal Rate R (217 units/hr), and Number of Good Units Made (1,000,000), we can solve for Scheduled Time, the number of hours needed to produce the units with the new OEE level. Adapting the formula from section 3.1,

$$\text{Scheduled Time} = \frac{\text{Number of Good Units Made}}{R \times \text{OEE}} = \frac{(1{,}000{,}000 \text{ units})}{217 \text{ units/hr} \times 0.66} = 6982 \text{ hr}$$

The impact of improving OEE has been to reduce Scheduled Time from 7680 hours to 6982 hours, a savings of 698 hours.

Suppose 96 of the 698 hours are used for training and the rest (602 hrs) are truly saved in reduced scheduled time. Using this reduction in scheduled hours, the reduction in Direct Labor expense for case B is computed.

$$\text{Direct Labor expense} = \frac{(7680 - 602)}{7680} \times \$24 \text{ million} = \$22.1 \text{ million}$$

$22.1 million is a savings of $1.9 million from the original cost of $24 million seen in section 3.1. This calculation of savings may actually be conservative. In practice, the reduced hours would probably be overtime hours. Then an even bigger expense reduction for Direct Labor would occur.

Furthermore, the education and experience gained with focused OEE projects should yield continuing benefits. Following the adage "Give a man a fish and he eat for a day. Teach a man to fish and he can feed his family for a lifetime". In this case, with four 24-hour days provided for training, every crew should have four full shifts of focused training about OEE improvement projects. Such training would leverage to additional projects.

The financial parameters for Case B, now reflecting fewer factory hours, follow: (figures in Millions)

Net sales			$100
Less			
Direct Materials used		$25	
Direct Labor		22.1	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplies	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	

Operating Expenses	
Selling Expenses	16
Administration Expenses	8
Operating Income	
(Earnings Before Interest and Taxes)	10.9

Notice that Operating Income has increased from $9 million in Case A to $10.9 million in Case B. Thus, a 10 percent improvement from OEE has led to a 21 percent improvement in operating income.

$$\frac{10.9}{9} = 1.21$$

Providing business case information in this format should help decision-makers in your company be more aware of the benefits as the information is linked directly to the key parameters for which they are responsible. Being sensitive to the interests of your audience will help you develop more win-win situations.

Realize too that eliminating root cause limiters, thereby improving OEE, will provide benefits year after year. You should also try to determine the strategy that set up the problem in the first place, then take steps so that the conditions of problem will not occur again. This avoids future losses.

In addition, information should be communicated quickly to all similar areas to hasten corrective actions throughout the company. In this way, improved OEE is engaged and sustained at higher levels for your factory and your sister factories.

3.3 Case C: Full Factory, Improved OEE

Case C provides the same improvement scenario as Case B, (OEE = 66 percent: Availability 71.6 percent × Speed Factor 0.97 × Quality Factor 0.95 = 66.0 percent). However, we can now sell everything we can make. Therefore, the objective is to leverage maximum output. As with Case B, OEE was improved by 6 percentage points, or 10 percent, over the original OEE in Case A. The question here focuses on the gain in Operating Income from a full factory with higher OEE.

Assume that the factory schedule is the same as in Case A (7680 scheduled hours). However, we will still provide 96 hours of planned training hours (part of excluded time in this scenario) to focus on aggressively improving OEE.

Given OEE, Scheduled Time, and Ideal Rate R (217 units/hr), we can solve for the Number of Good Units Made.

Number of Good Units Made = Scheduled Time × R × OEE

= 217 units/hr × 7680 hr × 0.66 = 1.10 million units

Both OEE and factory output have improved 10 percent. They directly correlate.

If we continue to sell the 1.10 million units for a net price of $100 each, then Net Sales will equal $110 million. The annual cost of materials increases by 10 percent from $25 million to $27.5 million, reflecting the increase in units. Factory Overhead expenses remain at $18 million for the year. The cost of Direct Labor for the year will be increased to account for the same level of planned training as in case B.

$$\text{Direct Labor expense} = \frac{(7680 + 96)}{7680} \times \$24 \text{ million} = \$24.3 \text{ million}$$

As a conservative approach, Selling Expense is increased by the same 10 percent as OEE and quantity produced. ($16 million + 10 percent = $17.6 million). This estimate is conservative because many portions of Selling Expenses (e.g. the cost of advertising -- we already can sell everything we make) would not necessarily increase just because more units were made and sold. Therefore, the actual increase in Selling Expenses may be lower, and in turn, the bottom line even greater.

The financial parameters for Case C follow:(figures in millions)

Net sales			$110
Less			
Direct Materials used		$27.5	
Direct Labor		24.3	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplies	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	

Operating Expenses	
Selling Expenses	17.6
Administration Expenses	8.0
Operating Income	
(Earnings Before Interest and Taxes)	14.6

Notice that for Case C, even though OEE increased 10 percent, Operating Income increased 62.2 percent, from $9 million to $14.6 million.

Part of the hidden factory is leveraged to the full benefit of the company. As a result, the long-term health of the business is stronger. For factories that find their products becoming commodity products with small profit margins, having effective factories is of paramount importance.

The overall power of an aggressive OEE strategy lies not only in the impressive improvement shown in this example, but also in the compounding of these results as the education tools of OEE drive continuous improvement year after year.

One sector of companies is in the enviable arena of new growth looking for more capacity. This exciting environment may drive quick decisions to add capacity via more capital. A better strategy would be to develop the discipline to drive higher OEE with the existing factory. Not only is capital for additional capacity avoided, but also the full rewards of an effective factory will exist throughout the life of the factory.

3.4 Case D: OEE Impact on Return On Assets (ROA)

At the 1999 Society of Maintenance Reliability Professionals Conference, one of the speakers, Carol Vesier, Ph.D., President of RonaMax, LLC, focused on marketing reliability improvements with her clients by first presenting the need to improve the company financial picture. This approach spoke to the heart of what matters to corporate managers; it also showed that significant opportunity often exists if factories produce at the high end of industry benchmarks.

She discussed using the 4 P's of marketing (publicity, product, place and price) as they apply to in-house marketing of reliability. The <u>product</u> is actually how (not what) reliability or productivity improvement gains achieve corporate financial goals. Publicity is the education that reliability improvement is far more valuable than just reducing maintenance costs. Placement is "picking where (and to whom) you decide to market reliability ….not all work processes will benefit equally"[2]. Often the support for reliability comes from beyond the factory gates primarily because the existing organization has a local paradigm and believes they are currently doing absolutely everything possible. "Price refers to shifting the focus from maintenance budgets to business benefits"[3].

This way upper management starts with a future financial picture, then works backward to find the pieces that provides the foundation for the results. Ms. Vesier indicated that, inevitably, managers find that higher equipment reliability and performance of existing systems can deliver the results they are challenged to produce. The managers become champions of a targeted OEE strategy and fully support a top down driven initiative.

Ms. Vesier discussed a client who determined that developing the capability of its existing factories was ten times more financially effective than constructing new plants for capacity. She indicated this client could spend \$10 for education, reliability improvements, and root cause problem elimination as equivalent to spending \$100 in capital for new capacity. Does this seem realistic?

If this were true, and because the vast majority of factories are not operating at world-class levels, why wouldn't companies leap at the strategy of improving reliability and productivity. Perhaps this book will provide the education necessary for positive reliability *publicity*.

To examine this claim, and to begin developing the *product* for this type of marketing approach, an understanding of the fundamental concepts of manufacturing accounting and the parameters of the Return on Assets (ROA) equation must be developed.

Using the ROA approach is very appropriate with the company decision-makers because it is the best way to demonstrate the effectiveness of manufacturing operations using the language of corporate financial managers.

> "The return on the total assets available to a firm is probably one of the most useful measures of the firm's profitability and efficiency. Return on assets, sometimes called the *productivity ratio*, is calculated by dividing the year's operating income (income before deducting interest expense and income tax expense) by the average total assets employed during the year.

$$\text{Return on Assets} = \frac{\text{Operating Income}}{\text{Average Total Assets}}$$

> Because the return for a year is earned on assets employed throughout the year and assets may vary during that time, we compute the return on the average amount of assets. We obtain the approximate average by summing the beginning and ending asset total and dividing by two.
>
> If the percentage is a true index of productivity and accomplishment, it should not be influenced by the manner in which the company is financed. Therefore, we use income before interest charges as a measure of the dollar return in the numerator….
>
> The return on assets is useful for comparing similar companies operating in the same industry. It also aids management in gauging the effectiveness of asset utilization…"[3]

As indicated above, ROA is determined before interest and tax expense, and this approach will be used for the following analysis. In some references, "income" is defined as before interest, but after tax expense. (If this definition were applied, a tax constant is applied and the rate of improvement is the same ratio.)

The definitions for Direct Material, Direct Labor and Factory Overhead are provided in section 3.1.

As before, to examine the specific impact of improved OEE, the effects of inventory levels will be removed from the typical accounting spreadsheets by assuming the beginning and ending levels are constant for finished goods, work in progress and raw materials. Inventory value is a portion of factory assets, which becomes a part of Average Total Assets.

R.C. Hansen's Factory will have Operating Income (Earnings Before Interest and Taxes) as developed in the earlier sections of this chapter, and use the results as input for the ROA equation. As before, the operating income categories and values are similar to an example provided in the accounting reference. If your factory figures are proportioned differently, you will need to modify the values to develop your own base case.

Again, in R.C. Hansen's Factory base case, the parameters were 1,000,000 units sold at a net price of $100 each for a net sales of $100 million. The Factory worked full out at 320 scheduled days or 7680 hours.

Assume the same breakout of the financial figures as provided in section 3.1. (figures in Millions) The definitions of categories was discussed on page 49.

Net sales			$100
Less			
Direct Materials used		$25	
Direct Labor		24	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplies	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	
Operating Expenses			
Selling Expenses		16	
Administration Expenses		8	
Operating Income			
(Earnings Before Interest and Taxes)		9	

If the values in the various categories vary with your situation, you should modify the example using your figures to develop your specific business case analysis.

The operating income is the numerator for the ROA equation. The denominator is the average of end of fiscal year report of total assets for the two most recent years. This may be directly available from your financial analyst. In the case of R.C. Hansen's Factory, assume base case ROA is 10 percent, therefore, Total Average Assets for the analysis time period is $9 million divided by 10 percent or $90 million.

Assume Total Average Assets consists of the following breakdown.

Cash and short term securities
Receivables
Inventories
Other current assets
(all of the above can be called variable with sales.)

Total current assets 50 percent = $45 million
Plant, equipment, long term resources
Other long term assets
(These would be non-variable or fixed assets)
Total long term assets 50 percent = $45 million
Total Average Assets $90 million

Total Asset proportions for a number of manufacturing industries have a 50 – 50 percent split between these two categories. If your company has a different proportion you can modify the formula as necessary. The proportion impacts the denominator of the ROA equation.

$$\text{Return on Assets, ROA} = \frac{\text{Operating Income}}{\text{Average Total Assets}}$$

This is the base case value to compare the "what if" values against. The review comparison would be, "What would ROA have been if OEE were improved?". Compare this to the need to add capital projects to provide more product.

As before, assume we have used the simple methodology to determine the combined Factory OEE of 60 percent. As in section 3.1, the ideal rate (R = 217 units per hour) can be determined by knowing the scheduled hours (7680 hours), OEE (.60) and the amount of good product produced (1,000,000 units).

All of the above parameters form case D, the base case ROA. The relevant business cases will be the examination of what ROA would have been with an improved OEE for two different scenarios. These would be 1. ROA if the same amount of product is produced and 2. ROA if the factory can sell everything it can make in 320 scheduled days.

3.5 Case E: Higher OEE with the Same Sales, ROA

This section will examine the base case scenario with OEE improved from 60 to 66 percent, a 10 percent increase, and we schedule to make and sell the same amount of product. With sales being constant, the variable part of the Total Average Assets stays the same ($45 million) as does the amount of Direct Materials used.

The marketing *product* is the improvement benefit in ROA. Requiring fewer hours to produce the units for sale and computing the financial impact resulting from this decrease generates this improvement.

With OEE at 0.66, the output rate is 66 percent of the ideal rate which is $217.0 \times 0.66 = 143.2$ units/hr. and the required scheduled time is one million divided by 143.2 or 6982 hours. The reduction of scheduled hours is 7680 – 6982 hours = 698 hours.

As before, assume 96 of the 698 hours are used for targeted OEE education and projects. The rest (602 hrs) are truly saved in reduced scheduled time and the Direct Labor expense for case D is computed.

$$\text{Direct Labor expense} = \frac{(7680 - 602)}{7680} \times \$24 \text{ million} = \$22.1 \text{ million}$$

A greater expense reduction in Direct Labor may occur if the reduced hours are overtime hours.

The financial parameters for Case D, now reflecting fewer factory hours and constant Total Average Assets follow: (figures in Millions)

Net sales			$100
Less			
Direct Materials used		$25.0	
Direct Labor		22.1	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplies	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	
Operating Expenses			
Selling Expenses		16	
Administration Expenses		8	
Operating Income			
(Earnings Before Interest and Taxes)		10.9	

Total Average Assets remain the same as in the base case ($90 million) because the amount of units and sales were the same as the base case. Therefore, ROA for case E is:

$$\text{Return on Assets} = \frac{\text{Operating Income}}{\text{Average Total Assets}}$$

$$\text{Return on Assets} = \frac{\$10.9 \text{ million}}{\$90 \text{ million}} \times 100 = 12.1 \text{ percent}$$

Thus, a 10 percent improvement in OEE has led to a 21 percent improvement in ROA:

$$\frac{12.1}{10} = 1.21$$

This rate of improvement in ROA becomes the marketing product part of the business case in selling an aggressive OEE strategy. Remember that we allocated hours for initial training and projects within the financial plan.

3.6 Case F: Higher OEE, Selling Everything Produced, ROA.

Case F builds on the previous scenario with OEE improved from 60 to 66 percent (a 10 percent increase). It also assumes that we schedule to make and sell everything we can for the same production schedule of 7680 hours (320 days).

From Case E, we know that the output rate with 66 percent OEE is 143.2 units/hr. At that rate and 7680 hours, the Total Number of Good Units Made is 143.2 units/hr × 7680 hours or 1.10 million units. At a net price of \$100 per unit, Total Sales are now \$110 million.

The marketing product in case F is the improvement benefit in ROA resulting from increased sales.

With increased sales, a number of parameters will vary in both Operating Income and in Total Average Assets. Also, as in case E, we will provide for 96 Direct Labor hours for planned OEE education and targeted improvement projects.

$$\text{Direct Labor expense with training} = \frac{(7680 + 96)}{7680} \times \$24 = \$24.3 \text{ million}$$

The Direct Materials expense and the Selling Expenses will be increased by 10 percent.

The above scenario duplicates the situation for Operating Income as shown in section 3.3. Review pages 54-56 to understand the background reasons of the values and to see how relevant this approach is to your own situation.

As in section 3.3 the financial breakout for Operating Income is: (figures in Millions)

Net sales			\$110
Less			
Direct Materials used		\$27.5	
Direct Labor		24.3	
Factory Overhead			
Depreciation	2.5		
Utilities	3.4		
Insurance	1.5		
Property Tax	2.8		
Indirect Labor	3.9		
Factory supplies	2.1		
Other factory Overhead	1.8		
Total factory overhead		18	
Operating Expenses			
Selling Expenses		7.6	
Administration Expenses		8.0	
Operating Income (Earnings Before Interest and Taxes)		14.6	

In case D, the proportion of Total Average Assets was assumed to be \$45 million variable with sales and \$45 million fixed. Therefore Total Average Assets will increase as follows:

Total Average Assets case E = \$45 M × 1.10 + \$45 M= \$94.5 M

Now we can look at ROA in case F with these new numbers:

$$\text{Return on Assets} = \frac{\text{Operating Income}}{\text{Average Total Assets}}$$

$$\text{Return on Assets} = \frac{\$14.6 \text{ million}}{\$94.5 \text{ million}} \times 100 = 15.4 \text{ percent}$$

Thus, ROA has increased from 10 percent in Case D to 15.4 percent in Case F. In short, an increase of 10 percent in OEE has resulted in a 54 percent increase in ROA:

$$\frac{15.4}{10} = 1.54$$

This increase becomes our reliability marketing *product* for case F, and it includes 96 hours of planned OEE education in addition to production scheduled time.

Earlier in this chapter, the claim was made that a company "could spend $10 for education, reliability improvements, and root cause problem elimination as equivalent to spending $100 in capital for new capacity". As we have seen, a 10 percent increase in OEE provides 10 percent more capacity with the same equipment resources. In a very rough manner, we can compare this with the capital required for 10 percent capacity increase.

For the aggressive OEE strategy, assume 4 days of focused training, education, and project work per person, along with an equivalent amount of reliability project dollars, are needed to improve OEE from 60 to 66 percent. This amount represents about 1 week of everyone’s time, which is about 2 percent of the expense for Direct Labor plus an equal dollar amount (an additional 2 percent) for project materials and changes. Thus, the investment expense for an improved OEE approach would be:

4 percent (approximately) × $24 million, or $960,000.

For the capital project approach, assume that capital expense for new capacity is a direct ratio of Total Average Assets. Therefore, a 10 percent increase in capacity would cost 10 percent of $90 million, or $9 million. This amount is approximately ten times the expense of aggressively driving OEE to higher levels, consistent with the 10:1 ratio discussed at the Society of Maintenance Reliability Professionals Conference (see section 3.4).

In addition to this ratio, a difference in tax rates applies in favor of expense dollars for OEE education versus capital dollars for new factory hardware.

These benefits are for cases in which OEE improves from 60 percent to 66 percent, and were applicable to Ms. Vesier's client. But what if we start with an OEE of 70 percent and improve to 77 percent (a similar 10 percent increase in OEE)? Using the same numbers and model provides the same ROA percent increase results. The difference, however, between starting at a low or a high OEE is that the opportunities to reduce major losses are more prevalent with low OEE. Breakthrough performance often occurs quickly.

Another important benefit of aggressively driving OEE over capacity projects is the timing of the benefits. If a decision is given today to start either program, timed to the point of achieving 10 percent more product capacity, the results might be as follows:

1. For OEE education championed and lead from the top down, with a focus on eliminating major losses, as well as identifying and eliminating root cause problems, assume three months for the education process and another three months for initial applications. After these six months, some increases in OEE should emerge. More prioritized focused projects should be completed within the next six months, achieving a 12 month target of 10 percent improvement in OEE. Furthermore, a workforce that understands and applies the OEE new tools will help drive OEE to even higher levels in the next and following years.
2. For developing 10 percent capacity via a capital project, the initial steps such as conception, set requirements, design, approval, breaking ground, purchasing, fabrication, installation, debug ging, and commissioning, might take 12 to 24 months. Then the steps to accredit production systems, allow for a learning curve for new employees, and build up to the nameplate capacity might add another 3 to 9 months. The entire project scenario might be 15 to 30 months. Furthermore, the new plant might only operate at the OEE level of the existing plant. (What fundamental principles would be changed to improve productivity?) In this case, the overall system might be designed from step one to be an extension of current systems and build in mediocre expectations for the life of the new factory.

Reaching new capabilities sooner has a great advantage in the time value of money, adding yet another argument in favor of aggressively driving OEE.

In conclusion:

- ❑ OEE links directly with critical financial ratios.
- ❑ OEE improvements can make a big change in Operating Income (Earnings Before Interest and Taxes).
- ❑ Aggressive OEE programs can be 10 times more effective than capital capacity programs.
- ❑ A workforce that understands and continuously applies OEE improvement projects yields compound dividends year after year.
- ❑ *If OEE improvement is used as an aggressive business strategy, a productive factory will evolve faster.*

References:

1. Gaber, B., P. Walgenbach, E. Hanson, and others. *Introduction to Accounting*. First Canadian Edition, Toronto, Ontario, Canada: Harcourt Brace Jovanovich Canada, Inc., 1993, pages 884, 885.

2. Vesier, Carol. "How Reliability was Marketed at Rohm and Haas." Paper presented at the annual conference of the Society of Maintenance Reliability Professionals, Denver, Colorado, 1999, page 2.

3. Gaber, B., P. Walgenbach, E. Hanson, and others. *Introduction to Accounting*. First Canadian Edition, Toronto, Ontario, Canada: Harcourt Brace Jovanovich Canada, Inc., 1993.

CHAPTER 4

THE PEOPLE FACTOR

The most important element of a factory is its human resource. Managers from companies everywhere indicate that their results are attributable mainly to their employees and their support for current developments. At the MainTech South 1998 conference, keynote speaker Randy Harl, President of Brown and Root Services, reinforced this observation. He related a benchmarking study in the oil processing industry to identify the most productive refinery. The benchmarking team had expected that a modern, highly automated refinery would be identified. Several such refineries in fact had excellent numbers. Yet the refinery providing the best numbers was a 25-year-old plant in northern England. It outperformed the others by an astounding 10%. With closer study, the best explanation for the difference was the people factor, the focus of this chapter.

To be more specific, I encourage you to re-evaluate yourself relative to this attribute. No matter what role you may have in the work force or might have in the future, the intent is to elevate your education process, and accept the higher road to continuous *active learning*. The challenge is to develop this habit in yourself and then lead others to form a synergistic, constantly developing, learning workforce.

4.1 The Most Important Resource: Actively Learning, Motivated People

A highly motivated, well-trained, and flexible workforce is invaluable in helping a factory succeed. At the same time, an unhappy, non-participative, and resistant workforce can bring quick demise to a factory. Based on a variety of circumstances, employees can fit either of these descriptions at different times.

I define the actively learning attribute as having a constant hunger for deeper understanding about all things, and putting new knowledge into action. This elevates a well-trained workforce from following practices and routines to leading and teaching constant improvements.

The quality aspect of active learning is learning from mistakes (yours and others), and not repeating them. This is a key trait to be conscientiously developed. Everyone can contribute to factory success by learning and understanding the causes behind problems and actively apply the knowledge to future tasks to avoid similar mistakes.

Active learning applies to physical and mental skills. People can and do change. An Asian proverb says "If you have not seen a person for three days, look closely to see the new person when you next meet." The proverb underscores the idea that one's life changes in small increments. The integrated total makes up our experience of learning, growing, understanding and aging. Furthermore, each increment adds to the previous, sometimes in dramatic ways.

Active learning is a valuable asset both on and off the job. School, training, books, and experience contribute significantly to everyone's abilities. Constantly learning and expanding skills directly linked with the factory equipment, processes, systems, and products will help them work more effectively. The total content of what a person has learned and skills they have exercised is the portable "toolbox" they bring with them wherever they go.

Outside interests and experiences can also contribute to stronger solutions in the workplace, as well as contributing to a persons' mental health and educational growth. Knowing what does and does not work in related fields and situations will improve problem-solving skills on the job. Creativity at work often comes from observations gained elsewhere.

Another key element is motivation. Employees who are motivated not only can complete the work, but are also self directed; they have the initiative to make things happen. Motivation is a personal characteristic inside everyone. In his influential book "The Seven Habits of Highly

Effective People,"[1] (see Appendix 1), Dr. Steven Covey notes that the first step of the seven habits is "Be Proactive". This is to realize that people have total control of how they respond to everything around them, including the work environment and their coworkers.

Motivation starts when you realize that, beginning immediately, you can change direction, taking charge of where you go next. Nourishing motivation on a daily basis will help you to be proactive in all aspects of your life, even beyond the work place. Our purpose here, of course, is to encourage you to be an active maker of change in your workplace. Go beyond just getting the job done. Strive to increase OEE and operating income, to eliminate waste of resources and materials, to simplify systems, and to meet challenging quality standards. As you and those around you contribute actively, your factory and even your job security, will be enhanced.

If your position in the factory is to lead people, then a direct portion of your responsibility is to constantly champion these characteristics with your employees. High performance work groups share this leadership task; all members accept personal responsibility to develop themselves and the group.

What attributes, other than specific trades or skills, make up an ideal employee? The Price Prichett employee handbook, "New habits for a Radically Changing World"[2], provides an excellent set of ground rules. I used these ground rules to help a work group move from a situation of great complacency to a downsized, lean manufacturing environment.

The employee ground rules are:

- ❑ Become a quick-change artist.
- ❑ Commit fully to your job.
- ❑ Speed up.
- ❑ Accept ambiguity and uncertainty.
- ❑ Behave like you're in business for yourself.
- ❑ Stay in school.
- ❑ Hold yourself accountable for outcomes.
- ❑ Add value.
- ❑ See yourself as a service center.
- ❑ Manage your own morale.
- ❑ Practice kaizen. (the relentless quest for a better way)
- ❑ Be a fixer, not a finger pointer.
- ❑ Alter your expectations.

The group I helped was part of a work center that was facing downsizing as part of reengineering. There was low trust between the workers and management. Employees were being asked to do tasks differently; some would change departments, while others would lose their jobs. The group was upset that veteran employees were being pushed out.

We talked about the business need for change. Although the group had read the Price Prichett handbook[2] to clarify expectations for the new organization, they were still resistive to change. I asked them to consider the situation if the business was sold to an outsider. What did they think the buyer would expect? I then asked them to assume they were the buyer. They could hire whomever they wanted of the current employees, organizing to make whatever profits they could, knowing that their livelihood depended on significant improvement. Although the members indicated they would hire back a majority of the workers, each also indicated many employees who would not be rehired. This exercise helped the group recognize areas for change and also that they knew the traits of a desirable employee.

Diversity is another important aspect of human resources. Just as cross-functional teams have strength, teams with member diversity frequently are stronger because of their wider spectrum of ideas, skills, and suggestions. In "Empowering Yourself, the Organizational Game Revealed"[3] (Appendix 1), Harvey Coleman discussed the "unwritten rules" that make up the barriers we face in many aspects of our life, especially at work. His message is that diversity is not about color, sex, or handicap, but rather about understanding the rules of the game. Coleman noted many successful people (e.g., Helen Keller, Colin Powell) from diverse backgrounds, explaining that they had made personal commitments and sacrifices to prepare themselves to reach high levels of achievement. Some of his major points are:

- ❑ No matter who you are, "You really are in control", it is your *Choice* to move forward, or not.
- ❑ "Organizational language is *total* communication, encompassing both verbal and not verbal behaviors". Learn to read your organizations' environment.
- ❑ Performance (hard work) is the <u>entry ticket</u> into the game.
- ❑ Volunteer, Assume more responsibility, Get Involved, Become active, Participate, Keep Abreast, Visibly Demonstrate a Team

Player Attitude, Learn New Skills, Experience Different Situations.
- ❑ Moving ahead is more than 40 hrs a week job.

The three books mentioned above form a foundation that sets the stage for a world-class workforce. It is recommended that you not only to read them but also teach them to your associates and subordinates. The goal is to drive factory productivity and effectiveness to much higher levels. The best starting place is to develop the human side of the equation into a synergistic, actively learning, motivated, workforce. These books guide a person to seek win-win solutions, to understand the larger perspectives, to participate and volunteer, and to do so by their own *choice*.

4.2 Group Centering Exercise

The way people work together is critical to the output of the factory. Dr. Steven Covey's "The Seven Habits of Highly Effective People"[1] describes habits that, when practiced, can lead to a synergistic workforce. In particular, the habits of "win-win" and "understand before being understood" are especially important for interaction among workers.

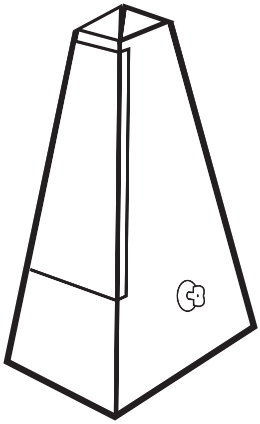
If OEE improves, everyone wins. For OEE improvements to be successfully implemented, employees throughout the factory, regardless of their position, must communicate, understand each other, and interact successfully. With this in mind, the following exercise provides a sample starting point for workers to develop the group skills that will help lead toward high OEE.

The Metronome Exercise

This group exercise involves a pyramid-shaped metronome with a pendulum that provides a beating noise to mark time. Musicians frequently use them to learn to play at a steady tempo (rate). Many metronomes have wind-up keys in the back to set the device in motion. The pendulum can be adjusted to change the tempo. For this exercise, use a metronome that has a removable cover over the pendulum (see figure 4-1).

The metronome should be placed on its side on a stand above a table so that it is at a seated person's eye level. A cardboard box should conceal the metronome until the start of the exercise. Identify the seating at the table as positions 1, 2, 3, and 4 going clockwise. Prior to the session, set the pendulum to produce a slow beat when turned on, then wind

Figure 4-1 Metronome

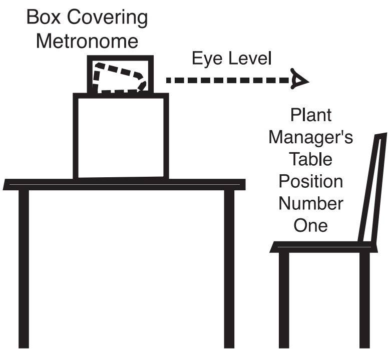


the metronome up. Replace the cover over the pendulum. Then tip the metronome on one side so that its top point is directed toward table position 1, with the wind-up key facing position 4. Use the box to hide the metronome from view (see figure 4-2).

Ask for four volunteers from the group. Announce their role and assign them to seats around the table at position 1 (plant manager), position 2 (head of production), position 3 (chief financial officer), and position 4 (head of maintenance). The remaining group members will serve as external consultants to critique factory improvement.

Give the four volunteers a marker and paper. Tell them that what is under the box represents his or her understanding of the factory process. Remove the cover and ask them to draw shapes of what they see to describe the process. In general, they should have (1) a square with lines coming to a point at the bottom center of the square, (2) a long triangle pointing to the right, (3) a square, and (4) a long triangle pointing to the left (with perhaps a detail showing the wind-up key).

Figure 4-2 Exercise Table Set-up



Tell the group that phase 1 is now complete.

Next, the four volunteers, remaining in their seats, should form a team and share their drawing information. By considering all four perspectives, the team should be able to accurately identify the true shape of the "process". By understanding how the four drawings fit, the volunteers have gone beyond seeing the process from only their own perspective.

Phase 2 is now complete.

Next, ask the consultants what they observed. The four volunteers should have related entirely different stories that reflect the differing perspectives in many of today's factories. Maintenance (position 4) sees a mechanical aspect of the process not visible to some of the others. Production (position 2) and maintenance see similar processes, but pointed in opposite directions. This difference might represent the conflict between operations driving production and the need to stop production for equipment maintenance. Finance (position 3) sees a short, flat graph. The plant manager (position 1) sees a process with a point very low relative to what it could be.

Now add four additional rules to the exercise.

1. The shape of the process can change only if *all* team members understand and agree to willingly implement an improvement project. Everyone should work synergistically. The process is constantly changing; only a proactive team can conscientiously impact it. Otherwise, successful change is difficult.
2. Any proposed improvement projects (acceptable to the facilitator and consultants) must identify the situation, the changes in actions, and the expected results.
3. The team can only work with what it already has. Achievements must be made with current budgets.
4. The height of the process represents the operating income of the company, both short and long term. Changes must bring sustainable results. (Downsizing may provide short-term, though not long-term, benefits.)

What will the team do? It may suggest simply standing the metronome up on its base. It will then be much taller and the relative financial picture will improve. Yet this is no different than simply drawing factory graphs with higher outcomes. It does not reflect reality, *unless things change inside the factory to make the results happen.*

The team should review current strategies, goals, and metrics to help understand the relative impact of each. For example, one goal may be to reduce waste by 10 percent. How would this reduction affect operating income? Use the financial income information from section 3.1, where materials cost $25 million and waste was 5 percent. A 10 percent reduction in waste leads to a saving of 0.5 percent in materials, or $125,000, as well as an increase in OEE of 0.5 percent. The overall impact on operating income is about 6 percent, assuming the factory can sell everything it makes. This increase is important, but by itself not so significant that the team can set the metronome upright to twice the current height.

Usually the biggest area of impact is productivity. For example, in section 3.3, a 10 percent improvement in productivity (from 60 percent to 66 percent) led to a 57.8 percent improvement in operating income. This size of gain would allow the team to reset the process on its base to nearly double its height. The sustained productivity improvement is both short and long term.

The facilitator can guide the discussion along these lines: Identify the bottlenecks. Start OEE programs to drive improvement. Subordinate the rest of the factory to maximize use of the bottleneck. Everyone's performance appraisal is significantly tied to the OEE metric of the bottleneck.

These changes would probably improve operating income significantly. The metronome can be set up on its base. Now everyone sees the same picture of the process and can easily understand other points of view. With this understanding, everyone can accept the new process quickly. Furthermore, the metronome can now operate properly, keeping time so that the factory heartbeat, or its rate, is regular and steady. Remove the cover and start the metronome. By optimizing OEE, the metronome beats as fast as possible for the current system. Operating the metronome for as much calendar time as possible maximizes TEEP.

With these observations, phase 3 of the exercise is complete.

The factory is now finely tuned, running the process at world-class levels. Short and long-term operating income have increased. But does this mean the upper limit has been achieved within the rules of the exercise? Have the group discuss what it thinks.

Ask what phase 4 would be like. How can operating income be further improved?

The group must move the process out of the box (or metronome). It must bring in other concepts such as simplifying processes, the Theory Of Constraints Management[4] to maximize operating income for factory output, or the Theory of Inventive Problem Solving[5] (TRIZ). For example, the rate of the process does not necessarily need to go faster. Such speed-up projects often require capital that is not available. However, the team may start using constraint minutes to chose the best mix of products to make, find a breakthrough for eliminating waste, or find a simple process improvement to dramatically improve yield.

Here are a few specific examples of phase 4 solutions.

In 1984, a Hewlett-Packard production manager of a silicon wafer production line presented his new concept of Total Quality Control to Eastman Kodak production managers at Windsor, Colorado. Because the yield was so low on his production lines, the manager was running low on raw silicon wafers. His line was below what was then an industry standard yield of 8 percent to 10 percent. Using Total Quality Control, he implemented a disciplined methodology of collecting and analyzing statistical data, identifying critical success parameters, and analyzing root cause of success limiters. His group found that a majority of the problems occurred in the etching process. They found the key parameters to control. Soon the yield went from below 8 percent to over 30 percent, three times the industry standard. Their contribution to operating income jumped significantly.

The book "The Constraints Management Handbook"[4] presents an example of allocating materials and resources to produce four different products with traditional cost accounting methods involving product profit and market demand. The factory constraint was being completely utilized with high OEE. The rest of the factory was subordinated to maximize the master production schedule. The weekly organizational profit was $1508. However, the concept of product profit relative to the *constraint work center* minute led to a significantly different priority of products to produce. This shift resulted in a weekly organizational profit of $2265, an increase of over 50 percent.

A Russian concept recently introduced in the United States is the Theory of Inventive Problem Solving, or TRIZ (from its Russian name). For more information about TRIZ, see the following web sites www.triz-journal.com and www.ideationtriz.com.

In the booklet "Introduction to TRIZ, The Russian Theory of Inventive Problem Solving"[5] several breakthrough ideas show how simple adaptation to current processes have yielded step level improvements.

One example addressed increasing yield for manufacturing nickel pellets. The molten pellets were cooled by dropping them down a tall column of cooled air into a bath of water. Increasing the rate caused significant waste and fractured pellets because the cooling process was insufficient. Using the TRIZ methodology, a unique solution was generated. By adding a foaming agent to the water and bubbling air through it, a tall column of foam was generated for the pellets to fall through. This cooling effect was far superior to the original process. Yield jumped significantly. This example is equivalent to elevating or adding capability to the constraint (step 4 in the theory of constraint management). Although the foaming agent and bubbling air were not part of the original system, adding them was a minor and inexpensive modification.

At the beginning of the exercise, what the team looked at represented the current factory process. The team then developed the hidden factory, that sizable potential (with possible increases to operating income of 100 percent or more) that exists in the factory today. Everything the team observed and changed came from within the original factory process. No new capital was needed to bring about significant financial improvements.

4.3 Skills, Interaction, and Action

Valuable factory workers are participative, synergistic and self-directed. What steps will develop these characteristics, and teach others to become more interactive? Although many classes are available to assist people with their communication skills, not all are focused on factory environments. However, one of the better developmental training sessions I have experienced is Development Dimension International, Inc.'s program called Interaction Management®[4] (Program methodology reprinted by permission). The program has evolved even further in the years since I first encountered it. The training fits completely into the principles recommended in section 4.1. It often introduces the "rules of the game" and "adding value" to many people so that they begin to interact much more effectively than before.

Interaction Management® explains that your value at work is the product of your skills, how well you interact with others, and what actions you take.

Thus,

$$\text{Skills} \times \text{Interaction} \times \text{Action} = \text{Value at Work}$$

Suppose the skills for your job are ranked on a scale of 1 to 10. A value of 10 represents the skills of the best person doing that job in your industry, whereas a value of 1 represents a new and inexperienced employee just hired for the job.

Similarly, a 1 to 10 scale measures your ability to interact or communicate with both your colleagues and your customers. This group includes all the people with whom you communicate: coworkers up and down the line and in other departments, management, and the shop floor, as well as internal and external customers and suppliers. The scale measures your total range of communication, including body language, tone, syntax, vocabulary, and context. It measures the core elements of organizational language as mentioned in section 4.1.

The last parameter is a 1 to 10 scale that measures both the actions you take and the actual results that develop from these actions. A value of 10 would be assigned when you can demonstrate significant positive improvement for the work center, a change that is recognized by your work community. Results of this type are understood by everyone and bring synergy to the group. Individual results that are valuable and may have significant bottom line improvement would merit a ranking from 6 to 9 (the scale is subjective). With this parameter, a measure of 1 would be appropriate for negative and purposely resistive actions or complaining that disrupts or undermines other workers or departments.

This rating system is for your personal use. It brings a more quantitative approach to the "add value" ground rule referred to in section 4.1. Consider, for instance, a worker with good skills, but one who works independently and rarely volunteers or contributes to team actions. This worker may have a ranking of 7 for skills, 4 for interaction, and 3 for action, for a total score of $7 \times 4 \times 3 = 84$. Another worker has only average skills (5), but also has good interaction (7), and merits a high value (7) in use of his or her discretionary time to implement key changes smoothly. This worker's score is $5 \times 7 \times 7 = 245$.

Next, consider a worker who continuously applies active learning with skills in the job, developing high proficiency and excellent output (skills = 9). This worker has mastered the "Seven Habits of Highly Effective People"[1] in communicating and interacting with others (interaction = 9) and effectively champions the implementation of successful improvements, earning quick acceptance by all coworkers (action = 10). This worker's value at work is $9 \times 9 \times 10 = 810$. Consistently high values should correlate with employees who are action oriented and who willingly take on tasks of higher responsibility.

Other aspects of Interaction Management develop the various dimensions of what make up good skills versus poor skills in communicating one on one, with groups, and in teams as well as in conflict situations. After explaining each characteristic to the class, an assessment test is conducted. Examples are shown by video (with a time clock in the upper corner). Students are guided to look for the correct traits, using a personalized score sheet to match the characteristic with the elapsed time on the video. Once the video is complete, the students can immediately confirm whether they have correctly identified the right characteristics at the right times. Subsequent discussions then clarify and sharpen their understanding.

Actual practice sessions follow this phase. Class members pair off for role-playing. Participants apply the techniques and build skills working through the key steps in a variety of situations. The roles are then reversed. Although this skill building exercise often makes students apprehensive, it is essential because it provides a safe way to apply the skills for the first time.

I used Interaction Management a few years ago after being reassigned to a new work area. At the time, there was an adversarial relationship between production and maintenance departments; goals and improvements were not being met. I had just successfully taught the program to the shop floor workers in my previous department. Now I intended to teach the classes to the leadership team of the new work area and ask that, in turn, the leaders teach them to their groups.

After the leadership classes, one maintenance foremen indicated that Interaction Management was not anything new; his people did not need the training. He honestly believed he and his people were good communicators.

After I offered to teach the foreman’s workers myself, he commented "my people really don't need this, but if they are going to have to take it, I'll be the one to do the teaching."

After he trained his people, he was astounded not only by their dramatic response to what they had learned, but also by how much he had misjudged their abilities. He completely reversed his concept of the program and offered to become a lead trainer. Over time, he trained many maintenance and production departments throughout the division.

Teaching Interaction Management was but one of several actions taken. However, over the following four years, productivity per person in this division increased by more than 85 percent.

Another important aspect of communication is the delivery. Developing delivery skills can significantly increase a person's ability to make proposals and present ideas. A person can develop delivery skills in many ways such as Toastmasters breakfast clubs and debate teams. My own experience is with the Dale Carnegie course on public speaking, recognized as one of the better formats to learn and practice building public speaking skills.

Why is delivery important? Nearly everyone will have some opportunity to participate on teams or to present ideas to other departments and higher management. This is especially true for actively learning, motivated people with the initiative to champion productivity improvements. Being effective at delivering concepts and alternatives to unfamiliar audiences is an interaction skill. It can bring acceptance for change in a timely smooth transition, overcoming resistance to and rejection of the proposal.

The Dale Carnegie®, course provides several major benefits. One is learning to deliver short stories with a strong punch line to an audience of 25 to 30 people. The class environment is friendly; and weekly routine practice helped develop this skill quickly. The principles of "How To Win Friends And Influence People"[6] help you become effective when interacting with others. You learn to show respect for the other person's opinion and let that person feel that an idea is his or hers. Another benefit is learning that everyone has interesting personal stories and experiences that can be recalled at a moment's notice. This realization makes interactions with others more personal. You learn to handle conflict, especially by understanding that previous experience may be the basis of the other person's position. Learning how prior experience relates to current proposals helps you address conflict. Finally, the life story of Dale Carnegie himself is a powerful example of motivation and active learning; it can bring you enthusiasm as you face daily challenges at work.

4.4 Observation and Education

Observation skills are important to your ability to make your factory more effective. They are especially important for data collection and analysis that help to eliminate root cause failures and supports key success parameters in every work center. To heighten your awareness of your own skills, try the following three-minute exercise. I assume you are reading this book in a classroom or by yourself.

Begin by sitting quietly and folding your hands in your lap. Spend 30 seconds to clear your mind, for example, by taking a deep breath and letting it out slowly. Then take 15 seconds to look at your surroundings as completely as possible. Close your eyes for another 15 more seconds to think of everything that is happening in your room. Now spend two minutes writing down everything that you observed during the previous 30 seconds.

Put down the book and complete the exercise.

Your list may not be very detailed the first time. However, with experience, your list can grow quite large. For example, did you list the light generated and reflected in the room, sounds you heard, smells, temperatures, pressures, clocks working, electricity being used? If you heard sounds, did you distinguish them, for example, as a tense conversation among coworkers, the regular hum from one machine, an odd ping from another? Beyond the basic senses, did you consider the radio and television waves going through the room, air convection currents, dust settling, vibration from air conditioning units, or floor vibrations? Did you consider even more abstract occurrences such as thirty seconds of aging or the change in your financial worth?

Now consider the list you could put together for an active factory. Numerous processes are happening. At the micro level, you will find worn gears, corrosion, and temperature and stress cycles, the life of each component being reduced. Good observation skills will help you get at root causes of failures and poor equipment performance, especially if these skills are applied to examining worn out parts, non-conforming product, and machine interruptions.

Among the biggest variables in a factory environment is the human factor and the multiplication of variables that develop when teams and crews interact and communicate to complete tasks. In this setting, objective observation skills can help you gather data, solve problems, and anticipate future actions. For example, ergonomics is an area of study that can help you adapt work conditions to employee needs. In observing each task, consider how a person's height and motions come into play. Do the motions of the task or the physical layout matter depending on whether the person is left or right handed? What if a person is colorblind or has poor eyesight or poor hearing? What about the various levels of light, heat and humidity? Do certain tasks require greater dexterity than others? Will some tasks lead to repetitive motion trauma? The answers to these and similar questions depend on measurements that are, in turn, based on thoughtful observations at the work location.

Furthermore, because of changes over time, a human factors monitoring process may be needed to maintain good work conditions. For example, a task may involve moving raw materials from storage to production rooms using barrels with wheels. By design, the barrels are large and heavy. At original conditions, with new wheels and good floors, the task is acceptable. With time, however, the wheel drag increases and the floors become worn and damaged. These factors slow the process and may even present safety concerns. If production rates increase, the problems with moving raw materials become more important. By necessity, this task may become more involved maintaining wheels and floors; an expensive automated system may need to be considered. On a regular basis, you should develop a habit of walking into a work area and stopping, even if just for 15 seconds, to look at all that is going on and assess the safety aspects of each area of the room. It is also beneficial to frequently take 15 seconds to make a similar assessment regarding OEE parameters. Good observation skills will assist reliability and productivity activities.

Basic education is also important for successful factory workforces. Extended education increases the likelihood that workers will detect opportunities for change or suggest successful improvements.

In many of today's factories, employees should have at least an understanding of basic chemistry and engineering. Orientation for new employees covers what is being made and the process by which it is made. Occupational and environmental safety are also covered. Employees who understand the overall science of the process of transforming incoming materials into product will be better able to make OEE suggestions. They should understand not only overall size, shape, and volume changes, but also the precision necessary for dimension tolerances and the molecular level changes that occur when materials are heated, distilled, reacted, stretched, and dried. In many cases, employees should have some knowledge of electronics, thermodynamics, and mechanical transformation, as well as the physics of conveyance and material handling.

Measurement is a significant part of factory life. Nearly every factory job involves measures and controls, if for no other reason than to evaluate good and bad product or work. Knowledge of statistics is extremely useful. Statistics helps us sort data and evaluate trends so that predictions can be made. Employees should know the characteristics of a normal bell-shaped curve. They should be able to generate histograms and understand the concept of standard deviation, especially relative to parameter specifications. Beyond these basics, designed experiments, statistical process control, statistical testing, and acceptance knowledge are powerful tools. Tremendous gains in productivity are often made by reducing the variability of key parameters such as incoming raw materials, important process factors, sequences of events, and the operating environment. Consistency (reduced variability) in set-ups, manual operations, and set points, both from shift to shift and from month to month, can contribute significantly to good factory output.

Business skills are also important. Basic understanding of waste costs, labor costs, and general operating costs will clarify the importance of value adding. Employees contribute not only by completing all their tasks correctly the first time, but also by contributing new ideas and energy. Learning to build successful business cases for improvement projects is a valuable tool. In addition, understanding accounting methods for budgets, taxes, unit costs, profit margins, cash flow, and income statements will allow for better decisions when it comes time to prioritize improvement efforts. To maintain world-class levels of operation, it is important to sustain the balance between production and production capability for both short-term and long-term viability. Planning and organizing are also important skills, used to optimize material flow, manpower, equipment resources and work order management.

At a more advanced level, understanding and applying the Theory of Constraints (TOC) is valuable for both in both operating the factory and managing improvement projects (see section 8.4). A portion of TOC involves five centering steps: Identify, Exploit, Subordinate, Elevate, and Go Back. These steps are highlighted throughout the rest of this book.

Both Overall Equipment Effectiveness (OEE) and Total Effectiveness Equipment Performance (TEEP) link the physics of the workplace with the business aspects of the factory. They directly correlate the quantity of good process output with the operating parameters on the shop floor. By identifying and eliminating the various losses, good production increases. This increase directly helps the factory's various business measures.

When OEE is graphed as the percentage of ideal output, the emphasis tends to be on the height of the bar. But OEE is really about categorizing the losses, prioritizing the improvement opportunities, and forming cross-functional teams to eliminate root cause of the loss. In short, at the heart of OEE, and TEEP, is a focus on effectiveness. The study of effectiveness consists of several components. One of these is RAM: equipment reliability, availability, and maintainability (see section 8.1). RAM examines three major aspects of equipment performance. How does the equipment work over time (reliability)? Does it start when requested (availability)? What is the ease of keeping equipment working or repairing it if it fails (maintainability)?

Reducing process changeover time (see section 8.3) is another area of effectiveness study. Changeover reductions, especially from 24 hours or more to less than 10 minutes, improve OEE dramatically by providing more run time. A valuable resource for this study is "Single Minute Exchange of Die"[7] commonly referred to as SMED. A third area of focus is performing all actions right the first time. Here the emphasis is on being mistake proof and fail safe in all factory tasks. The Japanese call these techniques "poke-yoke."

The Theory of Inventive Problem Solving[8] (TRIZ), introduced in section 4.2, is yet another area of study. TRIZ is a relatively new concept to Western technology. It comes from the observations and detailed analysis of Genrich Altshuller, an employee in the patent department of the Soviet navy. He developed a methodology to codify, classify, and methodically solve *inventive* problems in a way similar to the way we solve *engineering* problems. In Russian, the words "Teoriya Resheniya Izobretatelskikh Zadatch" or TRIZ can be translated into "Theory of Solution of Inventive Problems." This field enables many process simplifications and breakthough solutions to be generated so that factories and products can leapfrog to the top of their industries.

This section can only point to the various areas of study that play an important role in day-to-day factory life. Specific educational needs vary with individual factories. However, by having a basic understanding in many of these core groups, employees will have good portable skills applicable to many different work centers and factories. Creatively applying these tools helps them to add value on a regular basis.

4.5 Work Group Experiences

Many different types of work groups can be found on factory shop floors throughout the world. They range from traditional hierarchical groups with a single boss directing all subordinates to fully flattened groups in which each person there is his or her own supervisor. Some groups are unionized; others are not.

A traditional system often has a supervisor or foreman overseeing three to twenty workers who all perform the same functional work. In such cases, the entire organization is structured along functional lines. In union shops, workers may be grouped by their specialty or skill trade. Sometimes, supervisors have different functions reporting to them. Thus, the foreman may direct both production and maintenance workers, or those with multiple skills or trades. In these cases, supervisors may have 40 to 60 workers reporting to them, depending on their own skills and capabilities.

In other organizations, the workers can be called multi-skilled; they work at more than one type of task or trade. Similarly, workers may become multi skilled at different functional jobs so that production workers are doing maintenance work and maintenance people are running production equipment as needed. In all of the groups described thus far, the environment tends to focus on people working as individuals.

A different type of work community includes those that shift the emphasis from individual to group contributions. Numerous books are available that address the advantages of forming teams and developing an environment for employees to participate in decision-making and task execution. Forming cross-functional teams in a traditional functional organization can lead to improved communications, selection of best alternatives, and greater acceptance of proposals for change. Each functional representative becomes a stakeholder in the outcome and wants to be successful. Good communication, interaction, and action skills help the effectiveness of each participant and, ultimately, the team's effectiveness. Employees become more valuable to a company as they develop their technical understanding of the process, their interaction abilities, and their motivation for overall improvement.

Some groups are high performance work teams. In these cases, the group is self-directed, managing nearly all of its routine business and personnel functions as well as the majority of operations and maintenance functions. These types of work groups may have leadership positions through which various team members rotate over time. The leader's role is similar to that of a committee chairperson: the individual contributes to the regular workload, but also takes responsibility for organizing, focusing, and planning the direction of the team. Although high performance work teams are organized to be independent, they must strive for a strong degree of consistency and synergy with other teams in order for the division and company to succeed. Because each team is a part of the whole organization, clear guidelines are needed to establish the kinds and levels of action that the team may manage independently, and those that must be in conformance with the need of the organization.

The question arises: What type of work group is best? An appropriate answer is: It depends. The requirements of each factory need to be examined individually. Several factors must be considered in each case, such as an assessment of the tasks, the overall maturity and decision making ability of the workers, the importance of the process, the life cycle of the product, the compensation of the workers, and most of all, the desires of senior management.

I have had personal experience with four distinct types of work groups. First I was involved in a non-union hierarchical system with two foremen who directed the maintenance trades (including different skill disciplines), and production foremen who supervised operation crews. Maintenance and production reported to different division superintendents. The manufacturing facility consisted of a large polymer finishing operation (changing prepolymer into usable polymer) and an industrial-sized machine to melt, cast, stretch, and trim a continuous web of product. The process was 24 hours per day, 7 days a week. The product line was fairly narrow (two primary products) and product brand changes were sometimes days apart.

The maintenance foremen divided the responsibilities so that one foreman was in charge of the mechanics on shifts and the second was in charge of the day support mechanics or day crew. The second foreman also covered the building and miscellaneous peripheral work as well as planning for shutdown. Most of the work groups had about 15 to 20 people per foreman. Jobs and tasks were primarily functional. The work force was very stable with little or no turnover. Division superintendents usually remained in position for four to six years. In this setting, the functional approach worked fairly well. Over time, improvements such as integration of mechanics under one foreman and integration of maintenance into the production organization were implemented. Cross-functional teams were formed and given areas of responsibility to drive reliability improvements. Integration and team formation improved the productivity per person, as did implementation of statistical process controls and several process speed-ups. The group, which also completed a Reliability Centered Maintenance study (see RCM [9] by John Moubray) of their most critical process equipment, is now one of the low-cost manufacturers in the company.

On another occasion, I was again in a non-union, hierarchical system with two foremen directing the maintenance trades, including different skill disciplines. Similarly, production foremen covered operation crews. Maintenance and production workers reported to different division superintendents.

The manufacturing facility consisted of a large film sensitizing operation (unwinding webs of product; applying sophisticated, precise layers of wet emulsions; drying the emulsions; and winding up the webs into large rolls). The machine filled a large building. It was quite complex: it handled over one half mile of web, sequenced several process steps at very high speed, and completed the process in a dark environment. The process was run 24 hours per day, 7 days a week with a product line of over forty products from over fifteen process setups. One to three product brand changes occurred each shift.

As before, the maintenance foremen divided the responsibilities so that one foreman was in charge of the mechanics on shifts and the other was in charge of the day support mechanics or day crew. Again, the second foremen covered the building and miscellaneous peripheral work as well as planning for shutdown. Most of the work groups had about 17 to 25 people per foreman. Jobs and tasks were primarily functional. The work force was fairly stable with little turnover. Unlike the previous example, division superintendents seldom remained in position over two years. Although the functional approach worked fairly well, because the division superintendents changed about every two years, maintenance strategy was frequently redirected. At times, short term focus on production was demonstrated, often postponing maintenance shutdowns and improvement projects.

This area made significant gains moving from reactive to more proactive maintenance methods. It implemented newer process technology for higher web speeds and improved its TEEP using a different shutdown strategy (this case study is presented in section 6.1). Cross-functional teams were formed and given areas of responsibility to drive OEE and reliability improvements. In one four-year period, this area increased output by 45 percent. Since 1996, the area has also integrated the mechanics under one foreman and integrated the maintenance people into the production organization for the purpose of reducing overhead expenses. To date, these changes have worked successfully.

My other two experiences occurred simultaneously with two different finishing (converting and packaging) areas. At the time, maintenance and engineering formed a separate division that supported production operations. A long-term strategy was to integrate the dedicated support groups into their respective production organizations. My responsibilities included managing several maintenance groups dedicated to different finishing departments.

Two of the departments were far apart on the work group spectrum. One was a smaller group with an engineer-foreman directing a group of ten mechanics and technicians in a traditional hierarchical system that covered two shifts of five-day operation. This group was organized functionally and usually had specific work area assignments. For the most part, these workers had been in the department over 15 years. The product line was declining.

Production and maintenance talked using a 'we-they' approach. Suggested work habit changes often faced resistance. Although, a majority of maintenance work was planned periodic maintenance, a significant amount (30 – 40 percent) was highly reactive. Much of the reactive environment resulted from a production focus that product came first and maintenance was a repair operation. This area was not as productive as it could have been. In fact, although the organization desired the positive outcomes that OEE strategy would provide, the leadership team chose not to implement even simple systems that would measure the elements of OEE.

The other group consisted of approximately 35 mechanics and technicians integrated into a high-performance work community. This community divided about 140 people into four shift teams working 12-hour shifts to cover a 24 hour, 7 days a week operation. Each shift team was organized into four self-directed work crews. In turn, each crew was dedicated to one of four similar finishing machines. About 26 of the 35 mechanics were divided into the four shift teams. Each group of mechanics helped each other to cover the maintenance support of the four similar production flow-lines designed to convert and package film product using sophisticated precision equipment and staging robots.

This area had invested heavily in training its workers to be self managed. As a community, the workers had good business, manufacturing, and personal skills. Everyone had developed self-confidence and a willingness to try anything. People were encouraged to become multi-skilled in three or four operations jobs and to be flexible in work assignments. Positions such mechanic assistants were available to production operators. The area developed a good understanding of OEE and incorporated OEE improvement as a major measure for performance appraisal and compensation changes.

A number of challenging projects addressing major product revisions and cycle-time improvements on key bottlenecks were successfully implemented using cross-functional teams. Unique solutions, requiring relatively minor capital expenditures, were smoothly integrated into normal production operations. These transitions seldom required extra shutdown time for installation. This group emphasized a focused project list that allowed no more than three projects (ranked in priority) to be active at any one time. All other discretionary work was subordinated to the current project list. This list was generated and accepted by the community's cross-functional leadership team. The group increased its output rate by 43 percent from 1996 to 1998.

Every type of work group can be successful. In most cases, however, the basic characteristics of the people form the fabric that allows groups to rise to the top. In my experience, whenever the majority of the people in a community are actively learning, motivated workers willing to take on any challenge, a successful work group exists.

4.6 An Example of Expectations: Master Mechanics

As discussed in section 4.3, a person's value to the work area is the product of three factors: skills, interaction, and action. Workers should be provided guidelines—at least general ones—that explain how they will be assessed. These guidelines should factor in their roles and responsibilities toward both the business and the community. Because of the wide spectrum of production and maintenance work groups that exist, one guideline cannot apply to all groups. However, this section is offered as an example guideline. It focuses on Master Mechanic guidelines that were applied successfully in one manufacturing division to both high performance work groups (in teams) and to traditional hierarchical supervisor-subordinate groups. The guidelines helped define opportunities for individual development and were important to the compensation process.

The guidelines were generated for work areas with highly automated equipment used to manufacture different products into many formats. To be effective, the areas employed multi-skilled, versatile automatic equipment mechanics (AEM) who supported and cared for equipment ranging from simple to complex state-of-the-art technologies. Part of the area's business improvement strategy was to evolve from eight-person maintenance crews (with one or two master mechanics) to six-person crews (with three, possibly four master mechanics). At the same time, the division was moving from a reactive environment toward more proactive, predictive maintenance. Mechanics often developed beyond master level and became technicians (using the guidelines that will be discussed in section 4.7).

The leadership team of supervisors and department managers in the division generated the guidelines. Their task was to define the difference between a journeyman AEM and a master AEM. Consensus was achieved on the following categories. The categories were also weighted in importance. Though some areas were weighted more heavily than others, all were considered necessary. The categories were also considered essential for individual success in case the mechanic was moved to another department.

1. **Base expectation (must requirement). Above average-to-high technical knowledge in core disciplines (multi-skills expected): electrical, mechanical, controls, hydraulics, pneumatics, etc. (portable skills).** This requirement is basic, necessary for all mechanics, regardless of level. Master level mechanics must demonstrate technical skills appropriate for their disciplines. Master level carries the additional obligation of demonstrating the capacity to learn, keeping current with the technologies in both their disciplines and their areas of responsibility. (Price of admission: no option)

2. **Trouble shooting skills. Ability to solve unique complex problems to root cause, then take steps to eliminate them from recurring. Should be innovative and resourceful in finding ways to keep equipment running for production. Can fix anything anywhere.** This parameter helps differentiate Master-level work. Unique, complex non-repetitive work that is diagnosed, corrected, and eliminated from happening again (relative to repetitive repairs) is the standard for review. Also important is the use of creativity to permanently solve chronic problems as well as resourcefulness in keeping the business running, both while optimizing costs. (Weight: approximately 35 percent)

3. **Demonstrates being self directed and proactive with strong initiative to handle a high workload effectively. Understands the business. Willingly volunteers to help solve problems up and down the flow. Leads projects and people, recognizes what needs to get done (continuous improvement/best practices) and makes change happen. Results driven to deliver a complete job.** This parameter is the next most important parameter for a Master mechanic to demonstrate. "Understands the business" is especially important; Master mechanics make good overall business decisions and will always be working on items that make a difference and are in a logical priority. Master mechanics require little, if any, supervision. They can work effectively with the community and initiate behaviors in themselves and others to complete workloads and projects as well as to solve problems. They take ownership, following through all facets of each job. (Weight: approximately 30 percent)

4. **Is a good coach and teacher. Leverages skills and solutions to others.** This expectation brings several less technical skills together. These include demonstrating good interaction skills with all levels of the community: production, peers, technicians and engineers, and management. Master mechanics should have good communication skills (both written and oral), expressing observations and ideas with clarity, speaking to the level of the listener, confirming understanding, and asking questions when not sure. Master mechanics are good role models in the community. They exhibit an optimistic attitude and support management and the company. (Weight: approximately 20 percent)

5. **Technical knowledge of key equipment in your area (e.g., specific close tolerance, high-speed technical process equipment, critical assets, machine control, system maintenance). Are certified and licensed on the process and systems for which they are responsible.** This parameter is valuable to the local area where a person works. Master mechanics should be able to leverage their local knowledge to other areas with similar processes or technologies. They must be able to provide documentation, procedures, and information that would allow for process understanding or technology sharing, and to train at least

one backup mechanic in all key areas. (Weight: approximately 15 percent)

The first of these five categories is directed toward basic skill expectations and the capability of continuous learning. It mentions portable skills—those skills that workers have no matter where they are assigned. The other categories emphasize the expectation of important technical skills, interaction, and action; they also point to results that are visible and evident to others. This range of categories was important to this division because its compensation process used input not only from supervisors and team leaders, but also from associates and customers as well. Your own area may be different. However, having guidelines that identify skill areas, encourage interaction, and require evidence of results will help move your area toward your goals.

4.7 An Example of Expectations: Technicians

The guidelines that follow were generated for technicians in the same division highlighted in section 4.6. As with the master mechanics, the technicians who were dedicated to the work area needed clarification of general expectations. Recall that this area was evolving toward a proactive environment for equipment and system reliability. Technicians primarily worked day shifts. They usually had equipment and process reliability responsibilities for functional areas across several equipment flow lines. They were leaders in coaching, developing best practices for their areas, and eliminating root cause problems that impacted OEE.

As before, the leadership team of supervisors and department managers in the division generated the guidelines. Their task was to define the difference between a master mechanic and a technician. Consensus was achieved on the following categories, ordered from most important to less important (though still necessary). As with master mechanics, the categories were considered essential to success if the technician moved to another department.

1. **Base expectation (AAS or equivalent, a must requirement). High technical knowledge in core discipline (working knowledge and understanding of related disciplines expected): electrical, mechanical, controls, hydraulics, pneumatics, statistics, etc. (portable skills).** This requirement is basic, necessary for all technicians who must also demonstrate technical

and engineering skills appropriate for their disciplines. These skills include capability of designing or redesigning original equipment and systems in their field of expertise. Technician level also carries the obligation to demonstrate the capacity to learn, keeping current with the technologies in their disciplines and their areas of responsibility. (Price of admission: no option)

2. **Problem solving skills. Ability to solve unique complex problems to root cause, then take steps to eliminate them from recurring. Innovative at applying proper analytical and statistical tools to obtain data, information, and proof of problems and solutions in a professional manner.** Technicians should use a wide range of information gathering resources (e.g., people, monitoring devices, physical evidence, simulations, designed experiments) and apply judgment, risk analysis, and decision making skills to determine courses of action. (Weight: approximately 30 to 35 percent)

3. **Works in a professional manner and takes ownership of assigned areas. Demonstrates being self directed and proactive with strong initiative to handle a high workload effectively. Understands the business. Willingly volunteers to help solve problems up and down the flow. Leads projects and people, recognizes what needs to get done (continuous improvement/best practices), and makes change happen. Results driven to deliver a complete job.** "Understands the business" is especially important; technicians must make good overall business decisions and will always be working on items that make a difference and are in a logical priority. They require little, if any, supervision. Technicians can work effectively with the community and initiate behaviors in themselves and others to complete workloads and projects as well as to solve problems. They take ownership to follow through all facets of each job. (Weight: approximately 20 to 25 percent)

4. **Controls and coordinates small-to-medium improvement projects. Is detail oriented—projects are well planned and organized; resources managed; operators and mechanics trained; spare parts, drawings, and procedures in place;**

project results verified; and project follow through completed. Technicians need skills in communication, team facilitation, documentation, and customer focus. Their working knowledge of diverse disciplines, business skills (e.g., cost, schedule, asset life management), safety, and ergonomics can be demonstrated when project opportunities are made available. This aspect of technical and engineering work helps distinguish different levels of technicians. (Weight: approximately 15 to20 percent)

5. **Is a good coach and teacher. Takes initiative sharing information with the community (production, mechanics, peers, engineers, management, and related departments). Leverages skills and solutions to others.** This expectation brings several less technical skills together. Technicians should have good communication skills (both written and oral), expressing observations and ideas with clarity, speaking to the level of the listener, confirming understanding, and asking questions if not sure. Technicians are good role models and support the community. They exhibit an optimistic attitude and support management and the company. (Weight: approximately 15 percent)

6. **Technical knowledge of key equipment in your area (e.g., specific close tolerance, high-speed technical process equipment, critical assets, machine control, system maintenance) are fully qualified on the process and systems for which they are responsible.** This parameter is valuable to the local area where a person works. Technicians should be able to leverage their local knowledge to other areas with similar processes or technologies. They must be able to provide high quality documentation, procedures, and information that would allow for process understanding or technology sharing and to train at least one backup in all key areas. Technicians are key resources who willingly respond to and support critical demand maintenance calls outside of work hours. (Weight: approximately 10 to 15 percent)

Categories 2 through 6 support the three parameters of skills, interaction, and results. These guidelines should be made visible to others in their area to help technicians maintain credibility and build evidence of effective improvements for the area. Situations can occur where technicians are not recognized as they should be either because they were reluctant to divulge their accomplishments or because they interacted with only a select few people. These patterns can be self limiting for the individual, especially at evaluation cycles. The community should understand what changes have been made and how they help meet the goals and priorities. Clear communication helps build synergy between production and maintenance.

4.8 Interviewing and Hiring

One of the most important elements to factory success is the human resource element: interviewing and hiring the right people to operate the plant. Numerous books are available that cover this topic in full detail. This section covers my own experience with what worked and what didn't work when interviewing and hiring people for technical positions within a factory. The selection process applies not only to new hires, but also to already-hired employees who will be relocated among existing plant resources.

Selecting employees is similar to arranging marriages. You draw on experience and instinct, then match accordingly. Even when most of the significant criteria is compatible, not all matches stay together or work compatibly. The interview and hiring process is educational for both the employer and the employee. This chapter should be useful to both.

Interviewing and hiring build on a mixture of art and science; they can be handled in many different ways. They form a process. Like any factory process, they can be improved by applying successful tools and techniques. Deliberately following several steps can help improve the overall outcome, regardless of who is to be interviewed. The best outcomes are *win-win*, when selection brings a positive outcome to both sides, and *no deal,* when both sides walk away without losing. In fact, the best outcome in many cases is for both parties to determine that the match doesn't exist. It is far better to reach a no–deal conclusion than to be in a win-lose, or lose-lose situation where one or both sides are seriously compromised.

An *Inc.* Magazine article[10] estimates that the cost of hiring the wrong person for six months is 2.5 times the person's annual salary. This cost stems from the effects of losses in training and orientation, ineffective work, efforts made by work associates to accommodate the new person, rework of any mistakes, and the disruption of planned timelines. Other costs include the impact on relationships with customers (e.g., lost sales, current and future) and associated departments. Furthermore, everyone involved in the original hiring process must now repeat his or her efforts. Accommodating the miss-hired employee over time can be a root cause of team and community ineffectiveness as well as group dissatisfaction with fairness in compensation. This can be true even if the group is a self-managed team.

From the employee's perspective, being mismatched for a job can be both frustrating and humiliating. Overqualified employees can fall into situations where the job is not challenging; they become bored, settling for mediocrity. Bitterness often develops when compensation expectations differ between parties. Seemingly good employees then begin to turn negative and resistive, actively spreading their attitude to others.

To make a match, you must begin with the end in mind. Define the job and your expectations of not only the work to be done, but also the work, social, and technical environments as well as the organizational structure. Evaluate the current setting and any expected changes over the next three to five years, especially if the community is moving to change its work culture. It would be advantageous for a new employee to already share the vision and motivation for the future culture.

By defining the position and the expectations for the job, you begin educating candidates through the job posting or advertisement. Individuals seek positions based on their sense of the total picture. Make that picture as clear as possible to avoid misunderstandings. Carefully outline the compensation range of the position so that this expectation is also communicated. A good job specification will help get good candidates for a win-win match.

Once you have clearly defined a position, list the four to eight most important dimensions for the job. Consider the communication, interaction, and action portions of the position as well as the technical skills. The less technical skills are often as important as technical expertise. Apply a relative weight (1 to 10) for each dimension. Differentiate the various skills; try to have only one 10. Your list will bring a more objective review to the selection process. If the position has absolute requirements, such as a college degree in a specific discipline, then these requirements are the price of admission. They can be used to help separate resumes between those candidates who do not meet the basic requirements and those who can be further evaluated.

This is also the time to consider ways to test a candidate's job proficiency or skill levels. For example, whenever I have hired an administrative assistant, I've always given the candidates a hand-written draft of a letter to prepare. Candidates were told that part of the job involved preparing letters with the expectation that they would be error free and forwarded without requiring anyone else to proofread them. Candidates were also asked to record the time needed to prepare the letter. They were told that, together, accuracy and timeliness would have significant weight, 40 percent, to be used along with the interview to make a final decision.

Individuals have specific motivation buttons. Most people have developed patterns about how they work and accomplish things by the time they enter the work force. These patterns define how a person likes to do the work and which aspects of the work are motivational to that person. Many books are available about evaluating these patterns and finding jobs that match. One of the most enduring is *What Color Is Your Parachute?*[11] by Richard Nelson Bolles.

Recognizing people's patterns is important from the hiring perspective. Focus part of your hiring effort on understanding candidates' past patterns. Looking for compatibility with the job requirements. For instance, ask the prospective employee to list two or three things that they enjoyed doing and believed they did well. Ask for details. How did they get involved? What exactly did they do? How did they accomplish what they did? Perhaps most important, what was particularly satisfying about their accomplishment? As you listen, look for answers to questions such as these: Did the candidate work as an individual or as part of a group? What role did the person play? Was that role abstract or concrete? Was the project indoors or outdoors? Was it for a cause, for a company, for the individual, or for another person?

Compare what you learn about the satisfying aspects of the candidate's accomplishment with similar aspects of the proposed job. Is there a good fit. For example, a person's hobbies may include restoring old cars or putting together electronic kits. These would probably be a good fit with a maintenance mechanics job, especially if part of the person's satisfaction came from seeing how well equipment ran over time.

As you prepare to interview job candidates, develop questions that explore each of the dimensions used for selection. Sometimes several questions per dimension are appropriate so that different aspects of the dimension are covered. Have open-ended questions so that information is provided voluntarily by the interviewee. An example you can try is "Tell me about your most recent experience in handling a major deadline." Good communicators will effectively state the situation, explain the actions they took, and evaluate the results.

It is appropriate to have a specific scorecard of the dimensions you are looking for with each question. Then record a score relative to how well the person demonstrated that dimension. The content of each phase of the interview should help you learn the candidate's patterns for completing tasks. Take brief notes outlining these characteristics. Your questions should cover the range of knowledge and specific technical skills needed for the position. They should also explore the less technical skills as well as the types of work environment in which the person likes to work. Relevant questions about the logistics of making the transition to the new position should be considered. Finally, allow the job candidates to add any other information not already covered that they feel would make them a good fit for the position.

Use the same questions for all job candidates. Every candidate should have the same opportunity to address a consistent structured process. This consistency is especially important when you conduct internal company searches to fill positions; an objective approach can dispel charges of favoritism. Such charges can be very detrimental to work group morale, particularly if, in truth, the best candidate is not selected. When possible, have two or three people involved in the interview process so that observations and scores are averaged from different perspectives.

Once all interviews are complete and test results are available, the next phase of the selection process begins. By taking the scores on each question of the interview and multiplying by the relative weight of the dimension, you can rank the candidates.

Realize that, for many reasons, a large number of selected individuals do not accept the position. For example, they may have other opportunities. Some decide through the interview process that the position or culture is different than they expected. Others use the job offer to obtain better compensation or conditions where they are.

Anticipating the possibility of a job offer being rejected, you should rank the top three candidates. Notify the top candidate about being selected for the next step—an on-the-job experience, after which, if positive for both parties, the position will be formally offered. Confirm that the candidate is ready to commit to the offer and the logistics of moving to the new position. If this person rejects the offer, then approach the second candidate in the same way.

If the first candidate continues with the selection process, notify the second candidate that he or she ranked high, but another candidate ranked higher and is being given the first opportunity. If that candidate is not offered the job, then the same opportunity will be offered to that second candidate. Check whether this candidate is still interested and ready to commit to the potential offer. As necessary, you can follow similar steps with the third candidate. If all three candidates reject the opportunity, you should re-evaluate both the position and related benefits.

Carry out the notifications in a timely manner. Ask each candidate to respond within one business day. Notify all other candidates that they were not successful; you may share with them information about their perceived strengths and weaknesses. Never discuss with a candidate the scores or outcomes of other candidates.

Whenever possible, provide an on-the-job experience of one to three days. This experience is valuable to both sides. The job candidate can check the job conditions; the existing work group can observe the candidate's capabilities. Some companies use a probationary period of approximately six months before offering the position permanently. In such cases, you must on several occasions provide a formal review and assessment of progress against expectations. Specific assignments and monitoring results should be a part of this phase. Job candidates should demonstrate that they can actively learn (e.g., no repeat mistakes, demonstrating their ability to transfer ideas from one situation to another.). This is also the time to gauge the quality level of a candidate's work. Set a quality standard, then be consistent with everyone in the work center. Interviewing and hiring are extremely important to gaining and sustaining a factory's most important resource: actively-learning, motivated employees with proper skills for the job.

The process may seem involved and, at times, excessive. However, if it is followed through completely, the factory and its workers will both benefit. Just as a great deal of time and energy go into documenting, specifying, and selecting a piece of complex equipment, similar attention should be given when hiring employees. Investing time and energy at the beginning to define the requirements and then select the best employees will lead to the best short-term and long-term results.

4.9 Ranking and Compensating

Nearly every factory ranks its employees by work category. These rankings often form the foundation for determining levels of compensation. Although the details of ranking and compensating employees are beyond the scope of this book, I would like to share some of my own experience with successful systems I have encountered.

The example that follows focuses on a process of ranking maintenance mechanics in anticipation of compensation changes. Maintenance mechanics seldom have fixed work loads. They often perform abstract work while solving and trouble shooting complex systems. They are skilled in both disassembly and reassembly of many different kinds of equipment. Although they often work in one shift rotation, maintenance mechanics cover or support several different work areas and equipment set-ups.

The example is set in an environment in which the mechanics are multi-skilled and non-union. For the most part, they are either self-directed or assigned their tasks by a lead mechanic. Some mechanics are assigned straight day work; others may have short-term projects lasting six months or less.

Ranking is a process that compares actions, activities, and results against expectations. Even when expectations are well defined, rankings will vary depending on who prepares them. For instance, two trained supervisors in the same area may not have exactly the same understanding of the expectations. The information they each highlight may differ. Even when they supervise the same employees and have the same understanding of expectations, they may vary. One may work more closely with one subset of workers, the second supervisor with a different subset of employees. They may work with employees at different times of the day or shift and obtain different observations.

The ranking process might follow these six steps, or similar ones:

1) Provide a set of work expectations to the mechanics. Also give the list to any others that will be evaluating the mechanics, such as technicians, technical team coaches, and maintenance supervisors. An example of mechanic expectations is provided in section 4.6.
2) Have the evaluators weight the categories of expectations for importance to their own work areas. The evaluators should then communicate these percentage weights to the mechanics as well as the area leadership. This weighting and communicating must be completed at the beginning of the assessment period in order to

set standards and to educate everyone of what the measures will be. (Often, you will get what you request.)

3) At the end of the assessment period, provide worksheets to each evaluator with columns for each mechanic's name, each category, and the total score. Ask the evaluators to provide their independent input on all of the mechanics with whom they for at least two weeks or who have completed four to eight joint tasks (e.g. complex problem solving, small projects, equipment repair) during the assessment period. The evaluators must force rank the mechanics into three groups, with the top third receiving a score of three, the middle third a score of two, and the bottom third a score of one. (You may use some other division for force ranking, if you prefer.) Consider the actions and the results relative to each other, without regard to the mechanic's grade or experience. If no observations were made for a mechanic in a specific category, leave a blank in that spot by the mechanic's name. However, continue to rank the rest of the list in thirds. The objective is to measure performance level during this assessment period only.
4) Collect the worksheets. Transfer all the data to a master worksheet showing the mechanics' names and how they were scored in each category by the evaluators. Try to get more than two scores in each category for each mechanic.
5) Hold a review meeting with all of the evaluators to discuss the merits of the mechanics and any input differences. In some cases, you may find that a mechanic is, by choice, selective, working well with one group, but not with others. Such selectivity decreases their value to the overall community. Other differences may exist. For example, some good mechanics may have scored lower because they were observed with a relatively talented group. Reviewing the process with the evaluators helps with overall benchmarking of the total group.
6) After scoring inconsistencies have been discussed, the remainder of the review meeting should focus on ranking the entire group into thirds for each category. Multiplying each category score by its relative weight and totaling all five categories will generate a final score. The final scores represent the ranking list and become a key element of the compensation process.

This approach to ranking has several strengths over other approaches. Everyone—mechanics and evaluators alike—is introduced to the expectations and important factors at the beginning of the assessment period. This introduction helps focus overall performance.

Technicians who are knowledgeable in specific disciplines evaluate on-the-job performance. They usually have significantly more observation opportunities than supervisors. This approach addresses two main concerns individual mechanics might have: "My supervisor seldom sees me" and "My supervisor isn't skilled in my trade."

Using several evaluators for each mechanic significantly factors out personal bias or favoritism, while factoring in observations of inconsistent or selective performance over all the categories. Obtaining the input of the individual observers prior to the review meeting allows all of the assessment to be completed without interference or influence from others. The quality of the input is higher too because it can be provided without the time pressure of a group meeting. Mechanics should be given feedback about their strengths and opportunities for improvement in specific categories against expectations. This feedback establishes goals for developmental training and education. Even the best employees can be ranked and work toward improving their performance.

Compensation is an important element of any work place. The funds available for wages and benefits should balance total revenues minus all non-compensation costs, including reasonable profit and significant funds for developing growth and future products. When employees add value today, they raise the likelihood of future wage increases.

Guaranteed wage increases and job security that accompanies flat growth and revenues can cause the financial health of a company to deteriorate. This decline can lead to a spiral of cost cutting, wage freezes, downsizing, lost productivity, and distraction from core efforts that add value.

Having profits significantly exceed the demands for wages and benefits creates a win-win situation for the company, assuming that wages are equitable. This scenario also creates long-term job security. Profits fund company growth, raises, new jobs, new products, and new equipment. Shareholders also expect a return for their investment. Adding value, therefore, is important to employees and shareholders alike for both the short term and the long term.

Let's look at some different compensation philosophies through an example. Suppose you supervise a three person cleaning crew for a three-floor hotel. Each floor has 25 rooms. Your crew of three people, each properly trained and certified, is assigned one floor each. You find that employee A is consistently slow, employee B completes the work on time, and employee C is done early. To complete the work, you assign C to help A. The group has completed all rooms on time. In a simple pay environment, each employee earns pay for one shift.

If pay is based solely on time, then employee C will eventually settle back into an average output, completing one floor during the shift. Suppose overtime is paid, and employee A is held over to finish his or her work. Then A earns the most money despite being the least productive.

If compensation is based on rate (the number of rooms completed), then each individual is motivated to be more effective. Employee A is motivated to work faster to avoid losing compensation to another employee who will take over extra rooms. Employee C may not earn more dollars for working quickly, but will have more hours available for other pursuits (whether leisure or additional work). This rate-based system has the potential to sacrifice quality for speed, however, quality will remain high if a severe penalty is extracted for a room that does not meet standards.

I encountered a similar system several years ago on a tour at the Lincoln Electric Plant in Cleveland, Ohio. Workers there were responsible for their own specific part of the assembly of a unit. They had personal identification marks at each station. If a root cause problem of a returned unit was determined to result from their work, they could be penalized about two days pay (or more). Employee productivity was extremely high relative to industry benchmarks. Quality was also very good. Absenteeism was low as pay was only available when employees were at work completing their part of the assembly. Mechanics and other support personnel were paid relative to the output of the assigned area.

I also toured a small sawmill several years ago where workers, including the mechanics, were part of a long chain of activities in a continuous process that transformed rough logs into quality lumber products of many different sizes. Throughout the mill, workers were focused, steadily moving the work in progress to the next step. The mill was one of several in a large company. It also had regional competitors that were benchmarked for production, pay, and benefits.

The mill paid its employees the average base pay on a time basis. This plant's strategy was to set high productivity goals on a monthly basis, counting only final good product. If goals were met or exceeded, everyone received a 6 percent increase to base pay for the month. Individual employees who were at work 100 percent of the time during a pay period received a 4 percent increase to base pay; thus absenteeism was very low. In this system, supervision was minimal and employee turnover was low. This mill had met or exceeded expectations for over 14 years.

A comprehensive discussion of compensation theory is beyond the scope of this book. However, it is useful to note that, in order to promote high productivity and quality, low absenteeism, and long-term employee loyalty, any system of compensation must be fair. It should be objective, balancing the long-term needs of the company with the needs of the employees. It should be based on a fair system of ranking employees. As with ranking, the compensation system should be clearly explained to employees and evaluators, then implemented objectively and fairly to all.

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CHAPTER 5

PRIORITY AND DECISION TOOLS

5.1 The Value Fulcrum

Every manufacturing area is aware of the equipment and processes it uses to generate its products. The key equipment used for the majority of production time is usually the focus of many projects and improvement programs. Successful factories usually have a clear strategy in setting direction and handling priorities. They plan their future.

When considering large numbers of suggestions, establishing the best way to use resources for improvement is critical. One of your challenges is to prioritize these projects and programs.

To help meet this challenge, I use a graphic called the *value fulcrum* to help visualize and communicate priorities. It considers how the various interventions that can occur to a manufacturing area's bottlenecks can impact operating income. It can be used as one of the ranking criteria for all projects involving key assets.

Each organization and work center prioritizes projects and tasks using various techniques. The approach often changes with time or significant events. A single strategy will not apply to every case. This section does not provide answers to every situation. However, observing many different departments and work areas has helped me develop a general criteria that seems consistent with successful work centers.

Successful departments move from reactive environments toward planned ones. They communicate, coordinate, and control their plans and strategies, building a common understanding throughout their work place. Establishing a benefits criteria to assess the worthiness of proposed projects helps the work area reach an agreement that builds support for the top few projects. One area that I observed make significant improvements quickly used a decision matrix with several criteria columns. It derived a benefits ratio that measured the amount of time, money, and resources needed to complete a project relative to the life cycle value of the change. The area's analysis considered how well the goals and business strategy would be satisfied as well as how many people were impacted by the change or benefited from it. The analysis also reviewed the event frequency, duration, and impact on quality.

The value fulcrum lists various categories of downtime relative to use of key assets. (It does not include such catastrophic events as a fire or explosion. These are on the opposite side of the spectrum from effective runtime.)

On one side of the fulcrum is the single category of uptime that contributes positively to operating income. On the other side are events that contribute negatively.

The farther that a category is from the fulcrum, the greater its negative impact is on both short-term and long-term operating income. The relative spacing might vary for your individual operation.

Effective runtime is the key factor contributing to operating income. Activities that offset or interfere with effective runtime have negative impact on operating income. When moving departments toward planned environments, correcting or eliminating unplanned events can have significantly more impact on operating income than similar improvements in necessary planned events.

The value fulcrum also shows that key equipment downtime hours are not financially equal. Accounting practices often give relatively low value to unplanned downtime hours, especially when available headroom time exists on the key equipment. As a result, reliability and improvement projects that would eliminate unplanned downtime might be denied under the thinking that production would simply work whatever time is necessary. This view is a short-term view.

The better way to approach these types of projects is to consider the cost-benefit of their total life cycle, valuing them at expected future improvement rates and schedules. This view applies the long-term perspective that will help your factory stay in business.

This section began by noting that successful work areas were always moving toward a planned environment. Take a moment to consider how much more effective your area would be if all of the equipment, production schedules, and quality tests ran as planned, with no surprises. All of your work, including interdependent work, could be planned out for the week and executed without a hitch. Such planning has an almost synergistic effect on throughput. The equipment runs. Processes are always in control. Losses that result from waiting for information or quality reports disappear; retesting and rework evaporate. Projects get implemented as expected and perform correctly the first time. The stress of uncertainty is minimized. Because there is significant value in arriving at this type of environment, increased attention must be assigned to eliminating unplanned downtime efforts—such as root cause analysis projects and equipment reliability—beyond current considerations. This attention is especially important if your reactive work accounts for more than ten percent of all work.

Figure 5-1 the Value Fulcrum is shown on the next page. Turn the book so that the fulcrum can be viewed similar to a seesaw. This gives a physical sense of the leverage each type of category actions against effective runtime.

Detail description of time event title:

- ❑ Effective Runtime. This is the only time the factory is making money. Everyone's job in the factory depends on making good product for sale. High OEE is good.
- ❑ Statistically Designed Experiments. This time is committed to product and process development introduction. This is breakthrough thinking and can position the area for long term success.
- ❑ Proactive Maintenance. Time for conditioned based maintenance, quick changeover improvements. This will add or maintains capacity capability and is vital to high OEE.
- ❑ People Development. Time for focused training, development of skills and OEE workshops. This will add to manufacturing capability.
- ❑ Planned Improvements. Time scheduled for "proven" equipment

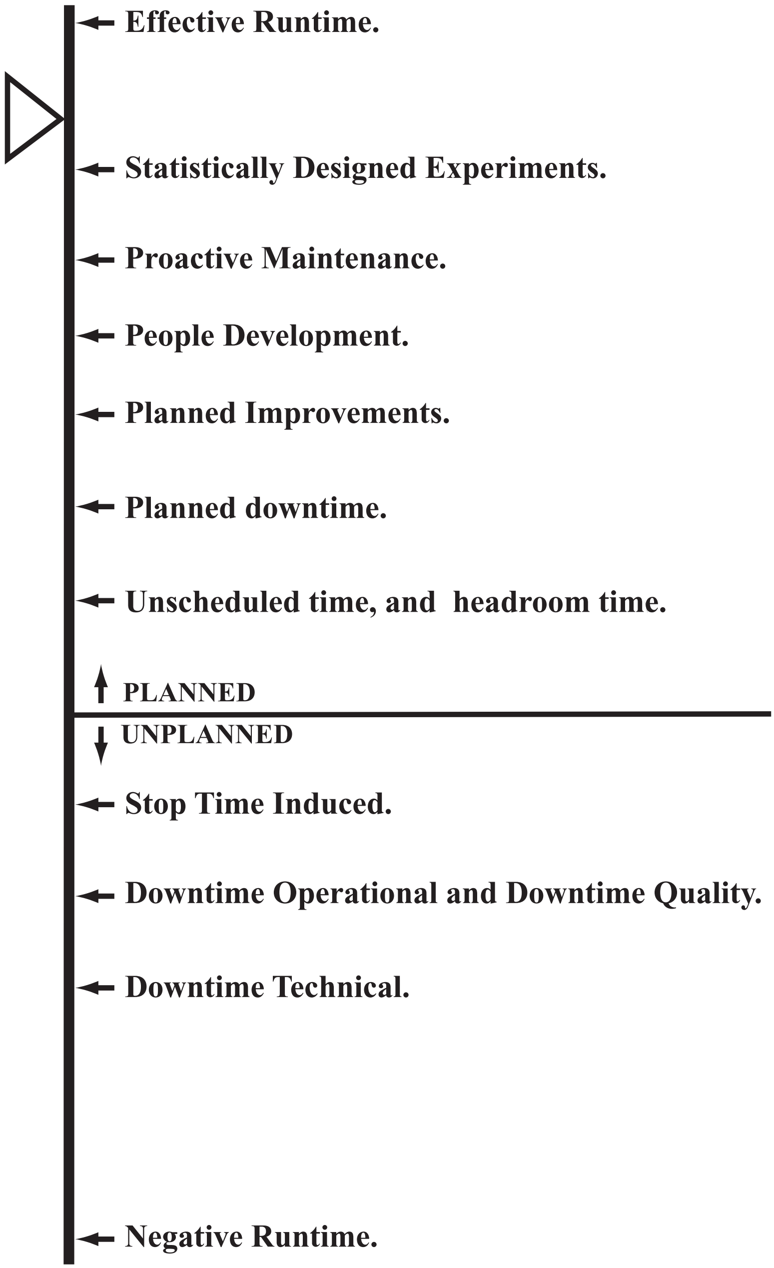

Figure 5-1 A Value Fulcrum

upgrades, RCM actions, and more frequent changeovers to reduce inventories. These actions contribute to the continuous improvement strategies.

- ❑ Planned downtime. This time is necessary for planned shutdowns needed for equipment maintenance, process clean up, periodic maintenance and normal product changeovers. All of these sustain the status quo.
- ❑ Unscheduled time, and headroom time. This time is a missed opportunity for the factory. TEEP decreases and fixed costs continue. Effective factories get filled.
- ❑ Stop Time Induced. When unplanned stoppage occurs and time and labor are wasted.
- ❑ Downtime Operational and Downtime Quality. This is more costly than Stop Time Induced because time, labor and materials are wasted.
- ❑ Downtime Technical. This is time spent for reactive rather than proactive repairs. These repairs are three-to-five times more costly than those that are detected and planned. Time, labor, materials and equipment are wasted.
- ❑ Negative Runtime. This loss is the most costly. It occurs when contamination or defective products are produced unknowingly, wasting time, materials and labor. Negative runtime can fill the delivery pipeline with unusable inventory. Customers are often lost. Raw materials to remake the product might not be available, causing additional delays and stoppages. In a filled factory, the time to make up good product may not exist.

5.2 Developing a Troubleshooting Guideline Decision Tree

Nearly every manufacturing operating area has a system for handling interruptions to the process. The system may be written or unwritten. If a formal system is not provided, miscommunication and periods of unnecessary downtime can occur.

Regardless of how well the processes and systems run when scheduled, it is helpful to develop a guideline that describes the sequence and timing of the steps to take if a downtime event occurs. Providing consistent guidelines for all crews and shifts to follow clarifies the standards for performance and helps avoid disastrous downtime events caused by poor communication. The guideline is also a good orientation tool for people new to the area.

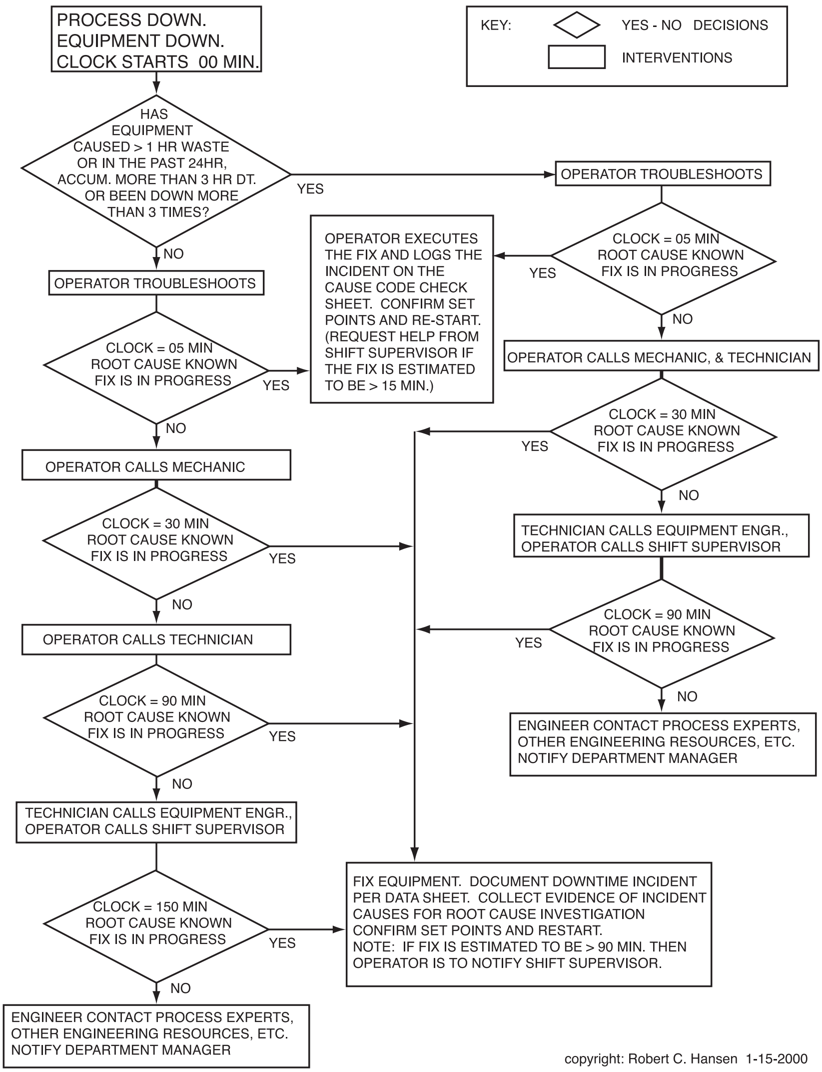

Figure 5-2 A Troubleshooting Guideline Decision Tree

The above example can be used to generate guidelines for managing unplanned downtimes in your work area. Using a yes-no decision tree technique presents a simple one-page graphic with all the information on handling equipment downtime events.

Because the guideline reflects procedures for everyone to follow, it needs to be generated, approved, and communicated as a top-down program. The combined leadership team for the area should establish and agree on the trigger points that will lead to action decisions. The guideline should be derived with input from crews that have demonstrated high performance and quality in handling downtime events.

These decision trees can be generated for various categories of downtime events. The chart in figure 5-2 addresses equipment downtime problems. It is similar to one used in an area with four complex, automatic equipment flowlines, each operating as a continuous manufacturing system operating 24 hours, 7 days a week. The area was staffed with four dedicated production crews, one shift advisor, six multiskilled roaming mechanics, and one or two technicians. You can modify the chart to apply to your specific operating area.

CHAPTER 6

EQUIPMENT SHUTDOWN STRATEGIES

The roles of production and maintenance are somewhat reversed during periods of planned equipment shutdowns. Just as production strives to be as effective as possible during scheduled operations, maintenance strives to be effective with equipment shutdowns. In each case the total community needs to support and execute the work plan in a manner of complete cooperation. Successful plants put together comprehensive plans for all activities and then make them happen.

When equipment shutdowns occur, all other activities should be subordinated to the shutdown plan. A real ‘win-win’ condition results if all shutdown work is completed as scheduled and a square start is experienced with the production start up. This can only happen through community teamwork and strategic resource planning.

Even with good plans and perfect execution, shutdowns may be longer than necessary. As each shutdown is like a separate project, the principles identified in "The Critical Chain"[1] should be applied to leverage the constraint resources. Certainly many of the concepts of quick changeover (see section 8.3) apply. Perhaps every work area should step back and re-assess their equipment shutdown strategies for maintenance.

6.1 Steps to Improve TEEP: A Case Study

In reactive environments, production will often issue annual schedules for the total operation, dictating the allowable time for shutdowns. This was the case at a plant where I worked several years ago. The special coating application department work center was the key asset to the entire plant site; all product lines had to sequence their product through the special process. This production area was the lowest cost producer for a multinational company. The corporate strategy was to use this machine to produce as much volume as possible. Consequently, production usually worked 24 hours a day, 7 days a week.

The special operation was very large. It occupied a large three-story building. The machine's continuous product length was more than half a mile long. The special machine system was also targeted for major programs to speed up, to improve process quality, and to upgrade several areas of technology. Significant project work was to be part of each shutdown. The process was classified as a continuous discrete system. Major changeovers were sometimes four days apart.

The existing maintenance plan when I began was to schedule a pair of two-week shutdowns each year. One shutdown was early in the year, the other one late because of summer seasonal volumes of some products. The work area's experience with startups after shutdowns was very poor. Therefore, the fewer shutdowns that were needed, the better. As you may suspect, overall equipment reliability and availability were not as good as desired. Maintenance and production had an "us versus them" relationship with each other. In between shutdowns the maintenance approach was to fix the equipment only when it broke. The only condition monitoring method used was tribology testing of oils from large gearboxes.

I learned from the maintenance foremen that the change to a seven-day schedule had occurred about a year before. Prior to this time, some of the maintenance could be completed routinely on weekends. Since going to the seven-day schedule, equipment availability began to deteriorate. (This change is typical. Many unrecorded actions on weekends that help reliability and availability are no longer completed. Therefore, that reliability benefit is lost. Small periodic items that had been handled indirectly off-line now become direct. In turn, the extra days of uptime gained by increasing the schedule are compromised to less than a 100 percent gain.)

Another complaint addressed the long time between shutdowns. The local area was staffed to support ongoing operations with a small day crew prepared to do off-line repair. Having only two shutdowns caused so much work to accumulate that even by using additional maintenance resources from other areas of the plant, completing all the maintenance was difficult. Furthermore, shutdowns in other parts of the plant reduced the available pool of maintenance people.

Clearly, the situation needed change. Otherwise, the same poor results would inevitably occur. The key questions were: what to change and how to move the whole community to a new approach.

The only way to bring about lasting change is to generate a win-win condition. Then the benefits would be good for both the coating department and the overall plant. With a more productive factory, the corporation would see significant improvement to the bottom line.

My experience with shutdowns had led me to the following conclusions about human limitations:

1. Given a few tasks, people can concentrate on all the details, and those tasks are usually done very well. Figure 6-1 displays the concept of concentration on detail versus number of tasks. A single complicated task is equivalent to a series of semi-complex tasks.
2. People prepare for and bring more energy to the start of a new work schedule or work challenge.
3. This higher energy level is seldom sustained for more than three or four days of challenging work. Figure 6-2 displays the concept of energy level versus days of challenging, 10-to-12 hour work schedules.
4. After the energy high has worn off, energy levels usually deteriorate over time into fatigue. People then concentrate poorly. They make more mistakes and miss opportunities to catch problems during this low energy time.

Regarding the shutdowns themselves, I learned that no two shutdowns are the same. Each one is a new project. Like projects, shutdowns are executed better if they start on time, everyone is synchronized, and everyone is fully informed. Uncertainties arise in nearly every shutdown; they often multiply relative to the calendar length of the shutdown. Local mechanics, technicians, and engineers, dedicated to the site and knowl-

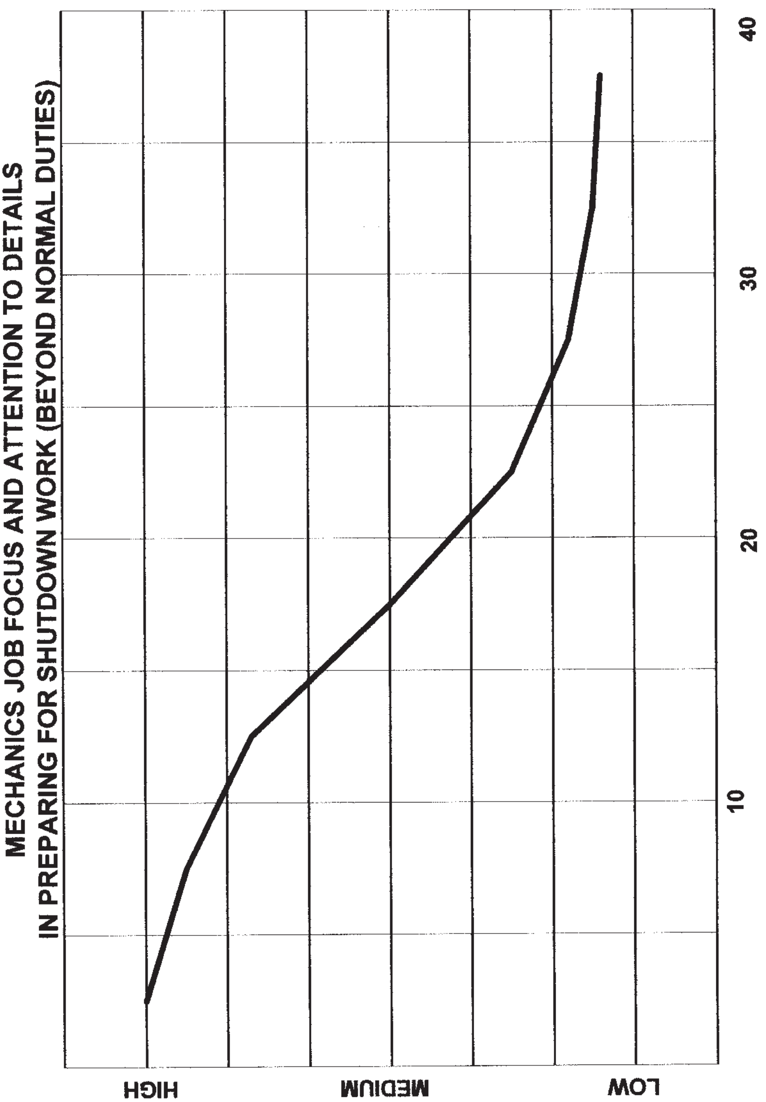

Figure 6-1 Attention to Detail versus Number of Tasks

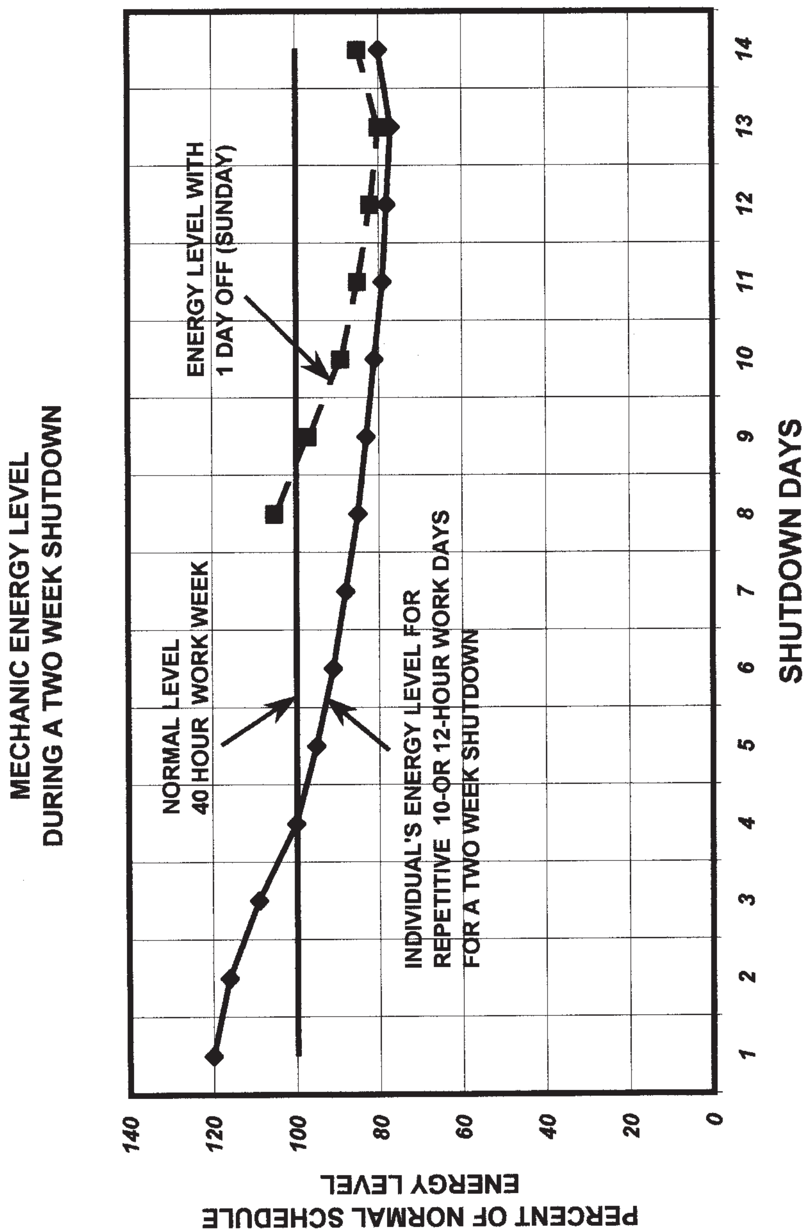

Figure 6-2 Energy Level versus Shutdown Schedule Days

edgeable of the specific equipment and processes, are the best resources for doing the work, especially the critical, nonroutine work. Because many of the upgrades have been developed internally, they should be implemented by those individuals responsible for the upgrade.

Learning curve studies indicate that repeat and similar maintenance work can be completed faster by using the same people each time. Usually these people are the local resources who get involved each time. We will call the local work area mechanics dedicated to the equipment and processes, key mechanics.

Given these general observations, it was clear that more frequent short shutdowns would be beneficial for the work area. My next step was to develop a plan that was workable for both production and maintenance. By intuition, a strategy began to emerge.

Critical Chain[1] by Eli Goldratt was not yet available at the time, however, it is now apparent that the strategy was consistent with the theory of constraints (TOC), as presented in his 1997 book. Critical Chain explains the steps and power of addressing Shutdown TOC. It also supports the principle that without attention to detail, most task estimates are inflated significantly.

The annual operation is like a critical chain. Shutdown events, just like production time, experiment time, and process verification time, are all part of the annual timeline. A shutdown must be treated as the critical chain's priority event during its execution. If this is accepted, the total community will assist in supporting the success of the shutdown through minimal time and good startups. Each shutdown includes several TOC components. These can be called: identify, exploit, subordinate, elevate, and go back.

Identify.

The first step in a shutdown is to identify the key constraint. In this example, as is the case with many maintenance organizations staffed primarily with shift mechanics, the key constraint was the availability of the local resources. These key mechanics are extremely valuable in that they know: the process, the equipment, the operation systems, and the geography of the building. People coming to help from other areas would not be as effective as the local people with local knowledge. Operators with mechanic skills can also be very useful and should be part of the resource base. Keep in mind that the cost of using local resources is already covered in the maintenance operating budget.

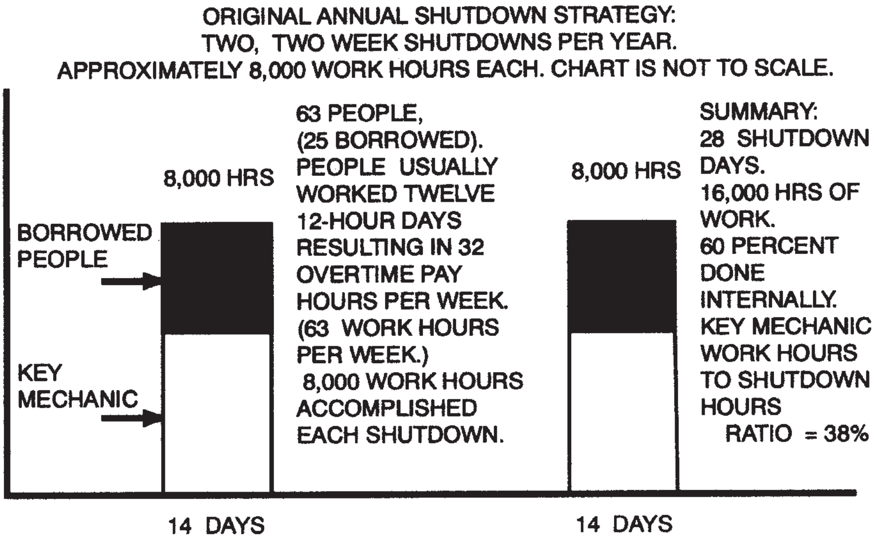

Figure 6-3 Original Annual Shutdown Strategy

Let's review how the current shutdown plans use the key mechanics. In each two-week shutdown, the key mechanics are scheduled for 12-hour shifts, with 30 minutes for lunch, and three breaks. This leaves about 10.5 hours per day for shutdown work. From the two weeks, one day is scheduled for rest. Furthermore, the last day of the shutdown is dedicated to clean up, check out, conveyance testing and commissioning, and startup. Therefore, a total of 12 days of task work is scheduled, meaning that the most task hours a key mechanic can provide during a shutdown is 12 × 10.5 hours/day = 126 hours each shutdown (or 252 hours annually). The total shutdown lasts 14 days × 24 hours/day = 336 hours. The key mechanics' work ratio relative to shutdown time is 38 percent.

$$\frac{126}{336} = 0.375 \text{ or } 38 \text{ percent.}$$

This particular area had 38 mechanics and technicians. As a group, they were able to work on shutdown maintenance for about 126 × 38 = 4788 hours each shutdown, or 9576 hours annually.

The average annual workload, however, was estimated to be

16,000 hours. Therefore, outside resources were needed for the additional 6424 hours of work not completed by the local group of 38 mechanics and technicians. Another 25 mechanics were needed to complete all the work. Realistically, the effectiveness of an outside resource was probably 80 to 90 percent of a local key mechanic. In addition, key mechanics were needed to show, direct, and orient the borrowed mechanics, placing a drain on their time and effectiveness. As a result, this work area usually had a number of carryover jobs each shutdown. Figure 6-3 illustrates the various portions of work for the annual workload.

Exploit.

The next step of a shutdown is to maximize the use of the key mechanics as much as possible. When the machine is down for 24 hours a day, the local workforce isn't scheduled for even half of that downtime. However, if the machine is scheduled to be down for 12 hours or less, then the key mechanics can work for the majority or all of the planned downtime. This kind of scheduling improves both the use of the key mechanics and their work ratio relative to the length of machine downtime. It is equivalent to having a brief maintenance time put into the regular production schedule and executed as if it was a product run. If you stop the machine for the length of a shift, or less, then almost everyone has the opportunity to complete one shift of maintenance work without leaving the job site for rest. This concept is called *maintenance linestop*.

The chronology of an ideal maintenance linestop might have the following schedule. The machine shuts down at 7:00 A.M. and is left threaded with non-product slack web. This process may take 30 minutes. Maintenance begins executing a priority work list at 7 A.M. beginning with periphery equipment while the machine is threaded with non-product web.

They complete as much work as possible and taper down the job size near the end to be completed at 5:30 P.M. The next steps are cleanup and machine prep, followed by conveyance checkout; these take approximately 90 minutes. The machine startup with product is conducted at 7:00 P.M. Allowing 0.5 hours for lunch, the amount of work time a key mechanic has available is about 9 work hours, providing a work hour to linestop downtime ratio of 75 percent.

$$\frac{\text{9 work hours}}{\text{12 hours total}} = .75 \text{ or 75 percent.}$$

This maintenance linestop approach is advantageous for low-risk, short-duration tasks that do not alter the existing process. It is perfect for both periodic maintenance (PM) and predictive maintenance (PdM) jobs as well as for modular replacement of bench tested (certified) subassemblies, which engages a spare part strategy.

For example, assume that twelve identical pumps are used in the machine and two spare pumps are stocked. Assume removing and replacing each pump requires 30 minutes and that rebuilding and testing a pump requires one hour.

With two long shutdowns, an annual PM strategy might be to overhaul five pumps during each shutdown by disassembly, replacing parts, reassembly, replacement and realignment in the machine, as well as modular replacement of one spare pump each shutdown. This approach saves one spare pump for infant mortality.

Removing and replacing the 12 pumps at 30 minutes each requires a total of 6 hours of shutdown time per year. With the above plan, five pumps will be rebuilt and tested during each of the two shutdowns, for another 10 hours. Thus, a total of 16 shutdown work hours is needed annually.

With frequent linestops, however, a pretested spare pump is substituted each time for the pump that will be overhauled. In turn, the actual reconditioning is completed external of shutdown time. Therefore, only the removing and replacing time is required for the twelve pumps annually, reducing the overall shutdown time for these pumps from 16 hours to 6 hours. Moving work items from internal to external is a quick changeover methodology for maintenance. See section 8.3.

A review of the shutdown tasks revealed that a good portion of the work was periodic maintenance jobs of 6 hours or less, and numerous jobs were similar to the pump example above. This work was well defined and had a high probability of starting back up without problems.

A linestop strategy not only exploits the key mechanics work time, it also reduces the total annual internal shutdown work hours. In this case it was estimated about 15 percent of the internal work was reduced. This means about 15 percent of 16,000 work hours or 2,400 shutdown work hours was moved to external (non-shutdown time) work to be accomplished by key mechanics between linestops.

If nearly all PM type work was accomplished on maintenance linestops, then the shutdown work plan could focus all resources on the project and major overhaul maintenance items, increasing overall effectiveness.

With this strategy, the key was to find windows of opportunity to plan and schedule maintenance linestops. Because waste would be increased if production processes were stopped during a normal run, the best window of opportunity would be when a product changeover fell near the start of the day shift, Monday through Thursday. Linestops were anticipated each month and attempted to be fixed 24 hours in advance. When operating conditions caused the target changeover to be early or late, the linestop would be postponed to the next potential window of opportunity.

With a maintenance linestop during the week, day mechanics would be available as well as some of the resources from nearby maintenance groups. Cooperation was needed from the product schedulers to review their plans and tentatively designate a maintenance linestop on some frequent basis. As a trial, a maintenance linestop was planned monthly with the goal to successfully have ten per year.

An additional benefit results by doing two internal actions in parallel. Because a product changeover could be scheduled in conjunction with the maintenance linestop, an additional 9 to 10 hours in product changeover time could be saved annually. Therefore, linestops exploit machine availability.

During each maintenance linestop, key mechanics could work about 9 hours. With 30 key mechanic available at a time, each linestop provided 30×9 hours = 270 internal work hours of maintenance. The remaining key mechanics could not be used; their time was reserved to support shifts before and after the downtime. By borrowing a few mechanics from other sources, about 306 hours of work could be completed per maintenance linestop. Thus, monthly maintenance linestops provided about 3060 hours of the estimated annual hours. Figure 6-4 illustrates the breakdown of a maintenance linestop.

From here, an overall vision of short frequent shutdowns began to take shape. About half of the original 16,000 total hours needed was unique project work or major PMs. Each shutdown , the critical path for one project would be selected as the determining factor to set the length of a shutdown. With proactive direction on projects, one of the specification requirements was to design and fabricate the hardware and software to be modular and capable of installation in three days or less. Work that was started during prior shutdowns could be completed with the final

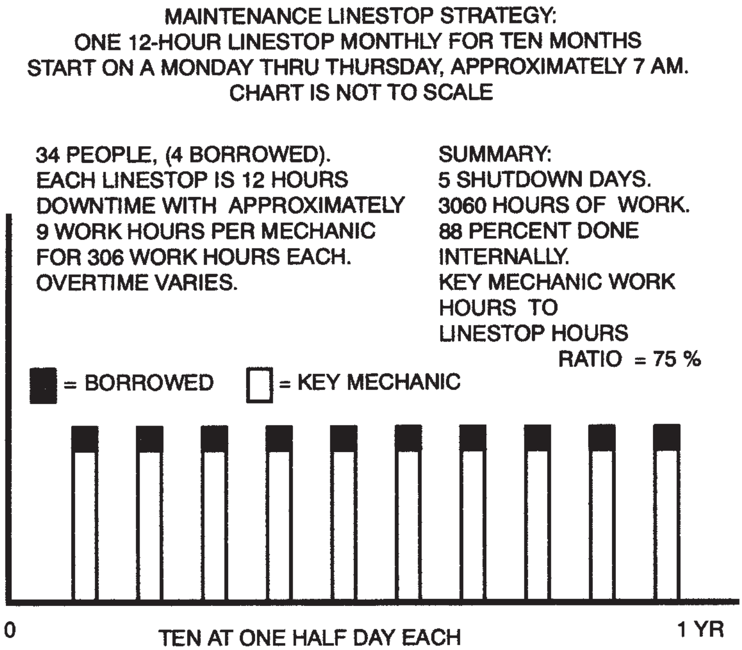

Figure 6-4 Maintenance Linestop Strategy

installation or activation step completed at the next shutdown. Short frequent shutdowns would allow a focus on a few areas of the machine each time, instead of trying to accomplish many things to all parts of the machine. This narrower focus would also simplify the conveyance and commissioning steps.

A short shutdown of 3.5 days would have a good work ratio if the conveyance and commissioning steps could be minimal. A planned shutdown from 7:00 A.M. on Monday to 7:00 P.M. on Thursday would total 84 hours. By focusing on just one or two project areas of the machine, the conveyance checkout time was reduced to two to three hours.

The chronology of an ideal 3.5-day shutdown would be as follows. The machine shuts down at 7:00 A.M. and is left threaded with non-product slack web. This step takes about 30 minutes on Monday. Maintenance begins by executing a priority work list. Most of the key mechanics would be scheduled for 12-hour shifts. They would work 10.5 shutdown hours on Monday, 11 shutdown hours on both Tuesday and Wednesday, and 7 shutdown hours on Thursday. They would be off the machine at 3:00 P.M. for 1 hour clean up and preparation, and checkout and conveyance from 4:00 P.M. to 7:00 P.M. The machine startup with product is then conducted at 7:00 P.M.

Because the key mechanics would be working on the machines a total of 39.5 of the 84 hours, their work ratio would be approximately 47 percent.

$$\frac{\text{39.5 work hours}}{\text{84 total hours}} = 1.47$$

Recall that the work ratio for a two-week shutdown was 37.5 percent. The increase in work ratio to 47 percent is a 25 percent improvement for key resources.

$$\frac{\text{47 percent}}{\text{37.5 percent}} = 1.25$$

With 38 key mechanics working 39.5 hours each, the amount of work completed per shutdown would be nearly 1,500 shutdown hours. If 20 mechanics from other sources were borrowed, each shutdown could provide approximately 2,300 hours of task work. See figure 6-5 for

LABOR STRATEGY OF A SHORT 3.5 DAY SHUTDOWN:
APPROXIMATELY 2,300 WORK HOURS EACH. CHART IS NOT TO SCALE.

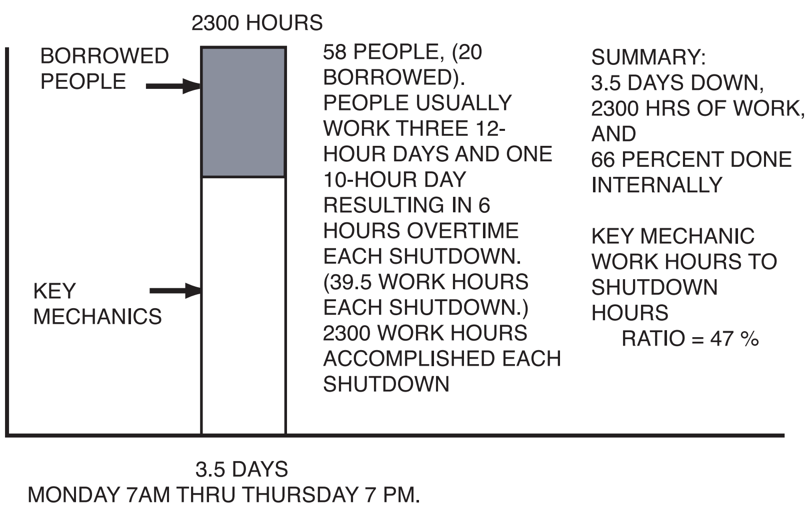

Figure 6-5 Short (3.5 day) Shutdown Strategy

another look at this shutdown.

Recall that linestops could possibly move 2,400 shutdown work hours to non-shutdown work, the annual internal shutdown work is reduced to 16,000 hours – 2,400 hours = 13,600 hours. With this strategy, four and one-half shutdowns (at 2,300 hours each = 10,350 shutdown hours) and ten maintenance linestops (at 306 hours each = 3,060 shutdown hours) would be needed to provide the approximate 13,600 shutdown hours of planned work. This plan would reduce the annual shutdown time from 28 days to about 21 days.

These improvements were very good. However, the maintenance foremen were confident that short frequent shutdowns and maintenance linestops would allow for high energy levels and improved focus, leveraging individual productivity. The newer approach would prevent the pitfalls of multi-tasking and student syndrome. With multi-tasking, a key resource rotates among several jobs, doing a little portion on each and taking longer to complete them all. Student syndrome is the tendency to start jobs late when work estimates are conservative; this happens if details are not well thought out causing estimates to be vague. By avoiding these problems, the foremen consciously lowered the estimates of the time needed to complete many tasks.

The foremen proposed four 3.5-day shutdowns and ten maintenance linestops for the annual plan. This request was entered into the forward 12-month production plan. The linestops were spaced approximately one per month. The shutdowns were evenly spaced about two months apart and avoided a seasonal volume increase.

This plan would require a total of 4×3.5 days + 10×0.5 days = 19 shutdown days; it would represent an improvement of 9 to 9.5 production days per year because some product changeover time would also be reduced.

With this strategy, the number of shutdown work hours a key mechanic could complete would improve to 4×39.5 hours + 10×9 = 248 hours relative to the total shutdown time of 19×24 hours = 456 shutdown hours for a mechanic work ratio of 54 percent.

$$\frac{248 \text{ work hours}}{456 \text{ hours total}} = 0.54 \text{ or } 54 \text{ percent.} = 1.47$$

The increase in the key mechanic work ratio from 38 percent in the original plan to 54 percent in the revised plan is an improvement of

42 percent for the key resources.

$$\frac{54 \text{ percent}}{38 \text{ percent}} = 1.42$$

With this plan more of the original shutdown work would be accomplished by the existing work area mechanics by completing the external non-shutdown work between planned downtimes.

The original strategy requires 4000 hours of overtime and about 7200 pay hours from external resources. The revised strategy results in 2440 hours of overtime and 4100 pay hours from external resources. Just imagine the improvement in this area's annual maintenance budget which directly flows into operating income.

Furthermore, the number of shutdown days was reduced from 28 to 19. If this plan was accepted, annual production could be increased by 2.5 percent. All in all, the revised plan represented a significant win-win strategy for the plant.

Subordinate.

Another critical part of the strategy requires fixed start times for all shutdowns and maintenance linestops. This request is a type of subordination and is necessary to allow maintenance planners to use CMMS tools to generate detailed plans for all work. In turn these plans leverage the individual shutdown schedules of the key mechanics for maximum use of their time, matching priority tasks with the right resources.

The product schedulers are asked to plan a standard high volume product just prior to the shutdown. Then, if the run is cut short, volume can soon be made up in the normal product cycle. If the process is running well, a small portion of the standard product can be moved up to make use of the machine until the shutdown is started.

In this work center, it was important to set the fixed shutdown date about four weeks in advance. The maintenance planners would then verify the manpower shift schedules and assign the tasks appropriately. Two weeks before the shutdown, the work plan was communicated to all those responsible for coordinating the advance work needed to execute their tasks. A significant amount of shutdown time can be saved by focusing the work that needs to be performed during the shutdown. With fewer task assigned, the amount of space needed to marshal equipment and materials is less than that needed for long shutdowns.

Elevate.

The next step is to look for more resources equivalent to the key mechanic, further leveraging the capabilities of the key constraint. One way to accomplish this is to develop operations workers with skills and knowledge to undertake some of the less complex, repetitive maintenance tasks. This is a form of Total Productive Maintenance (TPM).

At the work center above, this step was applied in several areas. For example, several operators from each shift were trained to remove the conveyance idler rollers, replace the bearings, and reinstall the rollers. Essentially, the operators took care of all machine idler rollers, which accounted for 90 percent of all rollers. Operators were also trained in the removal, disassembly, cleaning, rebuilding, and reinstallation of special treatment bars used in some product processes. The work center successfully improved reliability in several areas where operations workers also served as responsible mechanics.

Go Back.

The final step is to put together the entire business plan, then gain the support of the community to adapt this approach. Once it is accepted, a trial period is needed to monitor the results and confirm that the expected benefits are achieved. Assessing the results and making any necessary corrections completes the cycle of implementation.

Returning to the work center again, the business plan highlights were listed and presented to the production management and to each crew. The purpose was to learn of any objections and to communicate the benefits of adapting the new maintenance approach. The major highlights from the company perspective were as follows:

1. Adding 9 production days would translate into higher productivity numbers for the area and more profit for the company bottom line. About 12 product changeovers would be made in conjunction with the maintenance work, allowing more production.
2. Short shutdowns would cause far less disturbance to the product flow and inventory levels than the longer shutdowns previously would. They would also reduce the costs of materials on hand, further helping the bottom line.
3. Machine reliability was expected to increase. More frequent access to the equipment would catch failures before the process was impacted.

4. More focused work performed by the key mechanics would lower the product's maintenance cost. Work estimates could be reduced.
5. More attention to task detail would increase equipment reliability and reduce startup problems.
6. The annual maintenance budget should reduce with less overtime and lower requirements for external resources.

From the maintenance perspective, the benefits included the following.

1. More frequent access to the machine to care for deteriorating parts saving material costs and maintenance time needed to correct major failures. An increase in pride and ownership would come from better equipment uptime.
2. More tasks could be completed by key mechanics, leading to less negotiating with other departments for resources. In turn, getting additional resources would be far easier because of the reduced need for them.
3. The quality of life should be improved by having more manageable schedules. Weekends would be available for employees to enjoy with families.
4. More frequent access to the machine would lead to more proactive, predictive maintenance.
5. Focusing on fewer tasks at shutdown events would provide higher attention to detail and fewer mistakes. More work would be completed correctly the first time.
6. This approach would level out the maintenance workload over the year, smoothing the growth of technology and process improvements. Key mechanics could train at a less intense pace.
7. The maintenance budget would reduce demonstrating maintenance effectiveness and a step toward world-class.

Once this plan was communicated, both production and maintenance readily agreed to accept a six-month trial period. As the trial began, everyone was optimistic that the expected benefits would be evident soon. The transition to the new system was, in fact, smooth. The early results also shaped modifications to the plan.

A number of additional benefits immediately surfaced. With more focus on fewer tasks, along with more advance work on parts and tools, the estimates for shutdown and maintenance linestop work could be reduced significantly. The combination of fixed startups and better leverage of the key mechanics with clear priority lists (avoiding multi-tasking) enabled many jobs to progress ahead of schedule. With the shorter shutdowns, the energy level was maintained. The amount of work completed daily was impressive. The overall experience indicated that the historical requirement of 16,000 hours of work was now overstated. A new target was established of about 11,000 hours. A reduction of work of 5,000 hours.

Because more work was performed by local resources, fewer outside resources were required. The annual strategy was again revised, this time to have four shutdowns and eight maintenance linestops. (Linestops were not needed in the same month as a shutdown.) As a result, one more day was now available for production, an increase of another 0.3 percent in productivity.

The other major result experience was that the equipment reliability and availability improved significantly over the following two years. The reduction of approximately 170 equipment downtime hours per year returned another 7 days for production per year, also reducing associated repair costs and delivery interruptions. Several factors led to this result: frequent access to the equipment, new technology projects, and implementation of predictive technologies into condition monitoring such as vibration monitoring, thermography, and motor surge testing.

This area also implemented a series of speed-up projects. These projects altered the base condition for comparing reliability improvements, however over four years, the amount of equipment downtime per thousand linear feet of manufactured product reduced by 41 percent.

As indicated earlier, the process in the example was a continuous discrete system with major changeovers, sometimes four days apart. Does this shutdown strategy also work for discrete manufacturing? Experience from another work center with a discrete process indicates that this strategy would indeed work.

The discrete process work center evolved to a plan of having 2-hour linestops every other week and a 36-hour shutdown every seven weeks, based on the overall equipment conditions of its system. Using the same process as described above, the key mechanic work ratio was approximately 65 percent. High equipment reliability was maintained. In this case, as before, the work communities proactively approached the shutdown strategy with an open mind to having short frequent shutdowns and maintenance linestops. In both cases, more effective work areas emerged.

6.2 Shutdown Strategy Checklist

Every shutdown of a critical line of equipment involves detailed planning and organizing, Numerous tasks must be completed in advance in order to optimize the full use of the equipment downtime. When manufacturing operations are fully scheduled and the plant can sell everything it can make, the plant must drive Total Equipment Effectiveness Performance (TEEP) to a very high level through the effective use of all planned downtime.

Large factories and critical equipment maintenance organizations usually have maintenance task planners to coordinate downtime efforts. A significant amount of time and effort is often invested in developing a complete shutdown plan. The plan will generally organize the work by priority, matching key resources for each task and sequencing the work to avoid conflicts with time, space, and critical tools.

When planning a shutdown of critical equipment, it is essential that you establish a start date and duration of the event. These parameters are usually based on the maintenance and project work loads, the master production schedule, and the business decision to optimize expenses. In most cases, the area leadership teams provide the necessary time and establish an adequate shutdown schedule. The planners communicate their detailed plan to all stakeholders.

However, communities are not always satisfied with the quality or results of their shutdowns. In these cases, you should step back and consider the broader scope of a shutdown event. Be sure that everyone knows how they can contribute to making shutdowns successful. Just as everyone needs to support and make product runs successful, they need to give shutdown events the same priority so that they are effective, maintaining and even enhancing production capability.

Roles and responsibilities often change during a shutdown. However, all discretionary tasks and resources should be subordinated to the shutdown plan and schedule once they are established and underway.

The remainder of this section lists items that can help you have successful shutdowns. The list is by no means complete. Nor does it cover the detailed task planning efforts that must also be executed. It does, however, provide a significant number of issues, in no specific order, that you should review when you develop a shutdown plan. If you have additional suggestions, please submit them to the author for possible inclusion in future editions.

1. Use the condition of the equipment to determine what work should be done. Only do necessary work. Apply Conditioned Based Maintenance (CBM) principles. Only approved priority project work should be included.
2. Clearly identify the work hours that are needed for the shutdown. Develop a proposed schedule. Negotiate with the area leadership team for the proposed time and duration of the shutdown.
3. Understand the social and technical environment of your area. Negotiate accordingly. Does the community understand Total Effective Equipment Performance? Identify clearly the roles and responsibilities for shutdown leadership. What milestone reporting times are appropriate? What preparations are needed if the shutdown is completed early or late?
4. Recognize the importance of having a fixed timeline for all aspects of the shutdown. Keep the timeline fixed so that all parts of the plan stay intact and synchronized. Once the time is set, changing the start time by even one shift could require a complete change of assignments, in turn wasting the efforts that mechanics made to prepare for the shutdown.
5. Be sure everyone understands both the priority system and the sequence of events for the total plan. In short, plan the work, work the plan.
6. Prior to the shutdown, review the safety and proper procedures for every task.
7. Arrange for a contingency buffer of product so that any interruption to product supply is minimized, even if the startup is delayed.
8. Arrange in advance for sufficient raw materials to be available for checking and certifying equipment modifications. Sometimes, waste materials that are suitable for testing can be set aside weeks prior to the actual test.
9. Assess the skills of the resources and what they can do. The most important resources are those workers directly involved in the day-to-day process. They know how the existing equipment, employees, and system work. Subordinate tasks and actions as necessary to leverage the critical chain items and resources.

10. Allow for approximately 10 to 20 percent of resources to cover unexpected situations. Murphy's Law dictates this kind of contingency planning. Have necessary, but lower priority work available as well in case everything does in fact execute as expected.
11. Recognize that some resources may be unavailable at the last minute due to circumstances such as sickness, jury duty, and family emergency. Develop contingency plans in advance.
12. Understand the limitations of human effort. Three to four days of 12-hour work reduces physical energy and mental focus for everyone. Poor work and rework often result from too demanding of a schedule.
13. Recall that people's ability to focus and engage the detail of each job decreases with the number of jobs assigned and the time allowed for preparation. Focusing on two or three tasks is easier than ten or more tasks.
14. Set up win-win situations with production workers whenever possible. They can be good resources, assisting with many jobs. However, they can also be detrimental to the job if their skills or desires are not in line with the objectives.
15. Prior to the shutdown, check that all test equipment is calibrated and ready for use.
16. Prior to the shutdown, obtain all fire permits, lock out and tag out paperwork, and any other forms needed for the shutdown. Schedule the fire and safety departments, to be ready to support the shutdown.
17. Consider vibration and noise control. Communicate to all stake holders. Adjacent operations often continue to operate and could be impacted by the shutdown.
18. Provide areas to marshal materials and equipment.
19. Clearly tag and identify the various lines and systems that will be worked on during the shutdown.
20. Consider possible clean-up situations. Plan to contain dust, vapors, and liquids, keeping them from traveling to other areas of the operation.
21. Be ready to bleed down (empty slowly) and recharge the various systems using proper procedures. Some services may take considerable time to restore operational readiness.
22. Alert utilities and environmental services about any variations they may see as a result of discharging the chemical systems.

23. Think through how to communicate during the shutdown. Many areas have found radio communications at each job location to be very beneficial.
24. Check whether the right materials and spare parts are on site before the shutdown begins. Otherwise, cancel that task. Eliminate all surprises.
25. Determine the kind of training that production, maintenance, and support groups will need, given the new modifications. Schedule this activity to be held before or if necessary, during the shut down. The crews and mechanics will need to be up-to-date when they use the modified equipment for the first time.
26. Always provide a back-up resource, equally familiar with the tasks, for critical technical skills on key projects. Avoid having only one person for any critical key job during the shutdown. The first person may be too exhausted from completing the job to commission the work. Then, if problems develop, that person is required to do even more, leading to a cycle of mistakes and confusion. In this scenario, the entire site could be at risk if the system isn't operational. A second resource can verify the work and increase factory effectiveness by alternating shifts during the commissioning phase.
27. Break all jobs and blocks of work down to their smallest increment. Smaller parts of projects can then be implemented over time.
28. If possible, design project work and system modifications so that the original equipment conditions can be restored if the new design fails.
29. If several similar pieces of equipment are to be upgraded, work on only one initially. Confirm that the expected results have been achieved before changing the rest.
30. Use short, frequent linestops as the most effective way to perform routine maintenance and predictive maintenance checks. All day crews should be mobilized to provide assistance during the linestops. Complete all routine PMs during normal linestops. Use the shutdowns for major work.
31. Prior to the shutdown, complete all predictive monitoring tasks to assess the current condition of the equipment. Schedule only those things that require intervention. Take notes and measure-

ments for historical reference on items that may change during the shutdown. Then, original conditions can be reestablished, if necessary.

32. Provide the proper tools. Make equipment accessible, for example, providing moveable lifting devices. Remember that, in all cases, safety comes first.
33. Provide lighting, cooling, and heating as necessary to allow all jobs to progress without problems.
34. Plan for effective stores access. Stores may need to be staffed around the clock.
35. Establish a commissioning plan and readiness goal prior to the shutdown.
36. Plan to rotate all spares. If multiple spares for common items are available, rotate one per linestop. Then, build and test the removed item offline.
37. Plan positive reinforcement, based on milestone goals, for a job well done. Celebrate success, even as simply as providing free lunch or coffee.
38. Remember that many plant functions are coordinated with the shutdown. These include information systems upgrades, utility maintenance, special training coordination, and visits for special tours. Fixing the shutdown time is advantageous for the whole plant.
39. Complete longer critical jobs first. Use short, less critical jobs toward the end of the shutdown. The critical chain should drive the shutdown.
40. Install quick changeover connections and latches for many of the routine maintenance functions. Apply mistake proof techniques to eliminate errors on modular replacements. Provide common reference marks or stops so that automatic alignment occurs with modular equipment replacement.
41. Always have a large board visible for everyone to see; the board should update the progress and sequence of the jobs. Hold update meetings each shift change or at least every 24 hours. Keep the board current.
42. Use good communications to provide real time progress updates. These updates help revise timelines in case critical chain jobs finish early. They also help with reporting problems and requests for help.

43. Execute as many checkout plans and task verifications as possible while the shutdown is in progress. Attach the checkout procedure as part of the work order. Do not leave anything for last minute checkout unless absolutely necessary.
44. Always provide planned time to collect parts and information for root cause analysis and statistical equipment databases.
45. Develop or borrow special tools for precision alignment of all rotating equipment. This step contributes to high reliability.
46. In order to debug critical jobs, keep your paper work current. Maintain a chronological event chart. Record observations of what is happening and set point values at each milestone. Use designed experiment techniques, then stick to the arranged checkout plan whenever possible.
47. If changes or modifications have been made, check that the drawings and operating procedures have been updated and re-issued.
48. Try to develop a specific startup crew, then use the same crew every time. This crew develops a good learning curve and becomes efficient at this task.
49. Confirm the startup set points. Establish new set points for modified equipment.
50. Preheat large equipment items, if needed, to be at a set temperature for startup.
51. Measure the shutdown. How well did the plan work? How well did the startup go? How many surprises happened and why? What went well and what could be improved for next time? Use active learning to avoid repeat mistakes. Get feedback from all sectors.
52. Remember that every shutdown is different. You indeed need to always sweat the small stuff. Re-communicate the details to all stakeholders each time.

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CHAPTER 7

RELIABILITY 101

Fundamental reliability begins to take shape when a work community shifts its attitude of maintenance from "fix it when it breaks" toward something that is an ongoing and important function. It starts with two simple questions. In your work area:

1. Who is responsible for reliability?
2. Who is responsible for production output?

The answer should be *everyone*. This book has advocated the use of cross-functional teams and the development of active learning and multiskills for everyone. To sustain high OEE numbers, employees in the different manufacturing functions need to have basic understanding of concerns and aspects of the other functions before making decisions on priorities about their own functions.

7.1 Fundamental Reliability

Fundamental reliability is most powerful if plant managers, production and operation managers, maintenance managers and production supervisors champion it. This leadership team for the area must take stewardship of the overall system. It must balance production and production capability over the long term. They should build on the idea that "If you are not promoting reliability, then you are promoting failures."

Sharing a set of basic concepts and definitions will provide a platform for communication so that everyone can contribute to reliability, availability, and maintainability (RAM).

Because everyone is responsible for RAM, the expectations of that responsibility should be understood. These are:

1. Eliminate failures.
2. When failure occurs, reduce the impact or consequence of the failure.
3. When failure occurs, use both short-term and long-term considerations to optimize repair, and restore the systems.

The first of these is most important. If you could eliminate failures, then the other two would not be necessary. Optimizing repair for both the short term and the long term means that the fastest solution is not necessarily the best solution. Take the appropriate time to collect data, confirm root cause, and allow good workmanship so that the event is correctly understood. Prevent failures from reoccurring. All too often, the fastest fix requires a second time, or more, to correct the problem. A fast fix doesn't promote learning from mistakes.

Two of the most important steps in promoting RAM are collecting and analyzing data. These steps provide good information for problem solving and setting strategy. The data does not consist only of measurements and numbers, but also includes samples, diagrams, drawings, pictures, observations, procedures, and practices. Just as modern forensic study reconstructs a crime scene, many root cause sources of equipment failures can be uncovered by scientifically studying the failed part, then reconstructing the failure circumstances. This process can be the most exciting aspect of reliability: carefully determining the root cause of a chronic equipment failure, creatively injecting a simple solution, and monitoring results that show significant improvement on area throughput. Nearly everyone enjoys playing detective when they read mysteries. The same holds true for equipment reliability. Everyone should participate in solving the mystery. All factors should be suspected before eliminating them from being the root source problem. To set the investigative stage, let's set some common guidelines that we can use to identify these root source problems.

Begin by obtaining OEE data and categorizing the losses and summarizing event details, as outlined in chapter 2. Rank the loss events using the value fulcrum suggested in chapter 5. As appropriate, factor in actual business parameters (e.g., known costs) for various loss events. Use cross-functional teams to work on the top two or three items. Do not allow discretionary resources of people, time, or money to be directed at anything other than these top items. This focus will provide the greatest impact and the fastest rate of improvement for your area. Everyone wins when area effectiveness jumps significantly.

When resources can't be used directly on cross-functional OEE teams, focus them on developing best practice methods and procedures. This step could start with clarifying procedures and set points, collecting and categorizing all downtime minutes, and reviewing maintenance strategies. It would also include applying simple Predictive Maintenance techniques and statistical process control (SPC), then using these tools for proactive, conditioned-based maintenance (CBM).

Assume that equipment reliability of a certain subassembly is designated one of the top three items. Everyone in the community should be focused on solving this item. The necessary resources should be extended with priority; other discretionary activities should be subordinated to this investigation. Following the Theory of Constraints (TOC) steps modeled for shutdowns in Chapter 6, we have **identified** an important parameter for our attention. We will **exploit** the study and root cause analysis of this limiter. Meanwhile, we will **subordinate** other activities from distracting our resources. Once the root cause is determined, we will **elevate** the changes to eliminate the problem, using designed experiments and monitoring the results to prove that our analysis and action have addressed the problem. With this proof in hand, we will **go back** and tackle the next most important OEE limiter.

One of the most successful work centers where I worked used this exact approach. Over a three-year period, the work center showed dramatic improvements on an established system, having 70 percent throughput improvement with 12 percent fewer employees.

Once a specific subassembly is identified as a top priority, all pertinent data about downtimes, frequencies, and event details is required to begin root cause analysis. The work community's ability to collect and maintain a good database on all downtimes is very important. Good practices can prevent countless hours being spent guessing and verifying data after the fact. Good practices can reduce the risk of bad data being used which leads to incorrect causes. A good database will help you focus on the right information and allow your analysis to zoom in on the root cause.

These are among the reasons why a good database is valuable to your company. Everyone must understand this aspect, accept the responsibility, and maintain the discipline to report and record all the necessary data for each interruption. As the cost of personal computers spiral down and the need rises for vast amounts of information to be collected, organized, Pareto charted, analyzed, graphed, reported, and shared, every company should strongly consider using a computerized maintenance management system (CMMS). Good databases sorted quickly via computer systems are very useful for reliability studies.

With data collection in mind, let's review some key reliability definitions.

Failure is focused on function. If a piece of equipment fails, it is because it fails to perform its intended function. That function should be clearly defined. For example, a fuse fails if it doesn't break when subjected to high current.

Equipment can be classified into two categories: non-repairable and repairable. Failure data for the two types is collected and analyzed differently. Nonrepairable equipment, such as a light bulb or an inexpensive pump is discarded after one failure or use. Repairable equipment includes components and assemblies that are repaired, reused, or recycled back into the operating system.

When collecting data for equipment failures, record information as you might for a crime scene. Of the eleven types of data listed below, Items 1 through 6 and Item 11 should be recorded for all failures. All eleven items should be recorded for repairable failures. This list is suggested as minimum guidelines. Appendix 8 has more details.

Data collection can often be simplified by using codes for blocks of information, expediting input and sorting. See figure 7-1 as a sample code sheet.

Collecting this data, along with gathering any physical evidence such as parts or debris, is very important to identifying the root cause of the failure. Provide the necessary time to complete a data sheet at the end of the event. It can usually be completed in less than five minutes. See figure 7-2 as a sample report sheet.

The eleven types of data to document for each downtime:

1. What. The functional failure identification.
2. When. Event date and time, report date and time, and relative timing such as hour meter reading, cycle count of the system, and process time (e.g., start up, steady state, and transition).

MIXED DONUT PUMP PROCESS DOWNTIME CODES

OEE LOSS CODE	
STOPTIME	
OPER.	**STO**
INDUCED	**STI**
DOWNTIME	
TECH.	**DTT**
OPER.	**DTO**
QUALITY	**DTQ**
WASTE	**W**
SPEED	**S**

FAILURE MODE

	NO POWER	BROKEN	BLOCKED
PUMP FAILURE	1	2	3
	RATE TOO HIGH	RATE TOO LOW	LOST CAPACITY
PUMP RATE	4	5	6
	TOO HOT	CONTAM-INATION	MASHED MIXTURE
PROCESS DAMAGES MIXTURE	7	8	9

	NUTS	FRUIT	BOTH
PRODUCT TYPE	A	B	C

FAILED PART	
MOTOR:	
FAN	**1**
ROTOR	**2**
BEARING	**3**
BASE	**4**
WIRING	**5**
COUPLING	**6**
PUMP:	
SEALS	**7**
IMPELLAR	**8**
BEARING	**9**
PIPING	**10**
HOUSING	**11**
CONTROLS	**12**
SENSORS	**13**
VALVE	**14**
BLOCKED:	
INLET	**15**
OUTLET	**16**
POWER FAILURE	**17**
FUSE	**18**
OTHER:	
EXPLAIN	**19**

IMPACT	
DOWNTIME:	
< 15 MIN.	**1**
< 30 MIN.	**2**
< 45 MIN.	**3**
< 60 MIN.	**4**
< 75 MIN.	**5**
< 90 MIN.	**6**
> 90 MIN.	**7**
DONUT WASTE:	
< 3 DOZ.	**1**
< 6 DOZ.	**2**
< 9 DOZ.	**3**
< 12 DOZ.	**4**
< 24 DOZ.	**5**
> 24 DOZ.	**6**

REPAIR TYPE	
REPAIR	**1**
REPLACE	**2**

Figure 7-1 Sample Data Collection Code Sheet for a Pumping Function

MIXED DONUT PUMP PROCESS DOWNTIME REPORT (USE CODE NUMBERS FOR SHADED CELLS)

DATE	DOWNTIME START	WITNESS INITIALS	RUN HOUR CLOCK	OEE LOSS CODE	FAILURE MODE	PRODUCT TYPE	FAILED PART	DOWN-TIME	WASTE	REPAIR TYPE	RE-START TIME	BASELINE READINGS, ADJUSTMENTS AND COMMENTS

Figure 7-2 A Sample Downtime Report Sheet

3. Where. Business or process, work center, system, process stream, equipment component (specifically what broke), equipment iden tification (number and system). Save any parts for physical examination.
4. Significance or Impact. Safety, environmental, production, repair cost estimate, and frequency.
5. Witnesses. Who has potential information for follow-up questions?
6. Why? Cause of failure and failure mode. What was seen, smelled, heard, and felt (e.g., vibration, temperature, position).
7. Type of repair.
8. Who did the repair.
9. Parts used or adjusted (what adjustments were made).
10. Time required for repair. Did the repair go smoothly? If not, reasons for extended time.
11. Baseline readings at restart (e.g., amps, vibrations, and valve positions).

These items may seem to represent a lot of information for each failure. However, by consistently gathering this information on all events, you can generate a very powerful and useful database. This database will expedite the analysis for root cause, leading to successful solutions. Reliability is a data driven process. Gather data well and the rewards will come quickly.

7.2 Reliability Terms

Let's now review several acronyms and phrases associated with reliability management.

Acceptance Testing. See Reliability Quantification Testing.

Allocation. A process used to spread desired performance or failure rates across the blocks of a reliability block diagram. It also applies to spreading the percentage of occurrence of failure modes of a failure modes effects and criticality analysis (FMECA).

Availability. Equipment. Equipment availability is the percentage of time the equipment is available to run product.

$$\text{Equipment Availability Ae} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})}$$

Availability, System. This is sometimes called Overall Availability. It is similar to equipment availability but all interruptions and mean time to restore (MTTRs) are used to compute system availability, not just equipment downtimes and repair times.

$$\text{System Availability Ao} = \frac{\text{MTBI}}{(\text{MTBI} + \text{MTTRs})}$$

Baseline Equipment. A specific item or assembly of components that are standard for similar process systems, usually within a company. Baseline equipment allows sharing of spare parts, benchmarking, and common process and maintenance practices.

Batch Manufacturing. This is where individual recipes are produced in systems dedicated for each manufacturing cycle. It usually applies to chemical or process manufacturing and often involves a vessel, reactor or oven. Characteristically the equipment is cleaned or prepared for use, charged with materials, a transformation process takes place, the new material is discharged, and the cycle repeats. A new batch cycle cannot be initiated until the previous cycle is complete. Batch manufacturing can be dedicated to a single product or non-dedicated to a range of products.

Bath Tub Failure Pattern (curve). See Failure Patterns.

Benchmarking. The comparison of reliability or equipment performance between two or more like systems or work areas for a designated period of time. Entire industries can also be compared. Good communications and clean data sources are necessary for effective benchmarking.

Best Practices. The most effective method or standard to be applied as a task is executed. The standard may differ depending if the context is local, factory specific, company wide, or industry wide.

Cause and Effect Diagrams. Also known as fishbone diagrams, they are graphical representations that organize various categories of possible causes that could impact the targeted effect (outcome). They follow three types[1]: dispersion analysis, production process classifications, and cause enumeration. Categories for manufacturing are the 5 Ms: Machine, Manpower, Materials, Measurements and Methods.

Combined Manufacturing. This is where different manufacturing methods are coordinated together into a single system. It often occurs between discrete and continuous manufacturing. Examples would be a continuous web coating process with automatic roll loading and unloading, or converting the output of a continuous process by bagging, cutting or chopping into individual useable units.

Condition-Based Maintenance (CBM). A maintenance strategy in which periodic trending and monitoring of equipment or process indicates an impending equipment failure. Only with this trigger is intervention of the equipment planned and executed. This strategy minimizes infant mortality, maximizes equipment life, and initiates planned actions for mitigating the failure effects and minimizing repair time. It utilizes aspects of periodic, predictive, and proactive maintenance.

Continuous Manufacturing. This is where materials are constantly being brought together and transformed into something new. Characteristically a continuous stream of input material is conveyed through process equipment that transforms the material into something new and exits the process step without stopping. It usually is measured in volume or footage units. A cycle is a complete product run. It can be dedicated to a single product or non-dedicated to a range of products. A special category would be dedicated on-line continuous manufacturing usually involving a single product format, nearly the same as a utility company.

Cost of Quality. A loosely used term, generally meaning the total combined costs associated with accommodating unplanned manufacturing failures, of which equipment failures would be a part. For maintenance, it applies to each equipment failure and is broadly intended to include costs of equipment damage and repair, all associated product waste, capacity loss, community direct and indirect labor costs for the restore time, a portion of inventory carrying costs for manufacturing variability, a portion of staffing (maintenance and testing) for unplanned, reactive situations, and lost sales or customers for long delays.

Decision Trees. Graphical representations similar to flowcharts that lay out decision pathways. These pathways result in final recommendations or courses of actions. They usually rely on yes-no answers to sequential questions that are based on user information.

Designed Experiments. Use of statistics to set up specific tests that collect data and analyze the results mathematically. They provide confidence ranges to the question, "Is there a significant difference between two (or more) sets of data?" Because reliability is data driven, designed experiments can be used for showing process and reliability improvements, measurement error, and validating data. Every work center should have access to people who can actively design and apply experiments to all data collection and root cause analysis.

Design for Reliability. Generally refers to the concept that 80 percent of the reliability, availability and maintainability features of a process system are committed in the concept and design stages of manifesting the initial system. It refers to using reliability best practices to provide a robust, effective equipment system. The application of reliability best practices applies to all parts of every project: conceive, design, purchase, fabricate, install, commission, spare part, operate, maintain, and decommission.

Discrete Manufacturing. This is where parts or individual units are produced. It usually applies to the assembly of systems or the converting of materials into finished goods. Sometimes the cycles are so quick the appearance of continuous manufacturing takes place. Characteristically it results in individual units such as bags, rolls, parts, cars, etc. It can be dedicated to a single product or non-dedicated to a range of products.

Failure Modes. The different ways that failures can be categorized (e.g., a flow system might fail because the flow rate is either too low or too high.)

Failure Patterns (curves). The six patterns of conditional probability of equipment failure, relative to operating age. A good reference is "Reliability Centered Maintenance"[2] by John Moubray. The most familiar pattern is the bath tub curve with high infant mortality, followed by a long and constant low level of random failure, then a sharp increase of wear out at the end. Unfortunately, this curve applies to less than 10 percent of failures. The most common curves for complex equipment are infant mortality with constant random failure (approximately 68 percent) and a constant level of random failure (approximately 14 percent). Thus, there is little correlation between operating time and failures. More important, unnecessary overhaul often increases the probability of failure.

Fault Tree Analysis (FTA). A methodology of analyzing a general failure by identifying a set, or first level, of failure events that would lead to this failure. In turn, each of these failure events is broken down into a second level of events leading to their failure. The process is repeated down to detailed components or events, forming a diagram similar to a Christmas tree. Probabilities of failure are usually allocated down this tree and form a basis for risk assessment.

Failure Mode Effects Analysis (FMEA). A structured method for examining functional failures by reviewing the various failure modes, listing the possible causes for each. The effect of each situation based on the failure mode and cause are documented. Preventive actions are generated. FMEA is best completed by local cross-functional teams.

Failure Mode Effects and Criticality Analysis (FMECA). A structured method that examines the root causes of failures. Similar to FMEA, it combines the ease of detection with the consequences of failure. A local ranking system of criticality to the operation is applied and a criticality number is generated based on the frequency of the failure and severity of the effect. This criticality number helps to identify the degree to which resources should be applied to eliminate the original failure. FMECA is best completed by local cross-functional teams.

Failure Rate. This is the rate computed from the number of failures for a given time and is identified by the symbol l. If the system is in steady state, then

$$\text{failure rate, } \lambda = \frac{1}{\text{MTBF}}$$

where MTBF is Mean Time Between Failure of equipment.
Also, the failure rate of the equipment system is the sum of the failure rates of the components. Therefore

$$\frac{1}{\text{MTBF}_s} = \frac{1}{\text{MTBF}_1} + \frac{1}{\text{MTBF}_2} + \ldots + \frac{1}{\text{MTBF}_n}$$

Histograms. Graphs that categorize data with respect to the frequency of occurrence. They summarize large amounts of data, displaying unique information about averages such as the spread of the data (sigma). Histograms of Time to Failure for nonrepairable equipment quickly identify early failures and reliability successes. These can be studied for causes, with the learning applied to reliability improvement.

Infant Mortality. Early equipment failure relative to operating time, for any reason. Infant mortality is the first part of two failure patterns for complex equipment that account for over 70 percent of equipment failures1.

Life Cycle Costing (LCC). A business methodology that examines the total costs of providing, operating, maintaining, and decommissioning an equipment system relative to the potential benefits (income) over the total life of the unit, usually 20 to 30 years. Done well, this approach will show the importance of Design for Reliability. Reliability and maintainability strongly influence lifetime operating costs.

Linestops (L/S). Planned equipment downtime during which the equipment is stopped for a short period of time for small tasks. The downtime is usually 1 to 12 hours in duration. See section 6.1.

Maintenance Strategy. A broadly used term that acts as an umbrella for many categories and combinations of maintenance methods. Most often, it refers to reactive, periodic, predictive, and proactive maintenance.

Mean Time Between Failures for equipment (MTBF). This is the time interval computed by dividing the total run time of the system by the number of equipment downtime frequencies. It is a reliability statistic that can be specified in purchase orders for new equipment.

Mean Time Between Downtime Events (MTBDE). This is the time interval between failures of the overall system. It is a portion of the output from reliability block diagram (RBD see below) simulation programs such as RAPTOR (see below). It is used to denote the mean Runtime interval for redundant system configurations.

Mean Time Between Interruptions (MTBI). This is the time interval computed by dividing the total run time of the system by the number of frequencies for all unplanned interruptions.

Mean Time Between Maintenance (MTBM). This is the mean time interval between maintenance actions on equipment systems. It is a portion of the output from reliability block diagram (RBD see below) simulation programs such as RAPTOR (see below). It defines the mean time interval that maintenance work will be necessary to maintain equipment systems.

Mean Time To Repair equipment (MTTR). This is the time interval computed by dividing the total equipment repair time by the number of equipment failures. Defining actual repair time is not precise. This data may vary between work areas and should be clarified when using this statistic. It is commonly understood to be the actual wrench time used in trouble shooting and correcting or replacing parts. It is sometimes expanded to overall maintenance time, including mechanic travel time, waiting for parts, etc.

Mean Time To Restore system ($MTTR_S$). This is the time interval computed by dividing the total unplanned downtime of the system by the number of unplanned downtime frequencies. Restore interval is understood to be from the unplanned stop time of making product to the next start time in making product. Restore time includes downtime for all losses such as repair time, cleaning time, wait time, testing time, etc.

Mistake Proof/Fail Safe (MP/FS). Methods for designing systems or tools that either eliminate errors or, if errors occur, provide defaults to a safe failed condition. For example, MP/FS would provide unique hose fittings for each hose of a multi hose hook up. That way, hoses can only be connected to their correct counterparts during changeovers and module installations.

Pareto Analysis. This is a process combining one or more Pareto charts into a selection spreadsheet to identify categories of major influence.

Pareto Chart. This is a bar graph constructed by showing data frequencies for categories in descending order of frequencies, and then drawing a line graph showing the accumulated percent reached by the addition of each category. A general rule of thumb is that 80 percent of the problems are generated by 20 percent of the categories. Appendix 7 provides a methodology to easily construct Pareto charts.

Periodic Maintenance (PM). A maintenance strategy of overhauling equipment at a fixed frequency. The activity can be scheduled in several ways based on a cycle of time, the calendar, the hour clock, counts, actuations, or other measures. For example, you might replace the tires on your car every 30,000 miles regardless of their condition.

Periodic Maintenance Optimization (PM Opt.). A strategy of using PM only where appropriate and undertaking the overhauls, at just the right frequency to avoid failures, with the least overall cost impact. Few failure curves have an end wearout period. Final wearout often occurs randomly. Therefore, a standard PM strategy is often not effective at this stage. PM Opt. is an ongoing process of determining what work is appropriate for PM strategy. It reviews failure data to maximize the time between overhauls and to apply a SMED process (see below) to the overhaul in order to minimize turnaround or restore time.

Potential Problem Analysis (PPA). A systematic methodology of examining existing and future possible problems. It uses a rigorous review of validated information and relationships (including timing). PPA sets up cause and effect linkage to seek root causes or probable root causes (similar to FTA).

Prediction. An assessment of known or expected failure rates. The failure rates may be inferred from data resulting from benchmarking or from baseline equipment operation data. The failure rate information is applied to individual reliability blocks of a reliability block diagram (RBD, see below). The completion of this effort would allow solving of the RBD to estimate system reliability, or availability. Poor results as predicted from the RBD could be examined for alternative designs or redundancy considerations.

Predictive Maintenance (PdM). A maintenance strategy of monitoring or trending conditions of equipment, then overhauling only when an impending failure is detected. For example, you might frequently check the tread wear of your tires, replacing them at a specified minimum depth. PdM involves the use of technologies to measure the differences in key parameters. Typical technologies include oil and lubrication analysis, vibration monitoring, thermographic analysis, corrosion analysis, motor current analysis, ultrasonic detection, sound analysis, statistical process control of control loops, particulate monitoring, physical measurements, and on-line monitoring, charting, detection of set point differences.The technologies range from very basic to very scientific. Significant information can often be obtained using even simple tools. However, each technology usually has an entire discipline behind it.

Proactive Maintenance. The application of analytical methods, tools, and techniques to eliminate failures, extend component life, mitigate consequences, minimize downtimes, and optimize all resources. It consists of systematic identification and elimination of potential problems in all aspects of reliability, availability and maintainability (RAM).

Procedures and Set Points. These form a large portion of the methods category linked to high reliability. Procedures should be documented to establish consistency, then executed the same way by each person. They apply to all repetitive tasks (production, maintenance, testing, data collection, etc.) in the community. Procedures should also identify specific standards so that objective measures can be applied. Set points apply to both the process and the control systems supporting the process. Establishing consistent set points for process parameters meets the criteria of operating as planned. It also initiates proactive production and maintenance for any deviation. System reliability requires good procedures with established key parameter set points. This area should be investigated first when troubleshooting poor system performance.

Positive Reinforcement. An important human behavior element to sustain reliability improvement. Both reliability and OEE improvement require an approval feedback loop, similar to a control loop, to stay focused on making gains. Positive, immediate, certain, and sincere verbal and written reinforcement from both the leadership team and peers impact the rate of improvement as well as the sustainability of high performance. Positive reinforcement is a foundation tool for implementation.

Prognosis. According to author Carl Talbott (Society of Maintenance Reliability Professionals web site discussion page, August 2000), "Machinery prognosis is a point estimate (with confidence bounds) of remaining life for a machine in a specific operating environment presenting a set of condition-based symptoms of one or more pending failure modes." This definition stresses the need to temper a point estimate with a range of time in order to convey uncertainty. Prognosis can be statistically founded only if the same piece of equipment has a prior history of failing six times the same way from the same causes. Otherwise, it is only a best guess using prior experience. It then infers that similar equipment in similar conditions of operation and failure modes had a certain amount of life remaining, give or take a certain amount of time.

Quick Changeovers. These apply to both product changeovers and repetitive maintenance repairs. See SMED.

RAPTOR. A useful reliability block diagram (RBD) software program that simulates various RBD configurations at a basic level. It was generated by the Air Force and should be used as a tool for preliminary investigations. RAPTOR helps provide a rough analysis between alternate designs (redundancy). Currently, RAPTOR can be downloaded off the Internet. See Appendix 2.

Reactive Maintenance (RM). A maintenance strategy of fixing equipment when it breaks. For example, you don't replace your tires until you have a blowout. You have to trade off the risk of total failure and complete restoration against shorter term costs of maintaining equipment. RM often has a process impact before total failure is needed, such as poor performance of bald tires.

Redundancy. Occurs when two or more equipment systems are configured to be available or online to maintain system function if the original equipment fails. For example, an airplane with two engines that can still fly with one engine is said to have one redundant engine. A reliability block diagram (see above) would show the two items in parallel with the requirement that one of the two systems is necessary. Simple redundancy of like equipment significantly decreases the redundant system downtime because the probability of both units being down at the same time is small. However, having both units operating on-line approximately doubles the amount of maintenance needed to keep them in running condition. Refer to appendix 3 for example computations.

Reliability. The probability that an item or system can perform its intended function for a specified interval under stated conditions.

Reliability Block Diagram (RBD). A diagram that uses blocks to represent the equipment reliability performance of the various subsystems within the overall equipment system. The blocks are connected or linked to each other in a way that represents their association with the overall system. If failure of a block causes the system to fail, then the block is in series with others. If a block represents a redundant piece of equipment, it is in parallel with other blocks. In this case, an indicating logic condition such as 1 of 2 or 2 of 3 must be defined. An RBD can be constructed mathematically using formulas for failure curve probability and failure rates to model the approximate availability and repair times for the proposed system. Once the diagram is constructed, various scenarios can be tested to compare design choices. RAPTOR (see above) is a useful software program for generating and examining RBD's. See Appendix 2.

Reliability Centered Maintenance (RCM). A reliability methodology that originated in the aircraft industry to improve air travel reliability. It is a "process used to determine systematically and scientifically – what must be done to ensure that physical assets continue to do what their users want them to do[2]." RCM develops effective maintenance strategies, combining availability, reliability, product quality, safety, and environmental integrity. Major benefits are elimination and minimization of functional failures, PM optimization, elimination of non-value adding maintenance tasks, appropriate use of safety devices, and extensive use of PdM and CBM. Failure modes and causes are examined and ease of failure detection is assessed. RCM requires the user community to be involved. It becomes an excellent training and educational tool about their equipment and processes.

Reliability Quantification Testing (RQT). Also called acceptance testing, RQT is a designed experiment that quantifies the failure rate of equipment systems (both new and existing) with approximately 80 percent confidence level. It is explained in more detail in chapter 9.

Repair. The time during which the equipment is being diagnosed, disassembled, worked on, parts changed, reassembled, and made ready for service. This work is usually performed by the maintenance mechanic. It should be calculated from the time the mechanic arrives at the equipment. All time lost for travel, spare part delays, etc. are the result of the overall operating system strategy currently in place. This lost time represents opportunities to improve OEE. Therefore, good data collection should note all causes of lost time.

Restore. The time from the end of equipment uptime (making product) to the beginning of the next uptime cycle. Both planned and unplanned losses, including repair time, are included in restore time.

Root Cause Analysis (RCA). Similar to Fault Tree Analysis (FTA). A failure is investigated by stating the functional failure, then answering the question "What caused the failure to occur?" It usually results in a first-level answer, such as "the belt broke." The question is then repeated to generate a second-level explanation, such as frequent start-stop cycles with the motor. The question-answer process is repeated, generally four to six times until the root cause is identified. For example, debris that was allowed to accumulate due to an incorrect position of the guard over the opening which led to the raise-lower system being stuck which led to frequent start-stop cycles which led to the belt breaking. A mistake-proof method of installing the guard may be introduced, eliminating future failures.

Shutdown (S/D). Also called turnaround, a shutdown occurs when the equipment system is planned down for major overhaul and upgrade. Shutdowns should be extensively planned and organized so that materials, tools, manpower, and skills come together to recondition and improve the equipment system in a minimum downtime of the process. This time is excluded from OEE calculations, and included in TEEP. See the case study in section 6.1.

Single Minute Exchange of Die[3] (SMED) or Quick Changeovers. A methodology for minimizing product changeovers and maintaining quality through the transition. The SMED book[3] provides a case study of reducing changeovers of heavy dies for automobile manufacturing from over 14 hours to less than 10 minutes or "single minutes." SMED examines every action and activity with respect to being internal or external and is a major tool of OEE and Reliability. The principles of SMED directly apply to RAM, as well as most maintenance tasks. SMED promotes the use of built-in fixtures, templates, and mistake proof alignment so that quality is assured with the first item and testing is unnecessary. The SMED process requires the user community to participate; it also becomes a good training and educational tool.

Society of Maintenance Reliability Professionals (SMRP). An organization of manufacturing reliability practitioners from many different companies. The members share the common goal of promoting reliability methods and techniques for use in manufacturing. The society's web site can be found at www.SMRP.org. It promotes the idea that practitioners need skills in five key areas: reliability principles, manpower management, business management, work or task management, and process management.

Square Starts. Instantaneous high performance (vertical learning curve) at initial acceptance for operation after every downtime. A square start is the reliability goal for bringing projects on-line and after all shutdowns or turnarounds.

Statistical Process Control (SPC). The application of statistical tools such as control charts of the average (x-bar) and range (R) of sample data. Histograms of the process data determine process capability and define the upper and lower control limits of the normal process. Control charts are either indiscrete, with continuous measurements, or discrete, with data based on counting such as the number or fraction of defectives. Maintenance can use information from the process control charts. For example, it can use the SPC of service supply system control valve positions to proactively trigger actions of equipment investigations for out of control signals *before* the system reaches limits that impact product quality.

System Reliability of equipment. The *product* of equipment subsystem reliabilities, or

$$R_{sys} = R_1 \times R_2 \times R_3 \times \ldots \times R_n$$

A similar formula holds true for equipment system availability.

If the system is in steady state, then

$$\text{failure rate, } \lambda = \frac{1}{\text{MTBF}}$$

where MTBF is Mean Time Between Failure of equipment.

Also, the failure rate of the equipment system is the sum of the failure rates of the components. Therefore,

$$\frac{1}{\text{MTBF}_s} = \frac{1}{\text{MTBF}_1} + \frac{1}{\text{MTBF}_2} + \ldots + \frac{1}{\text{MTBF}_n}$$

Tattletale Techniques. This is building in a feature to signal impending failure. It also refers to use of a unique 'fingerprint' to identify specific equipment sources. Examples would be the wear bar showing tread depth of tires or dye 'tagging' specific oil sources to track root source of lubricant leaks.

Timelines. Chronological graphs of the Time To Failure of repairable systems. Timelines are necessary for identifying reliability trends or randomness of failure. Maintenance strategies can be altered as appropriate based on the results.

Total Productive Maintenance (TPM). This is where production operators build skills to complete maintenance tasks on equipment systems. It is a formal process of selecting appropriate tasks and transferring responsibility for specific equipment care to the production operator of that system.

Trending. This is collecting repetitive measurements of key parameters and the analysis of deviation of the values. Trending is important for applying Predictive Maintenance and Condition-Based Maintenance strategies.

Turnaround (see Shutdown).

Utilization. Most often defined as

$$\text{Utilization} = \frac{\text{Uptime}}{\text{Calendar time}}$$

Do not confuse this measure with OEE.

The use of these reliability terms and tools should apply to both proposed equipment systems and existing equipment systems already in use.

7.3 Beginning Reliability With What You Have

The top one or two focus projects should have priority for all discretionary resources so that the improvement rate can be maximized. Consider launching an aggressive OEE reliability improvement program for the number one priority project in your work area if a program doesn't already exist. Such a program could have the greatest financial impact for your area. If reliability is not selected as a priority project, yet resources are not used directly for cross-functional OEE teams, then use them to develop best practice methods and procedures.

Start by understanding the current processes. Incorporate run hour meters, cycle or speed counters and use chart recorders to document work stoppage frequencies. Begin collecting data as outlined in section 2.2.

Review maintenance strategies, clarify procedures and set points, collect and categorize all downtime minutes, and apply simple predictive maintenance (PdM) techniques and statistical process control (SPC), using these tools for proactive, conditioned-based maintenance (CBM). Now a reliability program for existing equipment can begin. Complete the objective assessment (benchmark) of the key parameters for OEE and equipment availability. Whatever level is detected will be the anchor point for measuring progress.

Ask yourself how much money is needed to start a reliability program. The answer is almost nothing. You can accomplish a great amount with what is probably already at your fingertips. Many consultants at reliability conferences emphasize that most gains can be made by establishing critical equipment lists, then generating or correcting procedures and methods to incorporate consistent best practices. Significant reliability progress can be made with collaborative understanding and communication among all employees in the work center community. No capital investment is required for this type of work.

Call the initial approach Phase 1. Clarify and confirm your understanding of the manufacturing process, working with a cross-functional leadership team. Define the physical transformation steps, then identify the functions required for each step. The list of functions can be used to create a functional block diagram. This list may also define the boundaries for the elements in a reliability block diagram. Construct a process flow map for your manufacturing configuration, labeling the points in the flow streams with volume numbers and relative cost numbers for the various product families. This map will help guide criticality lists and decisions on improvement strategies. On the flow map, highlight the major bottleneck operations for your major products. The bottlenecks may change for different product families. Next, generate a critical equipment list, giving preference to key bottleneck equipment. This list will prioritize reliability targets. Essentially, you have now identified the reliability target.

The next step in Phase 1 is to reassess the current performance and maintenance strategy for the reliability target. You should have validated the database and generated OEE, equipment availability, and equipment downtime information for the reliability target. (If not, begin doing this now.) Review previous Time To Failure data points in a timeline chart, checking for randomness or trends. Determine MTBF and MTTR. Evaluate the current equipment system while running the major products at common speeds. Record the set points, valve positions, amp readings, damper settings, process and service system flow values, motor temperature readings, and other appropriate measures. By recording this information during production, you can compare measures as often as a given product is scheduled. Use the key parameters from this data set to form the basis for maintenance SPC charts. If information is available from original design and commissioning, verify that the current system is still capable. Conditions may now be quite different, leading to a redesign strategy. Initiate data collection best practices of all downtime events, gathering all removed parts for forensic study. Collect the current documentation and procedures being used for all maintenance tasks. All of these actions support the reliability decision tree.

In Phase 2 you exploit the reliability target. In this example, you want to optimize the reliability of what you already have, the existing equipment system. Your ideal goal is zero unplanned equipment downtime, with minimal planned intervention occurring only as scheduled. Your first proactive step is to list the functions of the targeted process system, building a functional block diagram of this subsystem. Because this target is community priority, all key employees should be made available to perform a Failure Modes Effects and Criticality Analysis (FMECA). See Appendix 6.

Form cross-functional teams. "Each cross-functional team from the various production steps should typically consist of an operator, a production supervisor, a mechanic and/or an electrician, and a maintenance supervisor. These should be people who are peer leaders within their areas of the plant, and who feel the freedom to express their considered opinions. Other people could be involved as part of these teams, and this decision should be left to those leading the effort. The key is to have a team of people who understand where the plant's problems are, and who are willing to work as a team to help resolve those problems. Finally, there should also be a group of support staff who represents another team for the review process. This is likely to consist of a plant engineer, a member of the purchasing staff, a member of the human resources staff, a store person, someone from utilities, and perhaps others who can contribute to problem resolution as the review evolves."[4]

The local team should provide a criticality scale based on known consequences of the various equipment failures. This scale should be used for each function examined. Multiplying the assigned criticality number, the failure rate of the function, and the percentage of the failure rate for each failure mode provides a FMECA number. Each process function should have its own FMECA study and numbers. You can then generate a master table with all the FMECA numbers in descending order to prioritize the actions you need to take.

Each major equipment item or subsystem may require its own maintenance strategy. The various levels of maintenance strategy are reactive, periodic, predictive, proactive, and conditioned based (a combination of predictive and proactive). Because critical equipment is highly valued and zero unplanned downtime is the goal, proactive conditioned-based maintenance is usually the preferred strategy.

Planned reactive strategy is normally a last choice, appropriate when other approaches are inadequate. It may be used where redundancy (a proactive design strategy) is purposely used. For example, a planned reactive strategy is appropriate when redundant brake lights are used, and a single failed light would not affect safety and can be recognized and replaced immediately.)

Periodic (PM) strategy applies only if a proven wear-out failure curve is known to exist. This situation is rare, often shifting with different product schedules or equipment demands. PM may be appropriate for economic reasons when little or no impact may exist (e.g., lubrication of peripheral equipment). Periodic maintenance is usually a poor choice of strategy. Intervention cycles must be severely shortened to protect from failures; equipment is more often exposed to infant mortality. Studies of Reliability Centered Maintenance (RCM) show that about two-thirds of an area's PMs are inappropriate[2]. Thus, key mechanic resources and maintenance budgets are wasted most of the time when this strategy is used indiscriminately. The actual life of a component is never realized, increasing material costs. Finally, a PM strategy has significant (5-to-15 percent) early random failures.

Predictive (PdM) strategy applies to components for which the failure mode can be easily trended or signaled. These components follow a variable, but obvious wear-out pattern. The failure mode must correlate with parameters that can be accurately detected. Examples of these parameters include physical dimensions and shape, cycle time, temperature, velocity profiles, volume or flow rate, vibration, wear particles, electrical current or resistance, magnetic field, and hardness. For a predictive strategy to be successful, the frequency of trending must occur at a rate capable of detecting the impending failure and providing ample time for planning and correction. In some cases, continuous online monitoring may be appropriate. Creativity may be needed to select the measurement parameters, for example, using product quality that correlates with equipment performance or building in a tattletale feature to signal impending problems.

Proactive maintenance applies analytical methods, tools, and techniques to eliminate failures, extend component life, mitigate consequences, minimize downtimes and optimize use of all resources. It consists of systematic identification and elimination of potential problems. It is forward directed.

Condition-Based Maintenance (CBM) relies on periodic trending and monitoring of equipment and processes to indicate an impending equipment failure. Only with this trigger is intervention planned and executed. This strategy minimizes infant mortality and maximizes equipment life. It initiates planned actions for mitigating the failure effects, while minimizing repair time. CBM integrates aspects of periodic, predictive, and proactive maintenance. It is usually the most cost-effective strategy, both for its use of local resources and its reduction of the cost of quality.

To summarize, the foundation information and FMECA results reveal different courses of action for each individual case. A large spectrum of strategies exists for reliability targets. In general, the following four tools almost always provide large benefits.

1. Root Cause Analysis and elimination of frequent failures.
2. Eliminate unplanned reactive maintenance. Move from PM to PdM or CBM to avoid failures, and reconfigure for maintainability (MP/FS templates, isolation valves, onsite pretested modular parts, built-in diagnostics, and accessibility.)
3. Quick Changeover tactics on overhauls and dedicated tools.
4. Proactively managing a change in culture and training from reactive to Condition Based Maintenance (CBM).

7.4 Matching Maintenance Strategy to Equipment Function

Let's now look at how to match maintenance strategy to system function at a basic level. Consider two different pump systems. Both systems use the same size pump to supply water. Extra pumps and parts are in spare parts inventory.

The water from these pumps has two primary purposes. Case 1 the water makes up the primary portion of a cleaning solution used to clean the product tanks that go out on trucks. The areas operate as need-

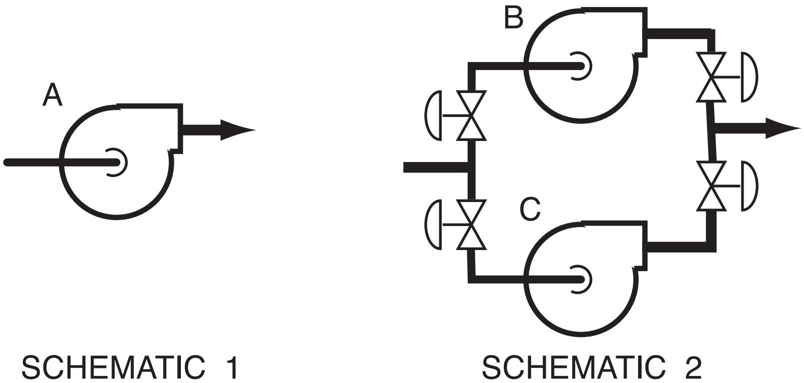

Figure 7-3 Schematics of Two Pumping Configurations

ed: one shift per five-day week. Case 2 the water is of critical importance for cooling a continuously operating incinerator. This incinerator rectifies the environmentally harmful byproduct waste gases from all of the plant's manufacturing processes. The incinerator operates 24 hours, 7 days per week. If it goes down, the plant goes down as well, and all the material in process is lost. When the manufacturing processes are shutdown, the restart takes several hours longer than the restart of the incinerator.

These reviews compare the option of using a single pump configuration with the option of installing an in-line spare pump for backup. In figure 7-3, Schematic 1 shows a system that supplies water with a single pump (A). Schematic 2 supplies water with redundant pumps: a duty pump (B) and a standby pump (C) that is automatically brought online for loss of flow.

The decision of which option to select should be based on safety, consequences, and life cycle costs. This example will examine consequences only. For each use of the pump, consider the consequence of a failure and determine what maintenance strategy should be used.

Start with Case 1, the use of schematic 1 pump to provide cleaning water for the product tanks. Here, the failure of pump A would cause portable tank cleaning to be interrupted. Cleaning would be delayed, with possible overtime, shortage of clean product tanks, or inconvenience for one day. Consequences are low. The appropriate strategy might be to have the cleaning operator be responsible for feeling the temperature of the pump and motor after use. The operator should report changes in temperature, noise, leaks, or flow. This strategy is a very inexpensive form of PdM. It borders on a modified run to failure, with a proactive operator avoiding second stages of equipment failure.

Using Schematic 2, the failure of pump B has no operational consequence because pump C is brought online. However, a run to failure may ruin pump B. As before, the appropriate strategy might be to have the cleaning operator responsible for feeling the temperature of the pump and motor after use, then report changes in temperature, noise, leaks, or flow.

What about using Schematic 2, however, when there is a failure of pump C? Such a failure of C would mean that pump B has already failed or is unavailable. As before, this failure would cause portable tank cleaning to be interrupted. Cleaning would be delayed, with possible overtime, shortage of clean product tanks, or inconvenience for one day. Consequences are low.

The best maintenance strategy might be to have the operator purposely switch to pump C at some frequency (e.g., the first Monday of each month) and follow the same checkout as with pump B. Because some failure modes follow bathtub wear-out curves, pumps B and C should not be alternated evenly. Otherwise, both might near failure at the same time. Non-use of pump C, however, can lead to other problems. In some equipment installations, bearings that are stationary for long periods of time are subject to vibration. An effect called brinelling takes place, causing early failure. Non-use may also result in corrosion or seizure. As long as pump C can demonstrate adequate performance, early stages of failure may be tolerated because its main function is to perform long enough for pump B to be restored.

In general for Case 1, because the consequences are low, PdM strategy with Schematic 1 is the more appropriate choice for normal circumstances.

What about Case 2, the use of the pump to cool the incinerator? The same equipment is available. Should the same maintenance strategy be used?

In Case 2 using schematic 1, the failure of pump A would cause incinerator failure and plant operations to shutdown. Consequences are very high. The appropriate maintenance strategy would be to review the existing equipment system, confirming (and correcting) the quality of the installation. Is the existing pump properly matched to the service load? Is the foundation and piping isolation appropriate? Was the pump installed using precision alignment? Is it rigged for rapid modular change out? Next, apply the latest PdM technologies to trend (possibly online) and predict impending failure. Proactive maintenance is appropriate to extend the life as long as possible, mitigate the impact of a stoppage, and restore original conditions quickly.

In Schematic 2, however, failure of pump B has no operational consequence because pump C is brought on line. Here, the appropriate maintenance strategy might be to run to failure with the option of the incinerator operator reporting changes in temperature, noise, leaks, or flow monthly. Keep in mind, however, the highest reliability for a continuous system is to keep it running without requiring a transition, unless absolutely necessary. Therefore, many of the actions—such as insuring purchase of a pump with highest reliability, designing special foundation and piping isolation, and installing the pump with precision alignment—would be proactive strategies to consider. By extending Time To Failure for pump B, these actions reduce the risk of system failure caused by pump C not coming online.

What if, in Schematic 2, there is a failure of pump C? Such a failure would mean that B has already failed or is unavailable. As before, the failure of pump C would cause incinerator failure and plant operations to shutdown. Consequences are very high. The best maintenance strategy for pump C might be to have it demonstrate its capability at some frequency (e.g., for one hour the first Monday of each month for six months, and then go quarterly) and to perform PdM technology (e.g., vibration or temperature) to assure good working order. Pump C needs only to perform for the duration that is needed to restore pump B to original condition, probably a fairly short time. Note the subtle difference for this strategy between Cases 1 and 2. In Case 2, a continuously operating pump B should not be shutdown to test pump C. Shutdown-startup often increases duty cycle on equipment, shortening life or even causing failure by not restarting. Therefore, provide valves to test C off-line. Because pump B is at risk when pump C is offline, minimize this risk with short duration testing. Extend the frequency once trends show no short-term effects.

It is important to understand the power of redundancy. Appendix 3 provides redundancy equations and a simple redundancy example. The appendix example demonstrates how a system failing once per month would fail *once every 4 years* if it were a redundant system. In that case, system failures were reduced by 98 percent. This is very beneficial for critical systems.

For Case 2, redundancy is the better choice for critical equipment. Factor into your decision the likelihood that both pumps would not fail at the same time.

Even though the equipment is the same in these two cases, a spectrum of maintenance strategy is used. Matching the maintenance strategy with the functional failure consequences of each major component will help you move from an unplanned reactive maintenance environment towards a PdM and proactive environment. This exercise should be undertaken, starting with the highest priority systems and continuing through all equipment in the area. Five to seven groupings or approaches of maintenance strategy usually develop for an area. However, individual maintenance procedures explaining the strategy for each equipment item should be documented. This approach lends itself to a computer database that is, in turn, usually a part of a Computerized Maintenance Management System (CMMS).

Overall, this approach matches proper maintenance strategy with the prioritized critical equipment list. It optimizes reliability of the existing equipment and leverages the use of the local mechanics by focusing planned interventions. It also forms a documentation tool for orienting new mechanics and operators, providing stability against the attrition of key mechanics and technicians. Understanding functional failure and the appropriate maintenance strategy is also useful as you develop the project requirements and design as well as set the expectations of area operations. Having a strong strategy in place before acceptance helps bring projects online with square starts.

7.5 Developing Best Practices

When you evaluate either manufacturing or maintenance processes, an important first step is to agree collectively on a fixed best way of completing repetitive tasks. You should then document the steps and any specific measurements (set points) so that all employees perform the task using these best practices. This approach should be an ongoing process that will continue to evolve as better and better practices emerge based on designed experiments and benchmarking information. It will leverage the best skills and techniques of the community, strengthening the group skill level in general.

Start by developing checklists for each equipment system that would demonstrate an "operation ready" status. Use these lists before each startup. In addition, standardize the measurement references to be used throughout the processes, testing, and maintenance. Then have all check and test instrumentation brought into current calibration, providing a test pattern to maintain the standards.

Construct a Pareto chart (see appendix 7) of frequent failures by equipment area. Review the chart and construct troubleshooting logic trees to help you diagnose the most common modes of failure for key equipment systems. Use team sessions to simplify these trees into best practices. Share the tools and information so that every mechanic develops good problem solving approaches to use on all failures.

Start collecting the data recommended for each equipment failure. Then link it to your equipment hierarchy or numbering system. Take the initiative to bring operators and mechanics together so that you can begin building a cause and effect (fishbone) diagram that emphasizes the undesired effect of excessive equipment downtime. Examine the five categories of machine, materials, methods, manpower, and measurements; list all the causes in each category that link directly or indirectly to the effect. This approach can often bring to the surface causes that can easily be addressed with simple changes to either procedures or communication channels.

At least half of a successful reliability program involves educating the community. Incorporating the useful methods and techniques found in this book and others related to manufacturing reliability will contribute to higher equipment uptime. Other sources for generic best practices are reliability and maintenance magazine articles, as well as the various sources addressed in the section on benchmarking.

The following is an example of best practice improvement. It starts with an investigation team focused on idle (non-driven) roller bearing failures for a large web conveyance machine. This machine had a large number of standard-sized idle rolls. The original maintenance strategy was to schedule a section of the machine and change all the bearings on the idle rollers at a frequency of about twelve months (periodic maintenance). Historically, there was a failure rate of approximately 40 to 60 roller bearings per year, each resulting in major waste and Mean Time To Restore of nearly 1 hour.

A root cause investigation indicated that most failures could be attributed to handling and installation problems, followed by bearing fit problems and infant mortality. With this information, several steps were taken. First, a test was conducted using a bearing center assessment of off-the-shelf bearings. This test, which provided objective data, resulted in a decision to select a single high quality supplier. Second, histograms of shaft sizes, and bearing internal dimensions, were constructed for a sizable population. With this data, action was taken to segregate new bearings into three size groups; these groups matched accordingly to three shaft-size groups. The intent was to measure the shaft of the roller with three sets of go and no-go gauges, then select the appropriate size bearing for proper fit. Third, in order to standardize proper installation techniques, special tools were built. These tools allowed heated bearings to be easily aligned and pressed on pre-measured and properly matched shafts by hand. Neither hammers nor the forcing of bearings into place were accepted any longer. Finally, the maintenance strategy was changed from periodic maintenance (PM) to condition-based maintenance (CBM). A method was developed to test and select only those rollers exhibiting higher drag than the standard population for bearing replacement. All rollers were tested for excess drag four times per year.

With these steps in place, the failure rate dropped from 40 to 60 roller bearings per year to between 3 and 4 per year. This level was maintained even through a machine speedup.

Consider the impact this program had. Nearly forty fewer failures occurred. This reduction provided considerable waste savings. Even though overall labor costs were about the same, maintenance material costs were reduced.

The greatest savings resulted from reduced equipment downtime. Over 24 hours of full production was leveraged out of the hidden factory. Almost all of the impact went directly to improving operating income. Furthermore, this improvement occurs year after year. In short, it pays to support gathering good data and aggressively developing best practices.

7.6 Building Reliability into Equipment Design

The greatest impact reliability focus can have is on proposed new equipment. Life Cycle Costing recognizes that 70 percent or more of operational and nonreliability expenses are committed during the concept and design stages of a project. Therefore, the strategy, requirements, and initial design stages of a manufacturing project are especially important for high equipment system reliability. Project cost overruns are inversely proportional to the amount of time and resources expended on documenting and clarifying requirements.

Let's review a basic design for reliability process to help prevent project failures.

Suppose you own a plain donut manufacturing process. Market analysis indicates significant profit margins could be gained by selling donuts with fruit inside. Your beginning project assumptions are to add the feature of fruit chunks to half of the current donut-making process. You will need a fruit chunk metering bin, a mixing tank, a mixer, a special pump to deliver the mixed material to existing ovens without crushing the fruit chunks, and piping and control instrumentation. The existing system will be divided to supply the fruit chunk process. Both systems will operate side-by–side, feeding existing (but now dedicated) donut cutters, and dropping donuts onto the oven belt. The business case requires that the fruit chunk flavored process have an OEE of 80.0 percent. Assume the existing system has 82.0 percent OEE, zero speed loss due to fixed speed equipment, and 1.0 percent quality loss. The current and future schedule calls for operating 120 hours per week.

Note that the new feature system has a lower OEE than the current system. Adding complexity to existing systems, without other changes, will always decrease reliability and OEE.

With this information, you can determine that the existing system has 98.4 hours of good production each week (120 hrs × 82.0 percent). The fruit chunk process must have 96.0 hours of good production (120 hrs × 80.0 percent). Therefore, the new equipment can not have losses of more than 98.4 – 96.0 = 2.4 hours.

These hours must now be allocated to the various loss categories. A team representing the project and the work area community should complete this step. Suppose they settle on the following: testing (1 out of every 400) plus quality losses = 0.8 hrs; operational losses = 0.8 hrs; and equipment problems = 0.8 hrs. Each group now needs to build into its design the appropriate strategies, procedures, and systems to comply with these allocations.

You now have a target for the new equipment reliability: 0.8 hours downtime per week. Earlier the quality loss was stated as being 1.0 percent and speed loss was zero. Therefore the current runtime for the equipment is

$$\text{Runtime} = \frac{\text{98.4 Good Production hours}}{\text{(1 - .01 quality loss)}} = \text{99.4 hours.}$$

Assume the database indicates that MTTR is 0.5 hours for this type of equipment. Therefore, the number of failures per week is the downtime for the week divided by MTTR.

$$\text{Failures per week} = \frac{0.8}{0.5} = 1.6$$

Now you can determine the MTBF for the new system. MTBF is equipment uptime divided by the number of failures, or

$$\text{MTBF} = \frac{99.4 \text{ hours}}{1.6 \text{ failures}} = 62.1 \text{ hours MTBF.}$$

Next you need to review a reliability block diagram (RBD) for the new equipment. See figure 7-4.

Figure 7-4 Reliability Block Diagram

These five blocks represent the new system. Assume both randomness and the fact that the system is in steady state. Then, the failure rate λ, is $\frac{1}{\text{MTBF}}$. Furthermore, the failure rate of the system is the sum of the failure rates of the components. Therefore,

$$\frac{1}{\text{MTBF}_{\text{system}}} = \frac{1}{\text{MTBF}_1} + \frac{1}{\text{MTBF}_2} + \ldots + \frac{1}{\text{MTBF}_n}$$

Because the system MTBF, calculated above, is 62.1 hours, the failure rate of the system is

$$\frac{1}{\text{MTBF system}} = \frac{1 \text{ failure}}{62.1 \text{ hours}} = \mathbf{0.01610} \text{ failures/hour}$$

Next, allocate or assign the system failure rate to the portions of the proposed system. You can use a weighted matrix to determine the proportions of allocation. This allocation can be made in several ways and

ITEM	ENVIRON-MENT	DUTY CYCLE	COM-PLEXITY	MAT-URITY	TOTAL
METERING BIN	2	6	6	4	288
MIXING TANK	2	3	1	1	6
ELECT. MIXER	2	9	5	3	270
PIPING/INST.	3	5	5	3	225
DELIVERY PUMP	2	9	8	8	1152
				TOTAL =	1941

Figure 7-5 Allocation Table for Failure Rates

should be agreed upon by the design and user team. For now, use a 1 to 10 ranking, with 1 being low concern, for the following categories: operating environment, duty cycle, complexity, and maturity of design. Assume the team agrees on the relative values listed in figure 7-5. The values of the four categories will be multiplied together to provide a total impact number.

Because 1941 equals the total for all the elements, the proportion for each element is the individual product total divided by 1941, as seen

ITEM	MATRIX NUMBER	MATRIX TOTAL	PROPORTION RATIO
METERING BIN	288	1941	0.14838
MIXING TANK	6	1941	0.00309
ELECTRIC MIXER	270	1941	0.13910
PIPING/INST.	225	1941	0.11592
DELIVERY PUMP	1152	1941	0.59351
		SYSTEM TOTAL =	1.00000

Figure 7-6 Calculating Proportion of System Failure Rate

in figure 7-6. Therefore,

Once you distribute the system failure rate by the individual proportions, you can assign relative desired failure rates. Multiply each individual proportion by the system failure rate (0.01610) to find the assigned failure rate. The inverse of each failure rate is the individual MTBF for each component, as shown in figure 7-7. The sum of the five assigned

ITEM	ASSIGNED PROPORTION	SYSTEM FAIL. RATE	ASSIGNED FAIL. RATE	MTBF = 1/(FAIL. RATE)
METERING BIN	0.14838	0.01610	0.00239	418.4
MIXING TANK	0.00309	0.01610	0.00005	20000.0
ELECT. MIXER	0.13910	0.01610	0.00224	446.4
PIPING/INST.	0.11592	0.01610	0.00187	534.8
DEL. PUMP	0.59351	0.01610	0.00956	104.6
TOTAL =	1.00000	TOTAL =	0.01610	62.1

Figure 7-7 Calculating Component MTBF

failure rates should equal the total system failure rate of 0.01610.

Figure 7-7 displays the desired performance of a capable system, providing important information for purchase specifications.

The next step is to predict the expected performance of your system, comparing those results with your desired performance. Start by reviewing the individual components, obtaining reliability information of MTBF and MTTR for such units used in similar environments and duty cycles as intended with your design. This information is best if it comes from similar equipment being used in like conditions to your own factory. Other sources of information include similar industries, common reliability charts of general equipment, vendor literature, and other experienced users. Be careful, however, when you obtain and use this information; your specific conditions and use often vary from that of other sources. For critical parts with unknown performance, reliability quantification testing (RQT) may be appropriate.

Assume you have researched the components and determined that MTTR equals 0.5 hours or less and MTBF is represented by the table in figure 7-8. By summing failure rate (λ) for the individual components, you

ITEM	RESEARCHED MTBF	FAILURE RATES
METERING BIN	350	0.00286
MIXING TANK	87600	0.00001
ELECT. MIXER	1000	0.00100
PIPING/INST.	1200	0.00083
DELIVERY PUMP	30	0.03333
	SYSTEM TOTAL=	0.03803

Figure 7-8 Predicted MTBF and Failure Rates

can derive the system failure rate, which in this case λ equals 0.03803.

In turn, the inverse of the system failure rate, or 26.3 hours, is the system MTBF.

Now compare the predicted value to the desired value. In this example, you will see that the proposed system's MTBF of 26.3 is less than half of 62.1, the requested system MTBF. The proposed system's performance does not meet your desired standard.

This information is very powerful because you have not yet committed either the business case or design dollars. Without this exercise, the project might have proceeded, locking you into a system that would either under perform for its entire life or require unexpected investment to increase capability to expectations.

By comparing desired and predicted results, individual item performance gaps quickly reveal areas for reinvestigation. These gaps are dramatically revealed by looking at the difference in failure rate between the desired and the predicted for each item. Dividing each component failure rate difference by the desired system failure rate (0.01610) and expressing the number as a percentage helps target improvement opportunities. These calculations are represented in figure 7-9.

ITEM	ACTUAL MTBF	ACTUAL FAIL RATE	DESIRED MTBF	DESIRED FAIL RATE	F. R. DIFF. /SYST. F.R. %
METERING BIN	350	0.00286	419	0.00239	-3%
MIXING TANK	87600	0.00001	20093	0.00005	0%
ELECT. MIXER	1000	0.00100	447	0.00224	8%
PIPING/INST.	1200	0.00083	536	0.00187	6%
DELIVERY PUMP	30	0.03333	105	0.00952	-148%
SYSTEM TOTAL=	26.3		62.1	0.01610	

Figure 7-9 Predicted System Impact by Component

As indicated by the table, the delivery pump has a large negative impact on the proposed system. The project team now has several options: purchase a more reliable pump, consider redundancy, or use a different technology such as overhead installation with gravity feed. All of this effort now takes place in the strategy, concept, and initial design stages of the project—prior to commitment of significant system configurations and project dollars. The results of successful reviews strongly support design for reliability projects.

Once the acceptable configuration and design system are derived, the individual component results form an important part of the purchase specifications; they must be included on the purchase orders. Each item can be specified for MTBF and MTTR requirements, with identification of any performance testing prior to acceptance. If you understand each component's expected performance, then you can establish the proper operating and maintenance strategy. This strategy can be documented and applied at startup so that high performance is obtained at initial operation. This approach supports square starts for new projects.

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3. Shingo, Shigeo. *A Revolution in Manufacturing: The SMED System*, Cambridge, Massachusetts: Productivity Press, 1985.

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CHAPTER 8

Reliability Availability Maintainability/System PerformanceAnalysis (RAM/SPA)

This chapter focuses on improving the output of equipment systems already in existence. Jobs depend on the company being overly successful. The backbone of the company is its effectiveness in manufacturing products. Low unit cost and high quality are common to factories with world-class OEE numbers. Other factors, such as raw material costs, wage rates, distribution costs, and taxation are obviously important as well. But even if your factory is the only one in the world making your product line, your best way to protect your position is to be so effective that no one else can conceive a way to provide a competitive product at a profit.

Assume one of the following: Either you are in an existing manufacturing work center and have challenged yourself to make improvement at a faster rate, or you have just arrived at the work center and have the responsibility to improve performance. In both cases, you must maximize output and capability of the existing systems before you can acquire capital money for new equipment or capacity. You may even face the directive, "This area must cut costs of manufacturing or it will be eliminated!" This order can actually be just the type of motivator to smash old paradigms and generate new thinking for breakthrough improvements.

8.1 RAM/SPA

Existing equipment systems can be measured for their reliability, availability, and maintainability (RAM). Reliability is often expressed as mean time between equipment failures (MTBF) or mean cycles between equipment failures (MCBF). Recognize the significant difference between equipment reliability, which focuses on the machinery, and equipment performance, which focuses on the work system throughput.

$$\text{MTBF} = \frac{\text{Uptime}}{\text{Number of Equipment Failures}}$$

Maintainability is considered to be the average time needed to repair the equipment, or mean time to repair (MTTR).

$$\text{MTBF} = \frac{\text{Total Repair Time}}{\text{Number of Equipment Failures}}$$

Equipment availability is the percentage of time the equipment is available to run product.

$$\text{Equipment availability or } A_e = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})}$$

Disagreements exist about how to best define the availability parameter. They stem from differences in the terms *repair* and *restore*. Repair should be the actual wrench time needed to correct the equipment to previous operating conditions. (Both repair and restore can be as short a time as switching the equipment to a standby module.) Restore is the total time that production is interrupted. It includes stopping production, deciding the kind of repair that is needed, contacting the repair person, travel time, diagnostics, waiting for parts, the actual repair, checking out and testing the repair, and formal startup time. Further disagreements about the definition of the parameter arise when additional activities such as clean up are combined with the incident, causing the restore time to be extended. When communities collect data to measure overall performance, they must clearly define *repair* and *restore* so that misunderstandings are avoided, both locally and in benchmarking activities. Know the various details of each event so that root cause analysis for improvement will correctly focus on the true cause.

System Performance Analysis (SPA) provides a higher level of review. Although similar to the RAM metrics for equipment, all minutes of interruption are recorded and used in the analysis. Instead of MTBF, system performance analysis uses MTBI, Mean Time Between Interruptions.

$$\text{(MTBI)} = \frac{\text{Uptime}}{\text{Number of Interruptions}}$$

$$\text{(MTBI)} = \frac{\text{(Total Scheduled Time - Uptime)}}{\text{Number of Interruptions}}$$

$$\text{Overall Availability } A_o = \frac{\text{MTBI}}{\text{(MTBI + MTTRs)}}$$

This measure is equivalent to the efficiency parameter in the OEE calculation because it reduces to Uptime divided by schedule time. Work areas might use this metric as a stand-alone measure to set goals when they have a fixed speed process with constant low waste. Actual production will correlate with true OEE, the product of efficiency, speed rate, and quality rate. Because throughput rate is a vital factory success parameter, OEE is the key measure that links manpower performance with factory performance. In essence, OEE relates how well employees make product when they are actually scheduled to make product.

8.2 Starting Reliability

Your first step in making progress is to understand where you are today. Begin with an objective assessment using validated data of the current system performance. This assessment applies to all aspects of the work center. It should cover the following categories that I call the five Ms: Machine, Manpower, Materials, Measurements and Methods.

These five Ms form the categories of a cause-and-effect diagram for every production system, with a focus on improved output. Construct a fishbone diagram using these categories. Then brainstorm, with a cross section team in your area, the kinds of items within each category that impact output. The diagram may be crude and simple at first. It should be updated with new items and information as each investigation reveals new aspects of impact on output. This will become an education tool for your work center.

Let's examine *objective assessment* and *validated data.* You can choose among many approaches to obtaining the information you need. One preferred choice is to have external sources complete a thorough audit of best practices across several categories in your operation. Many reliability and maintenance improvement consultants offer assessment services. You should consider them for this external review of your area. I'm familiar with one particular group that provides an in-depth assessment. They plot the results on a Reliability Continuum Matrix chart that measures low performing, competent, and high performing operations. They also benchmark groups against a five-stage spectrum, from daily maintenance efforts up through operational excellence. Their web site www.samicorp.com has good maintenance performance information.

A sample of a proposed audit can be found in section 8.10 on benchmarking. The audit requires actual evidence that the function, practice, or procedure is being performed, and further, that the accuracy of the information can be confirmed. The audit forms the baseline. It can also be used as a benchmark for other internal or external areas. You could complete the audit yourself. However, your current paradigm may bias some of the information. You also risk accepting loose data simply because you have always believed it to be valid.

As an example of validating data, you can check the actual count of product transferred with the summation of the crew reports for each shift's output over a set period of time. Similarly, you can compare the report for production schedules and system uptime, as reported on shift reports, with the actual hour meter readings or cycle counts on the existing systems. When meters are not available, a chart recorder can be applied for a period of time to validate the accuracy of the reports.

Maintenance reports of equipment repairs and downtime can be reconciled with production figures for actual stop-start times of the process. These figures will be somewhat different. However, you can reconcile the portion of restore time that production indicates was used for repairing the equipment with the time that maintenance indicates was used for repairs. As another example, reported changeover time for different products can be calibrated with actual clock time. Be certain that if other circumstances cause delayed start times, the time differences are properly recorded and accounted. What is most important is making sure that the official database is accurate and can reconcile every minute of the calendar. Furthermore, everyone should be using the same information.

It is imperative that you begin any reliability improvements with good data accepted by the whole community. This first step alone often reveals large gaps of previously unrecognized opportunities. What should you do, however, if you find that the database is not accurate or doesn't even exist? The answer is simple. Start immediately collecting the data that will properly reconcile every minute. See figure 2-1 for a recommended product run order form. In just three to six months, you will have a valuable database. Your business's survival may depend on having such a database. Have the discipline to initiate this activity, throughout your work center and manufacturing flow lines.

One of the key measures to validate is your current true OEE. Even if an OEE number is already generated in your area, validate it. Confirm the actual transfer of good product relative to the potential amount of product that could be made by having your operation producing 100 percent good units, at the highest accredited rate for 100 percent of the scheduled time. Once you have this figure, you can compare it to recognized world-class levels of performance in your industry. In general, dedicated continuous online types of operations should have an OEE of 95 percent or better. Non-dedicated continuous and dedicated discrete operations should have OEE values of 90 percent or better. For discrete and batch processes, OEE should be 85 percent or higher.

Additional value is generated with even higher performance. Ron Moore of RMGroup Inc., a consulting firm with worldwide clients, reports that the best OEE he has observed was 98 percent over a two-year period for an olefin-producing plant in Borneo. Think of the value of matching that kind of performance!

The difference between your OEE and world-class OEE provides a first look at the hidden factory for your area. This number defines the end point for how you run your process. It points toward a tangible picture of what your company's future state could be. Developing the understanding of what your factory could be and accepting this new vision is one of the most important aspects of this book.

8.3 Quick Changeovers: Single Minute Exchange of Die (SMED)

Shigeo Shingo's book[1] A Revolution in Manufacturing: The SMED System, describes a methodology to optimize product changeovers. SMED represents single minute exchange of die. It was first introduced in the Toyota manufacturing system where heavy metal dies were used to stamp out fenders, hoods, and other automobile parts. Changeovers to produce different parts would often take ten-to-eighteen hours. Shingo developed a way of strategically analyzing all of the tasks for a changeover. By systematically identifying and streamlining the essential tasks, he reduced changeovers to less than ten minutes or "single minute." Because product changeovers cause ongoing repetitive losses, Shingo's approach is very powerful for improving OEE. It also helps to improve restore times for repetitive downtimes, including those for operational and maintenance items.

Quick changeover methodology is best implemented by the employees performing the task. They have the credibility of local knowledge and can also claim ownership of the results. Quick changeover methods can also be applied to new tasks, such as conditioned-based maintenance, so that any the interventions are optimized. See section 1.4 for the results of a quick changeover pilot project.

Quick changeover targets should be focused on critical bottlenecks so that benefits impact OEE directly. Its best use is on frequent changeovers or planned maintenance interventions (both repetitive and nonrepetitive) that interrupt needed capacity.

Assume you have targeted the most often used changeover process for your most common product. Reducing this changeover time would contribute significantly to the bottom line on an annual basis. Your first step is to form a team of willing participants from the crews that perform these changeovers. Inform the community that this team is formed. Explain that the team will be completing a quick changeover process to reduce changeovers and that the methods and procedures will become the standard for all crews to use on these changeovers. The team members should be told that they are to be champions of the new method; they will be asked to train other crews.

Until groups have experienced the quick changeover process a few times, a facilitator may be needed to lead the process. This is because quick changeover methodology requires specific training on several principles involved.

Let's review the major steps of quick changeover methodology.

1. Videotape the entire changeover event, including preparation and follow-up actions. Use extra personnel to film the changeover. All usual operators and mechanics should execute the changeover in a normal fashion. Several video cameras may needed; they should be time synchronized and stay on continuously.
2. The team should review the videotape together. Document each action and the elapsed time, explaining why each action is performed. Each action should be listed on a sticky note that is temporarily placed on a timeline representing the total event. Often, the process of reviewing the video identifies significant wait time that can possibly be eliminated. The time may be wasted because information isn't available, or because materials or supplies are missing. Document the overall time from the video. Assuming no unusual circumstances, this timeframe is now the reference point for reduction.
3. As each item is generated, analyze it as follows. Is the item *internal*, absolutely essential to be on the timeline, or is it *external*, something that can be prepared or followed offline? Use different colored notes to identify the two types of items.
4. As you develop the timeline, identify those internal items that can be performed at the same time (in parallel) or overlapped in some way. When this is possible, the internal timeline becomes shorter.
5. Review the specific reasons for each item. Brainstorm how to perform each in a more expedient way. For example, could a connection with bolts be replaced by quick release clamps, or could a heat-up cycle be preheated off line?
6. Consider reducing trials and testing time. Build fixtures and registration devices so that the first part will automatically be right the first time. This solution may mean that all dies are machined to identical reference points. Also consider having proven set points or valve positions programmed to show "production ready." This is similar to the Christmas tree or ready board on submarines that lets the officer on deck know exactly when everything is proper just before diving.
7. Time may be saved if more resources (employees) are available. Communities with good cooperation and communication often swing support resources onto the changeover as needed, especial-

ly if the community goal is to improve OEE.

8. Going through the quick changeover process will generate a new method of doing the changeover. Next, have the quick changeover team actually experiment with the new approach, collecting information on what did and did not work (active learning). This critique will help clarify the key actions to add to standard operating procedures. Repeat this step for the next two to four changeovers, continuing to look for improvements. A newly revised timeline should then be prepared and reported to the community, along with training on any new procedures.
9. Identify area goals and reinforcement plans. The new practice can then be enthusiastically received and used by all crews immediately. Give all necessary modifications, fixtures, and dedicated tools priority, especially if shorter changeover time has been identified as one of the community focus projects.

Communicate to the master schedulers if a preferred sequence of production processes favors shorter changeovers or startups. For example, after major maintenance shutdowns, starting up on the area's primary product using a standard set point list can provide a rapid learning curve, while assisting square starts.

Areas completing a quick changeover process for the first time usually shorten their timeline by 20-to-50 percent. Once the new timeline has stabilized (between six months and a year), completing the total exercise again can often improve the timeline by 10 percent each iteration. Therefore, applying quick changeover methods and principles to product changeovers and maintenance interventions can have a large, positive impact on OEE. These methods reduce both operational losses and startup waste.

8.4 Theory of Constraints (TOC)

The Theory of Constraints (TOC) was first discussed in section 4.4 of this book. According to the APICS Dictionary, it is "a management philosophy developed by Dr. Eliyahu M. Goldratt that can be viewed as three separate but interrelated areas—logistics, performance measurement, and logical thinking."

As section 4.4 noted, a portion of TOC builds on five centering steps: identify, exploit, subordinate, elevate, and go back. These steps have been used in various examples in this book (e.g., section 6.1, and

8.7). They are helpful in the drive to improve OEE, itself a measure of throughput.

Several scenarios of breakthrough improvements are described in *The Constraints Management Handbook*[2]. Constraints Management (CM) is the active application of Theory of Constraints.

Examples of the magnitude of breakthrough performance are:

> "a custom cabinet maker routinely takes five to six weeks to make a custom designed set of kitchen cabinets for a new home. ….one company was able to reduce its lead time to 10 days using just in time (JIT) techniques. When this same company reduced its lead time to two days using constraints management (CM) techniques, it became a competitive advantage no one in the company wanted to discuss with outsiders.
> A producer of lickless postage stamps could produce two million booklets a week using a continuous manufacturing process, (4 shifts for 7 days a week). Using CM this same facility with 8% increase in capital equipment is now producing 25 million booklets a week on a three shift, five day a week time frame."

The handbook also develops financial aspects of constraints management relative to factory bottlenecks. The goal of companies and factories is to make money over both the short term and the long term. The insight on bottlenecks relative to the amount of time needed to produce specific products and the size of each product's profit margin is worthwhile. The authors provide examples that demonstrate how strategic production plans should be optimized in order to generate the highest net profits based on product "constraint minutes" relative to profit margins. Higher net profits can be generated without any change to capability or schedule time of the bottleneck. See page 75.

Both TOC and CM are ultimately beyond the scope of this book. This section considers some aspects of throughput TOC thinking. You may well want to look further into TOC and CM for more specific applications to your factory. You can find one of the best-known applications of TOC to factory operations in Eli Goldratt's book[3], *The Goal.*

Goldratt compares factory throughput with the progress of a scout troop walking in single file on a day's hike. The scouts can not pass one another. Therefore, the troop's progress is limited to the slowest scout. You can *identify* the slowest scout as the bottleneck. The scouts behind the bottleneck are bunched up whereas the scouts ahead can walk at a faster pace into the distance. The objective is either to have the entire troop walk as many miles as possible, or cover a fixed amount of miles as quickly as possible. In either case, the initial marching system is ineffective.

The next step in TOC is to *exploit* the bottleneck resource. Here, you could unburden the slowest scout by redistributing his pack to others in the troop. This action helps him go as fast as he can. At the same time, a guideline is established: Whatever any scout can do to make sure that the slowest scout is hiking as long and as fast as possible, he is to do it. This step is the *subordination* step. Examples include giving the slowest scout the first position in line for food so that he can keep hiking as much as possible. He could then continue hiking while others take their refreshment break.

The next step is *elevation*. Here, the slowest scout is equipped with tools or systems that enhance his original abilities. These may include special shoes or a walking stick. With these capabilities, the slowest scout will may no longer be the bottleneck. The final step then is to *go back,* assessing the troop for the new bottleneck, and starting the process over again.

Within the factory setting, TOC can be used in several ways. From an overall perspective, start by identifying the bottlenecks. Then apply OEE metrics and set up key equipment maintenance strategies. All other priorities should be subordinated and prioritized relative to the list of key equipment. Decision trees, Failure Mode Effects, and Criticality Analysis depend on the hierarchy of critical equipment systems.

TOC is a continuous process. In dynamic factory situations, the application can be complex with bottlenecks seeming to bounce all over the place. This will be especially true in a highly reactive environment, and also where all of the units are essentially equal.

TOC is not limited to the physical aspects of throughput. In his book *Critical Chain*[4], Eli Goldratt applied TOC to project management techniques and tools. Project completion requires many individual steps to be performed in order to generate something. Critical chain techniques develop a clear understanding that all elements for completing individual tasks need to be considered when setting priorities and establishing the critical path. Assigning and managing resources (primarily key people) can be a common bottleneck. The critical chain, therefore, encompasses key resource availability into the plan.

Critical Chain also compares a factory operation to a chain. Each link represents a department. The operating budget of each department determines the weight of each link. Similarly, the throughput of each department is the strength of each link. The bottleneck is the weakest link in the chain. Many factories today undertake cost cutting actions. Across-the-board cost reductions weaken every link, threatening factory existence. Redistribution of resources and subordination of stronger links to bottleneck links however, build a stronger overall system.

8.5 Data Collection and Information Sharing

This book has covered several approaches to gathering the data necessary for building a good database. This section brings these approaches together. It discusses the range of reliability data and discusses useful ways of examining the information.

Let's look first at the information that would be beneficial to derive from a database. The list in figure 8-1 is not in order of priority. Nor is it all-inclusive. However, it provides a starting point for thinking about the magnitude of the database. If data is collected in different systems, then you need a master plan for linking and sharing the data among the systems. Your data system should either reconcile numbers among the individual systems or require each system to access the same common database.

Many other pieces of information that contribute to good decision making can be listed as well. This list demonstrates the range of data that would help teams drive a work area toward higher effectiveness while, at the same time, balance the cost benefits. Computer systems allow databases to be queried in many different ways.

Much information is available about selecting and implementing Computerized Maintenance Management Software (CMMS). CMMS helps maintenance departments construct equipment hierarchy, collect data, document procedures, record repair actions, schedule maintenance work, and control equipment spare parts. A good source of information, submitted by practitioners about selecting and initiating CMMS systems, can be found in the magazine Reliability and Maintenance Technology. Another good resource is the "Plant Engineering, Maintenance and Reliability Resources" web site: at www.maintenanceresource.com. When you select CMMS at this site, you will find hundreds of CMMS software companies and products. In addition, the Society of Maintenance Reliability Professionals provides a forum for practitioners.

- ❒ Average machine speed by product run
- ❒ Crew schedules
- ❒ Cycle counts of equipment systems by product run
- ❒ Detailed OEE loss accounting information
- ❒ Equipment downtime and downtime frequencies
- ❒ Equipment hierarchy
- ❒ Financial data
- ❒ First pass yield numbers by product run
- ❒ Hour meter readings of equipment systems by product run
- ❒ Inventory data
- ❒ Key equipment constraint minute usage by product run
- ❒ Labor staffing and costs
- ❒ Maintenance procedures and maintenance strategy per equipment item
- ❒ Maintenance repair reports
- ❒ Maintenance SPC data by product run
- ❒ Material costs
- ❒ Operating procedures
- ❒ Overtime information
- ❒ Parameters for computing OEE
- ❒ Planned maintenance work
- ❒ Process set points for each product
- ❒ Process Statistical Process Control (SPC) data by product run
- ❒ Product changeover time
- ❒ Product schedules
- ❒ Quality and waste data by product run
- ❒ Raw material lot numbers
- ❒ Re-work OEE data by product run (see section 2.2)
- ❒ Spare part usage
- ❒ Throughput numbers by product run
- ❒ Utility usage and costs

Figure 8-1 Information Provided By A Database

When you evaluate CMMS systems, consider the ease of entering data into the system and extracting useful reports from the system. Also consider the user-friendliness of the various screens. Most important, the work community must commit to recording all actions and events so that the various reports and investigations are based on complete data. The database must also be capable of reconciling information from other databases used to run the business. Otherwise, cross-functional groups will face credibility gaps and, in turn, make poor decisions.

A good CMMS will help you plan and organize the work orders needed for maintaining equipment systems. Consistently executing planned work orders is fundamental to moving from a reactive to a proactive environment. Maintenance reliability service providers are available to help factories begin this transition.

Equipment Performance Systems (EPS) can extend the software systems used to sequence the automation of the manufacturing steps. An EPS may accumulate and report all stoppages and out-of-limit actions occurring anywhere along the process line. It can also collect ongoing average speeds and cycle times. One work area developed its EPS so that production and maintenance employees could quickly select cause codes for each event, automatically generating for each shift OEE figures and downtime-frequency charts on each subassembly. This tool was extremely useful in every reliability investigation. It quickly helped the work area to prioritize improvement projects and verify success of implemented solutions.

Product ID __________ Crew ID __________ Date ___________

Format _____________ Lot # _____________ Machine # ______

Scheduled Production Time _______________

Actual
Start Time _________________

Actual
Finish Time ________________

Beginning
Cycle Counter #_____________

Ending
Cycle Counter # _____________

Beginning
Run Hr. Clock ______________

Ending
Run Hr. Clock ______________

Input Material, Quantity _________ Units Produced __________

Number of Good Units Transferred ____________

Crew Notes (DT problems and frequencies, Quality, issues, ST Operational, ST Induced, Set point changes and actions). Mark up and attach process uptime chart recorder output to this report.

____
____
____
____

Use back of form for notes on Functional Failures, Equipment failures, Technical notes.

Figure 8-2 Example Run Order Report Form

A good EPS should be able to generate the data needed for reliability histograms and Time To Failure timelines. Routinely collecting and reviewing this type of information provides a great advantage for proactive maintenance strategies. Figure 2-1 provided a minimum data collection table for works areas to use with each scheduled product. That table is repeated in figure 8-2.

Figure 8-1's list of information provided by a database includes ten items related to individual product runs. If you collect the overview information from figure 8-2 and link it with the EPS information, you can develop a detailed picture that can be used proactively to drive higher OEE. When downtime events do occur, good observation and data collection skills can contribute to identifying and eliminating root causes. Your main reliability goal is to prevent failures from occurring. If you can not totally eliminate them from occurring, your next best goal is to learn from the first failure and proactively prevent reoccurrence. To help, you should have the suggested set of data listed in section 7.1 and provided again in figure 8-3.

1. What. The functional failure identification.
2. When. Event date and time, report date and time, and relative timing such as hour meter reading, cycle count of the system, and process time (e.g., start up, steady state, and transition).
3. Where. Business or process, work center, system, process stream, equipment component (specifically what broke), equipment identification (number and system). Save any parts for physical examination.
4. Significance or Impact. Safety, environmental, production, repair cost estimate, and frequency.
5. Witnesses. Who has potential information for follow-up questions?
6. Why. Cause of failure and failure mode. What was seen, smelled, heard, and felt (e.g., vibration, temperature, position).
7. Type of repair.
8. Who did the repair.
9. Parts used or adjusted (what adjustments were made).
10. Time required for repair. Did the repair go smoothly? If not, reasons for extended time.
11. Baseline readings at restart (e.g., amps, vibrations, and valve positions).

Figure 8-3 Equipment Downtime Documentation List

Recall that the information in items 1 through 6 and 11 is needed for all failures; the information for all eleven items is needed for repairable failures. This list provides minimum guidelines. Data collection can often be simplified by using codes for blocks of information. Codes expedite input and sorting. Collecting this data, along with any physical evidence of parts or debris, is essential to solving the failure. Therefore, provide the necessary time for filling out the data sheet at the end of each event.

Reliability engineer Scott Broussard likens the process of collecting data to that of a crime scene investigator. In his November 1994 article for *Reliability* Magazine, Broussard discusses the 5 P's of investigation: Parts, Position, Paper, People, and Paradigm. Excerpts of his article "Become a Reliability Detective: Preserve Failure Data" appear in Appendix 8.

Cameras and video recorders with internal clocks are useful data collection tools. They can record much information and detail. Consider recording typical procedures and processes when they are running perfectly. You will then have a benchmark to compare and examine whenever losses are discovered. Video equipment coupled with recorders using endless (circular) tape can watch an operation for long time periods. When the infrequent chronic event occurs, the tape is stopped. The events leading to the failure will then be captured for root cause analysis.

Factories with high speed automated equipment often use high speed cameras (5,000 or more frames per second). The cameras capture special events for root cause analysis or to optimize operating set points of rapid processes.

Tattletale markers can be used in processes or materials to provide fingerprints or evidence of root cause. For example, lubricants can have different additives so that leaks or stains quickly determine which equipment system is at fault. Conveyance rollers can have different diameters or microgrooves so that scratches or repeats are fingerprinted to specific locations. Chain bushings can show different color or material relative to depth of wear to signal potential problems. Wear bars on automobile tires expose the need for replacement.

Data collection can also be in the form of maintenance Statistical Process Control (SPC). Equipment and process information are measured and tracked to monitor the health of the equipment. An SPC can provide a proactive way of eliminating impending problems from impacting the production process. You can start with as little as paper and pencil.

Monitor the various positions of control valves. Measure process service quantities or parameters. Analyze them statistically. For example, monitor the damper position control valves that supply temperature process air to a manufacturing process. If the damper becomes cyclic or trends toward full open (or closed), investigate the upstream blower or heating coil before the manufacturing process is affected. The maintenance area in a pulp and paper factory routinely measures the temperature of black dots on their electric motors. Failures are avoided by early investigation of increases in temperature.

Sometimes creativity must be used to get at the desired information. I was involved in a maintenance SPC study to determine if a change in bushing materials would significantly improve the life of large drive chains used in a plastic stretching process. The chains were approximately 200 feet long. They were accessed every four-to-six months. It was important to predict the overhaul schedule months in advance. Because the conversion to the new material would be expensive, only a short section of chain was upgraded to field test. The wear on an individual bushing would be too minute to measure accurately.

Therefore, a sensitive dial indicator was assembled onto a five-foot hook rod, allowing a relative fixed length measurement of approximately 16 links. We recreated the temperature and chain tension, and replicated chain position each time maintenance had access to the chains. Overlapping areas of measurement provided an accurate assessment of wear rate between bushing materials. We needed just two measurement cycles after the initial set up to make good decisions about which material to select. We also predicted approximate overhaul dates for each kind of bushing. Without good information, a move to the new material would have involved guesswork that could have led to a poor business choice. By continuing to measure and plot the data, we could apply predictive conditioned-based maintenance to small sections of the chain—an improvement over a mass overhaul based on overall chain length. The life of each section was maximized and shutdown length was shortened. A new chain maintenance strategy developed.

We could discuss data collection endlessly. We haven't addressed the vast amount of data generated by predictive sciences such as vibration monitoring, motor testing, thermography, and tribology. Each predictive technology has its own database that can be statistically condensed into useful historical information, then loaded into the general maintenance database.

There are as many ways to share information as there are to collect data. You can query and report a database in numerous ways. The following discussion looks at information that can be helpful to shop floor teams as they drive OEE improvements.

Charts and tables provide useful ways to summarize and communicate information. Some charts and tables display OEE numbers, detailing the various losses described in section 2.2. This information should be updated often. Results should link individual and community performance and compensation. Once goals are established, employees will naturally want to compare progress toward the goals.

Information should be made visible to shop floor employees. If a paper system is used, special care must be made to keep it up to date. In

Equipment Reports:

- ❒ Overall equipment downtime for the area
- ❒ Overall equipment frequencies
- ❒ Overall equipment performance (downtime and frequencies) relative to total production volumes
- ❒ Key equipment performance (bottlenecks) for downtime and frequencies
- ❒ Major equipment reliability timelines
- ❒ Spare part usage by major equipment
- ❒ Nonrepairable equipment time to failure histograms by item
- ❒ Percentage of maintenance work that is reactive, periodic, predictive and conditioned-based, as well as planned work versus unplanned work
- ❒ Root cause analysis of successful investigations with no reoccurrence
- ❒ Key mechanic overtime
- ❒ Maintenance expenses by category
- ❒ Reliability improvement project results
- ❒ Total maintenance hours per unit of output
- ❒ Completed OEE and Reliability workshop hours

Production Reports:

- ❒ Percentage of delivery satisfaction
- ❒ Quality reports
- ❒ Changeover effectiveness by product family and by process setup
- ❒ Production overtime
- ❒ Production expenses by category
- ❒ Total production hours per unit of output
- ❒ Completed OEE and reliability workshop hours
- ❒ OEE improvement project results

Figure 8-4 Informational Reports for Equipment Reliability many instances, internally networked computers can be used effectively to share information throughout the work area. In these cases, access to terminals, as well as appropriate training, is prerequisite to success. Otherwise, some employees will be left out of the communication circle.

With equipment reliability and production in mind, you can consider several other reports, including those listed in figure 8-4.

8.6 Pareto Analysis

The previous section focused on forming and collecting a database that documents the actual performance of your work area, division, or plant. An accurate database summarizes the benchmark position so that you can verify if changes are making a difference. However, a database is most powerful when it can reveal key areas that, if improved, will make a significant difference to the plant's success.

Because many factors influence a plant's daily operations, a single chart can seldom capture all of the reasons for identifying a key target. However, you can construct a series of Pareto charts, then conduct a Pareto analysis by combining the results into a selection table. A Pareto chart is a bar graph that arranges information so that you can determine priorities for process improvement. It focuses on those efforts that will provide the greatest improvement. Appendix 7 summarizes the steps you need to easily construct Pareto charts on your personal computer.

As you prepare a Pareto analysis, keep in mind that all targets are not equal. Your leadership team should weigh the significance of each category in order to refine the selection process even further.

The first step is to develop the manufacturing process flow map. Show the steps and flow of the materials through the various equipment areas for each product made. Make several copies of the basic map so that different information can be recorded on each. On one copy, indicate for each step on the map the ideal equipment speed rate and total capacity. Identify the theoretical bottleneck or constraint of the system by finding the point with the lowest capacity. You may find several points with nearly the same capacity.

On another map record by each product the actual speed rate and actual OEE of each process step. Summarizing the data from the product run sheets using figure 2-1 will generate this information. On this second map, record the difference between actual OEE and world class OEE for the areas previously identified as bottlenecks. Also record the difference for the areas of actual lowest capacity, if these differ from the bottlenecks.

On yet another copy of the map, record the actual manufacturing expenses (materials, utilities, labor, maintenance costs, and cost of quality) involved at each step. If your production steps or products have unique or other important aspects, then use additional maps to enhance their visibility.

Once the maps are complete, set up a selection spreadsheet. List your products in column A. In column B, enter the amount of actual production time at the bottleneck for each product. Use a timeframe of at least six to twelve months for the information in column B. For other parameters, use column C to list the total unit production cost of each product and column D to list the percent margin for each product.

Next, develop a Pareto chart of the amount of actual production time through the bottleneck over the last six to twelve months. This step will identify those products currently using 80 percent of the total production time of your bottleneck.

If your bottleneck is scheduled for around-the-clock production, then develop a Pareto chart for the constraint speed rate per unit of product. This chart will help your plant managers and marketing division establish proper product margins. It should help optimize company profits if it is used to manage the production schedule.

In the same way, develop a Pareto chart of overall manufacturing expenses for list of products. If margins per unit vary for your products, then develop a Pareto chart for this attribute as well.

Significant improvement usually involves time and money. Using the information you have gathered, construct a selection spreadsheet. List the products down the left side. Use separate columns for each of the Pareto charts. Then, for each column, check the products that are in the top 80 percent of each Pareto chart. The products with the most checks will be your focus targets. If the categories are weighted, then your check total should be adjusted accordingly.

If these targets are improved, then significant benefits should result. After all, this method focuses on high profit, high expense items that run a high percentage of the time on the bottleneck equipment. Consider stopping or subordinating all other improvement projects to the target projects generated with this approach.

You have products to target. The process maps have identified the bottleneck equipment areas for further review. Now, using the master database, extract the loss information generated only when running the specific target products in the bottleneck equipment areas. By selecting this subset data, future results should directly improve the target products. If the solutions happen to benefit other product production as well, then you have gained additional benefit. This subtle difference prevents the total database from compromising the key project selection process. Develop a Pareto chart of downtime minutes for the selected downtime loss categories. With this chart, the bigger opportunities will be identified and improvement gains in the top two or three categories will flow through more quickly for higher operating income.

Once the top downtime categories are identified, generate another series of Pareto charts for each of these categories. The new charts will highlight the most important losses to eliminate. At this level, include Pareto charts for frequencies and causes.

For example, if equipment downtime is one of the top categories, develop a Pareto chart for both downtime and the number of failures for equipment components of the bottleneck equipment system. Also construct other charts for type of failure and cause of failure. As the targets of the equipment components are revealed, then you can apply creative, proactive maintenance strategies and problem solving tools to eliminate or mitigate future problems.

When you have captured significant gains for the top targets, then update the process maps with the new results. At this point, recycle the analysis engine (go back) and review all product process maps.

Once your factory starts to improve, look at how to reduce variability throughout the processes. An entire methodology called six-sigma can be used for this effort. Once again, process mapping provides the format to collect the information. By reducing variability, you can eliminate the uncertainty of delivery or yield. Consider using cross-functional teams to investigate and eliminate the causes of high variability.

8.7 Project Management and Asset Life Cycle

Recall from section 7.6 that 70-to-80 percent of an asset's life cycle costs (LCC) are locked in during the concept and design stages of the initial project. The first stages of project work, therefore, are extremely important in manifesting good rewards and successful projects. A project's overrun is inversely proportional to the investment made defining requirements and design specifications. Overrun projects often result from poor operational start up and long learning curves. Your up front investment must include *both* money and key people. Include an employee who is experienced with current operations and will be a stakeholder in the future operations of the equipment. Your best choice is often someone who is knowledgeable in operations and who has recent shop floor experience acting as a client advocate.

Project management is too broad of a subject to cover fully in this book. However, this section will look at aspects of project management that often make the difference between success and failure. Begin by establishing that asset life cycle is the total period, from conception to grave, for a manufacturing system. This period can be broken up into several phases: the project phase to design, build and commission the equipment system; the operation and maintenance phase of staffing, running and maintaining the system; and the dismantlement phase of removing and discarding the equipment systems. Life cycle costing (LCC) usually assumes an operating period of 20-30 years, or a reasonable time period for the industry involved. The financial success of a system is clearly improved if the project portion of the asset life cycle is completed early and under budget, and if the system both starts up at name plate capacity and operates at projected reliability, availability, maintainability (RAM) levels. According to benchmarking information developed by the Society of Reliability Maintenance Professionals from its membership, a few major manufacturing companies consistently achieve high marks in all of these categories. One can conclude that this achievement isn't just luck.

Success starts with securing up front the proper involvement of key employees and decision-makers. They should help formulate and define the requirements of the project. Significant expenditures in resources and money may be needed to prepare the good engineering drawings and specific deliverables used to develop the project and life cycle cost estimates. Thus, 20-30 percent of the capital project cost, or even more, may be spent before a final business case is fully developed and high level approval is requested.

At first, this may seem risky. However, this cost is often less than ten percent of the proposed LCC. The probability of meeting or exceeding expectations is often over eighty percent for approved projects. The uncertainty of projects is nearly eliminated. Furthermore, poor projects are identified and rejected. You have probably encountered projects that were marginal and suffered ongoing problems, draining resources for extended periods of time before they were finally put to rest. Avoiding such projects is beneficial for all companies.

Another important practice is to have an identified gatekeeper, someone other than the project manager. This person is charged with holding the various teams accountable for properly using the practices. At each major phase, the teams, the project sponsor, and the gatekeeper must sign off on completion before starting the next step. The gatekeeper is similar to an auditor charged with upholding the quality standards of the company.

The stages of good practices are strategic, requirements, conceptual, technical deliverables, funding approval, project execution, and commissioning.

Strategic. In this first stage, a team identified the business need. It proposes and investigates preliminary requirements and alternative solutions. It then selected the best alternative and presents it to the sponsors, who must decide whether to risk the 20-30 percent of the potential project cost needed to launch a potential project investigation. If approved, the sponsor provides the investigation money and resources.

Requirements. The team is expanded to develop complete and specific requirements. It verifies the information in the business alternative and refines the business case using LCC. It integrates into the business plan the impact of the project on all related areas, including customer and supplier needs. The team develops the preliminary timeline and organization of the master plan, then presents the plan to the sponsors for approval.

Conceptual. The team is again expanded, this time to bring in technical experts who can address all aspects of the requirements documentation. The team completes process flow maps and generates various equipment concepts and layouts for review. It develops proof of principal experiments. The team then holds formal technical reviews of alternatives and refines the master plan. It presents the completed plan for sponsors approval.

Technical Deliverables. Now the team completes the final process, instrumentation, and controls drawings. It fixes the equipment layouts. It identifies many equipment components and quantities and formulates the specific technical deliverables. The team holds technical reviews, including reliability modeling, and reevaluates the master plan timelines. All information goes into the final business case, using LCC to assess the value of the project. If this presentation to the sponsor is approved, then the team submits for company approval its request for project funding.

Funding Approval. The project is now considered at the appropriate level in the company. It is either approved or rejected.

Project Execution. This stage is the final engineering and drawing stage, with final reviews, presentation to the sponsor, and sign off. The team orders and expedites long lead time items, while launching the resources, equipment, and project master plans developed earlier. It prepares the site and begins steps such as training, procedure writing, and operator and mechanic orientation. In addition, it fabricates assemblies, installs equipment, per drawings and plans, and begins preliminary testing.

Commissioning and Customer Acceptance. Now the time has come to debug the project, and to perform both functionality testing and on-site Reliability Quantification Testing. The team gathers baseline information and executes designed experiments for process understanding. It completes final orientation and training, along with process capability and certification. It addresses the punch list items. Now, formal customer acceptance should takes place and product accreditation should be initiated. After the team reviews all documentation for record management, the project phase of Asset Life Cycle ends.

This discussion covered only the highlights of the process. You should compare your current process with this overview, then consider changes to strengthen your process.

Now let's look at the application of the Theory Of Constraints (TOC) to project management. Much of this discussion is drawn from Eli Goldratt's book[4] Critical Chain, as well as an application training session.

Why would this approach be of benefit? One of the examples provided in the application class, Project Management the TOC Way, gives a glimpse of what is possible with the following project example.

"Harris Semiconductor:
New Technology product-first 8-inch discrete power wafer fabrication manufacture
New raw material, new automated technology
New facility, doubling capacity
Project Scope-construction, installation, ramp-up

Focus on actual delivery of production via the Critical Chain
Industry Norm:
1. Groundbreaking to first silicon – 28-36 months
2. Time to ramp production – 18 months

Harris Results using *Critical Chain* methodology:
1. Groundbreaking to first silicon – 13 months
2. Time to ramp production – 21 *days*"

Critical Chain addresses several points about project uncertainty. First, *time estimates* are conservative, often by 200 percent or more. A second point addresses *multitasking*, when two or more tasks are covered at the same time. While it may be helpful in some circumstances, multitasking of key resources is disadvantageous. Third, overruns are usually the result of the *student syndrome*, the tendency to procrastinate the start of a task until just before it is due, no matter how much time has been given to complete the assignment.

Project timelines generally include a critical path of the tasks. This path determines the length of the project. Each task is typically given a normal time estimate including time for uncertainty, rather than a more conservative (and more accurate) actual work hour estimate. Critical path methodology usually adds additional buffer (contingency) time at the end.

Critical chain methodology often reduces the task estimates by 50 percent. A similar approach is often used with the non-critical tasks that parallel the critical path timeline. Where a non-critical task path connects to the critical path timeline, a feed buffer (contingency time) is inserted.

Key resources (skills, people, and equipment) may be needed in multiple tasks at the same time. Rather than multitask the resources, prioritize the conflicts. Then schedule the resources as tasks into the critical path timeline. The critical path now encompasses resource management as well as task management. It becomes a critical chain of constraints, one that indicates the shortest timeline for completing the project.

Multitasking often occurs in companies managing multiple projects, which require the same resources at the same time. In such cases, the company must coordinate the timelines of the multiple projects, strategically using the key resource to complete single tasks in a sequence that makes the best use of the resources relative to prioritized projects. A strategic buffer should be inserted on the timeline prior to each key resource task. Therefore the key resource is never idle, even if his or her prior task on another project is completed early.

The TOC five focusing steps are applied to the project timeline and help develop the critical chain. Recall that these steps are:

1. *Identify* the constraint tasks
2. *Exploit* the tasks to minimize the timeline
3. *Subordinate* all other tasks, paths and resources to the critical chain tasks
4. *Elevate* the critical chain timeline with added people, resources, or pre-assembly of equipment sub-systems
5. *Go back* to the first step as constraints are erased. Projects are dynamic. Constantly monitor for the shortest critical chain.

Work is sometimes completed by outside resources. Often it is uncertain whether you will have the resource available at the right time to expedite the critical chain. You may need creativity to get the commitment you need from the outside resource. It may be cost effective to pay a premium price for the contracted work, with the requirement that it is executed as estimated and *starts whenever the prior critical chain task is finished.* A small cost increase for a few tasks is often negligible if it allows the completed factory to reach production days or weeks sooner, and the LCC is improved.

Once the plan is completed, and the buffers and feed buffers are identified, then project management turns to monitoring the ongoing impact on the buffers. Variability will occur. Some fluctuation, even reduction, of the buffers occurs naturally and is acceptable, up to about 25 percent. Further reduction, however, requires that you assess and develop alternate action plans. Then, if the buffer goes below a set trigger point, say 65 percent reduction, you implement the alternate action plans.

This section has only touched on the project management process, as well as the application of TOC to project planning and execution. Consider the LCC benefits from having projects completed in minimum time, under budget, and at name plate capacity, while operating at projected reliability, availability, maintainability (RAM). This can happen!

If the knowledge and expertise to apply these practices do not currently exist within your company, then seek external help. Do not let current practices and approval systems stand in the way of getting breakthrough results on projects. Today’s projects are the foundation of tomorrow's operating environment. Eliminating uncertainty and driving toward both high reliability and operating performance at initial startup are the trademarks of world-class factories.

8.8 Speed Ups

Higher throughput can be achieved by speeding up the rate; essentially, turning up the dial. Sometimes this result is reached by adding capital improvements that increase capacity. However higher throughput is achieved, the speed factor for the OEE equation needs to be adjusted. Once the higher speed is accredited with producing product, it becomes the ideal rate. The maximum speed ratio is 100 percent.

There are three strategic categories of manufacturing processes: continuous, dedicated, and batch. Each can be further defined as to dedicated and non-dedicated products. Speed up is used generically for all categories. However, a discrete process speedup will be discussed in section 8.9 on cycle time improvements.

Continuous processes are systems where a flow-stream, web, string of material, or some other product is produced without stopping. They are usually manufactured at a steady state, where the series of steps must be precisely coordinated relative to an aim speed rate. The ideal rate is the highest speed at which sustained good product can be produced. Technically this is the name plate design speed of the system, or higher, as demonstrated by the best rate attained without downtime or quality problems. Imagine the impact your area would have if the ideal rate were achieved without compromising quality and you could sustain that rate for at least 95 percent or better of the production schedule! That would be world-class OEE for continuous dedicated manufacturing operations.

Let's look at two scenarios. In the first case, often encountered, a work community environment is reactive. It has OEE levels of less than 70 percent and is already scheduled as a 7-day-24 hour operation. The community is currently producing everything it can. However the desire for more product provides the temptation to turn up the dial.

The result is usually high frustration for everyone involved. The source of this frustration is the key descriptor of reactive environment. A significant percentage of surprises routinely occur: more than 15 percent of the work is unplanned. A trademark of this type of environment is the absence of time for planned experiments or root cause analysis. Decisions are often made using unverified data or guesses.

For this case, assume that the intended speed up was to run the same amount of production time with the equipment system speed increased by 10 percent. Seldom does the system actually generate an additional 10 percent more product. Results of 3-6 percent are more likely, especially in the short term. Sometimes disaster strikes; an unforeseen quality problem is generated due to the speed up and the product channel to the customer is filled before customer complaints surface the problem.

Any number of reasons may increase the losses with higher speed. Without good information, the current bottleneck piece of equipment might be successfully modified for a higher rate, yet you may find that another part of the process is now incapable. The supporting services or material flow may not be capable. Waste factors may increase. Equipment maintenance may increase due to higher duty environment. The faster rate for continuous-discrete systems might lead to a greater number of product changeovers. Sometimes the biggest factor is the human side of the equation. Employees reluctant to change may resist the transfer to higher speeds. Area leadership may have poor management of change processes.

Whatever the reason, the OEE chart should be identified with an intervention point noting the significant process change. This point helps you understand OEE deviations, usually negative, from prior history. It also acts as a reference point for setting OEE goals—for the community to reestablish this level or higher with the new speed rate.

In the second case, a work community is proactive, with OEE levels of 80 percent or better. The community may already be scheduled as a 7 day-24 hour operation, producing everything it can. Such communities are usually data driven, with good understanding of the loss categories and equipment system capabilities. The maintenance strategy is predominately conditioned-based maintenance; a range of diagnostic tools and trending already take place. Statistical process control (SPC) is usually evident, and designed experiments are part of the planned master schedule. The area leadership has good management of the change processes. The community is focused on significant common goals such as OEE.

Proactive communities with low OEE numbers are not included in the second case. In such communities, the desire for 10 percent more output can usually be achieved more effectively by driving OEE to higher levels. For example, driving OEE from 65 to 72 percent gives 10 percent more product. As discussed in chapter 3, Rohm and Haas found that adding capacity by building new factories was ten times more costly than improving existing system reliability and productivity.

Getting back to the second case, the difference from the previous case is a disciplined approach to achieving a desired speed up. Data collection—before, during and following—and analysis are important steps.

Actively driving OEE improvement and understanding the losses help an area to observe all aspects that impact the manufacturing process. Being proactive means leading the change in a way that eliminates all surprises.

In my experience, being proactive begins with informing the community about the objective, timing, and business reasons for the speed up. Once this information is conveyed, a request for all issues, concerns, and potential problems from any source is helpful. Every item raised by the employees should be addressed with sincere investigation. A cross-functional team of factory floor employees should be designated to be the team that accepts and implements the speed up.

The capacity of the various equipment systems must be clearly understood. If such knowledge doesn't already exist, then develop designed experiments to achieve the proper information. If equipment modifications are necessary, then apply the design for reliability practices (see section 7.6) and, if possible, carry out reliability quantification testing before implementing the modifications into the existing line (see section 9.1). Using reliability block diagrams and the historical information of the current system, a prediction of the proposed system will help focus attention on critical items. The model also provides the game plan for speed up as well as for predicting the business case results.

Use systematically designed experiments to verify and implement speed up phases. Establish new set points and revised procedures. Carry out necessary training on new equipment and processes before speed up implementation. Test and verify quality aspects of the new process with trade trials and end user (paying customer) feed back, before final acceptance and accreditation.

Using this approach will help transform the processes with minimal impact on current OEE levels.

Does this mean success every time? No, as the following experience I had testifies. A factory I observed achieved speed up on a high-speed web conveyance and coating machine. After release to the paying customers, a number of crease defects began to surface.

The problem originated in manufacturing and did not exist before the speed up. It seemed random and occurred infrequently—only parts per million, but still an unacceptable increase from before speed up. We made a significant effort to discover the root cause of the defects. As it turned out, the higher speed caused more boundary layer air to be pulled in with the web. This problem occurred at the web-roller nip as the web was going over rollers and being wound at the end of the process.

Therefore, equipment alignment and roller deflections were at the boundary limit for some product at infrequent intervals. Still, we were not sure why. A single source supplier provided the raw web.

With enough data, we determined that the creases correlated with one of several machines at the supplier's factory. This machine provided about 20 percent of the high-speed web raw material, consistent with past operations. The new tests for raw paper did not show any differences. However, the supplier began an examination, using a more restricted definition for bagginess, the planarity parameter for the raw web.

A slight difference was detected for a very low percentage of the product from the suspect machine. The bottom line: the increased speed, coupled with a series of upstream process parameters, led to a defect in about 0.05 percent of the high speed web product. The process parameters were all within specifications. But, when uniquely coupled, they caused a planarity difference. To the credit of the manufacturer, the machine speed was reduced until the problem was understood and eliminated. This problem, however, delayed the speed up benefits for over a year.

All of these actions in the second case reduce the risk of failure or poor performance for a speed up project. Some may argue that this approach requires too much time and too many resources. Observe the source of this argument. Often it comes from a reactive environment with relatively low OEE. World-class operations eliminate the surprises. They have detailed the path of change. Not only can they measure their progress, but they can also deliver the expected outcome on or before projected time. This ability is powerful and valuable to a company’s business plan. It begins with establishing the high OEE environment before launching a speed up project. By taking control and leveraging the hidden factory first, an area can develop a breakthrough understanding of its processes and equipment systems.

8.9 Cycle Time Improvements

Cycle time improvements apply to discrete and batch manufacturing systems and usually targets one or two steps. This is slightly different from speed up of a continuous process where all systems are coordinated together at a fixed rate.

The objective of higher throughput is essentially the same for both. From a business perspective, that difference often seems transparent. As with speed ups, once the new ideal rate is accredited, the cycle time rate standard for OEE is increased so that 100 percent is the maximum possible rate. The specific equipment system that is the constraint within the work center may change. However, the bottom-line for production, scheduling, and management is the amount of good product that is produced for the given schedule.

A factory usually incorporates a series of functional discrete manufacturing steps. Even work centers may have their own internal discrete steps. In turn, these steps are usually separated with distinct time or space buffers. Consider, for example, the following discrete manufacturing process within a work center. The equipment flow line takes a coil of product, then unwinds, chops, stacks, bags, boxes, cartons, and automatically loads pallets with product. The line is highly automatic, using robots to perform repetitive tasks. The system uses conveyors as dedicated space buffers within the flow line. However, as a production order starts, the full order is produced before a different order can be introduced. In The *Constraints Management Handbook*[2], this kind of a line is defined as a T system, one in which many different customer orders, sizes, and types come from a production line, but are produced with equipment steps in series. The steps in this case are automatic.

In discrete manufacturing, steps take place individually to cause the transformation or positioning of materials and products. Sometimes the cycle and sequencing of the steps occur so quickly that the process appears to be continuous. Each discrete portion of the system has input, process, and output. Multiple discrete actions, such as taping, labeling, and dating, are often performed at the same time, in parallel. When all systems are operating properly, the subsystem or process step with the longest cycle time becomes the bottleneck; it constrains the rate of the overall system. The bottleneck often changes with different products. As explained by the Theory of Constraints, it may jump around on closely balanced systems, depending on the normal variations between equipment performance.

In our example, the original design rate for the system had never been achieved. The reasons included delayed project acceptance—many systems software communication problems—and urgent business decisions to refill delivery channels with whatever could be made. Over time, the product format had changed and new products were more pressure sensitive. Therefore, a slower cycle time evolved and was the performance standard for over two years. The department clearly wanted to improve its cycle time to design rates. Such an improvement, however, was much easier said than done. Adding to the challenge was the continual shift of the bottleneck among the different products.

As with root cause analysis, defining the problem, then gathering and analyzing the data, were the first steps. A few special products had unique problems. However, the vast majority of products had common problems and bottlenecks. The original design intended chopping and stacking to be the overall system bottleneck. The rest of the system was supposed to be capable of handling all of the product that flowed through chopping and stacking. Yet, in most cases, bagging was the constraint, followed closely by boxing. This discovery was made by gathering data on the conveyor buffers before each step, when the system was running without problems. Remember that the focus is on cycle time of the process. Reliability problems often cause production flow problems as well as poor performance.

Many cycle time improvement projects had been implemented previously, only to find that another function or step became the bottleneck. Therefore, overall cycle improvement was minimal. Furthermore, capital for new equipment or upgrades to existing equipment was almost nonexistent.

Cycle time improvement became a focus project for the area. A team of engineers, technicians, operators, and mechanics directed their attention to this effort. They needed to model the existing system, then use the model to determine what improvements might result from different upgrade scenarios.

The team recognized the similarity of determining critical path via project management software and minimal completion time for a cycle time timeline. Therefore they used project management software tools that were already available.

The smallest element in the software program was minutes. The team creatively scaled 0.001 second of cycle time to be equal to one minute of project management timeline. They then built a model of the boxing process by assigning project parameters for each task and function within the boxing station. The various movements of the robots and the different functions became part of the model.

Once the model was constructed, it was validated with actual equipment performance. After several corrections, it was representative of existing sequences.

One of the first benefits from this approach was the recognition of differences in robot movements, some being much quicker than others.

A knowledgeable robot technician soon found that, in some cases, the degrees of freedom mode for checking arm positions was on throughout some activities, instead of being only on for final precision placement steps. As a result, the control software was required to spend significantly more time controlling arm motion than was necessary. The robot was on the critical path of the cycle; a simple software correction reduced cycle time by 10 percent.

The next benefit of the model was identifying the critical path for the scenario of any proposed improvement. This feature helped the team to prioritize the benefits from various changes and also to predict the expected performance for each change. Confidence and credibility increased and, in turn, a clear business case could be provided,

The software model was plotted and studied relative to the principles of quick changeovers (see section 8.3). This plot helped the team visualize relationships and relative synchronization of all the steps. They set the plot out on the timeline for the total process cycle. With the critical path highlighted, the plot was used to identify items to move from direct to indirect, such as a bag printing function being moved from online to preprinting bags at the bag staging area.

Another design change surfaced by listing the robot functions. The original process had the robot perform several tasks, one of which was to grab and locate the bag for the stack to go into. Bag placement was critical. A much simpler, almost passive device was given this task, saving a significant amount of the robot's time.

With all of its adjustments, this area improved output by 70 percent over 40 months. About 50 percent of the 70 percent improvement came from the cycle time project.

Improving cycle time improves productivity for a work area. The cycle time rate factor in the OEE equation is limited to 100 percent. Therefore, once the improved cycle time is accredited for production, the higher rate becomes the standard. As OEE improves, faster cycle times also apply to the increased good production time. Improved cycle times can be reached with creative modeling and application of quick changeover methods.

8.10 Benchmarking

Benchmarking can be an excellent tool for identifying opportunities for improvement. Unfortunately, it can also be an activity trap, leading to interesting information, but no improvement. Benchmarking may fail because the key resources in different areas participate reluctantly, they do not have proper data and they challenge the final results.

Most literature about benchmarking emphasizes the need to begin with the end in mind. To be successful, your organization must commit to supporting the process and implementing improvement recommendations, if a clear business case is developed. In other words, benchmarking should be elevated to the level of a focused project. The community will then supply the necessary resources and actively drive the recommendations.

Benchmarking can focus on many aspects of manufacturing. It is often narrowed to examine specific areas of concern regarding a work area's current goals and strategies. Recognize the dynamics and interrelationships of the existing work area; the current process is the equilibrium of all parts. An improvement to a specific portion of the process often influences other portions of the community. Therefore, good management of the change process is needed to attain maximum benefits.

For example, suppose that a recommendation is made to reduce a factory's spare part inventory by 50 percent. This recommendation might be made if the annual inventory turns for spare parts is one and the industry standard is two. If the work environment is highly reactive, this reduction in spare parts might significantly increase equipment downtime. Existing maintenance strategy must be examined, and possibly adjusted, before changing the level of the spare part inventory. Designed experiments with measured results are appropriate. The approaches used for benchmarking vary depending on the level of investigation (e.g., corporate financial, strategic, operational, and individual department). No two factories are identical. Benchmarking numbers, therefore, usually vary and probably should. Your goal is to determine when the variation significantly differs from the expected. Then, the better practice can be identified. Large companies with many similar factories sometimes develop an imaginary factory that uses the best results, or company class, for each category. This hypothetical factory may be unreachable. However, individual factories can help themselves by championing improvements in the two or three categories with the largest gaps relative to the imaginary factory.

Figure 8-5 provides a list of fifteen categories that influence work area effectiveness. You should review these categories for benchmarking. They are aimed primarily at the operating department or shop floor level.

1. Production Capability Study
2. Process Understanding
3. Management Support
4. Organization Strategy and Culture
5. Performance Measures
6. Training Strategy
7. Basic Maintenance Assessment
8. Stores Strategy
9. Periodic Maintenance
10. Predictive Maintenance
11. Proactive Maintenance
12. Operational Excellence
13. Safety Process and Audits
14. Calibration Practices
15. Integration with Infrastructure

Figure 8-5 Benchmarking Reliability and Maintainability

A list of specific questions pertaining to each category is provided later in this section. Other categories may apply to your specific area or company.

When you benchmark, it is important to use resources that are knowledgeable in evaluating best practices for the various categories. At the least, they should understand best practice definitions and industry standards for the categories selected and also be experienced in several main categories.

Benchmarking is seeking consistent evidence demonstrating the level of understanding and implementation of good methods in each category investigated.

When the specific benchmarking categories are investigated, I recommend using the value system illustrated in figure 8-6. It subjectively quantifies the overall level of maturity or understanding demonstrated by the work area. Figure 8-6 shows statements that represent the levels of understanding that can be used when placing values on the different questions within each category. The overall category value should use the same one-to-ten scale. It should be based on the strength of the answers and evidence found in answering the various questions.

LEVEL OF UNDERSTANDING	VALUE
Little or no understanding of best practice.	0. Not Evident, no knowledge of. 1. Awareness of in general. 2. Some deatil knowledge of the practice, but it isn't in use.
Best practice is understood by everyone. The purpose and benefits are visible.	3. Beginning to use the 'tool' or practice in a learning mode. 4. Use of the practice in one area for at least six months. 5. Practice is used regularly by all areas 6. Regular use of the practice. It is documented and visible.
Best practice is vital to everyday use. It would be sustained regardless of leadership changes. It is company or world class. It is linked to workers appraisals.	7. Used and Supported by all levels in the functional organization. 8. Multi-functional acceptance. It is budgeted and supported. It is considered a strength. 9. The practice is vital to the organization and is a key parameter in appraisals. 10. It is a key business parameter. It is used and the results charted. All levels have wisdom.

Figure 8-6 Value System for Demonstrated Levels of Best Practice

Every category plays an important role in world-class manufacturing. However, some categories often have greater opportunity to influence the bottom line of a plant. Therefore, I have included a recommended importance factor for each category. The final score for a category is the level of understanding value multiplied by the importance factor.

The team preparing the benchmark could use the following questions for each of the categories. Additional questions specific to your plant or industry should be added.

Production Capability Study
* Is OEE assessment completed daily or weekly and reconciled with actual out put? Record past six months OEE: ________
* What was the actual output versus the ideal amount for the last six months?
  Record the amount of good product transferred: ________
  Record the amount that could have been made without losses:_______
* Is detail loss accounting completed and charted weekly or monthly with all categories included. Record past six month values below.
  Waste percent ___________________
  Incident Waste percent ___________________
  Downtime (by percent)
    Equipment losses ___________________
    Operational losses ___________________
    Quality losses ___________________
  Stoptime (by percent)
    Operational losses ___________________
    Induced losses ___________________
* Does this total100 percent? ___________________
  Category value _______ × Importance factor of 9
  Overall score _______________

Process Understanding
* Is a current process flow map or block diagram with ideal rates available?
* Is a reliability block diagram or a statistical model available and used for process improvement?
* Is a prioritized critical equipment list available?
* Are process bottlenecks identified for different products and processes?
  Record the products and bottlenecks: _____________________
* Has a formal FMECA been completed?
  Category value _______ × Importance factor of 10
  Overall score __________

Management Support
* Does the work area's mission statement support reliability efforts?
* Are shutdowns and linestops provided in the production schedules to properly maintain the equipment?
* Does management routinely review OEE and reliability information?
* Is management proactively leading reliability efforts, including tours of the shop floor improvement projects?
* Are reliability resources dedicated full time and recommendations supported?
* Is there a maintenance mission statement?

* Is the maintenance strategy documented and adequately budgeted?

Category value _______ × Importance factor of 10

Overall score __________

Organization Strategy and Culture

* Is reliability focused into a single function?
* Is a multifunctional leadership team evident?
* Are time and attention given to investigating and preserving failure data?
* Are communications good among maintenance, operations, engineering, planning, and management?
* Are job roles and responsibilities documented?
* Are operators involved with PMs, equipment monitoring, and shutdown work?
* Are scheduled shutdowns and linestops completed as planned?
* Is OEE understood and communicated?
* Is benchmarking completed routinely?

Category value _______ × Importance factor of 8

Overall score __________

Performance Measures

* Are performance goals understood?
* Are major production parameters measured, current, and displayed?
* Is OEE charted and displayed?
* Is a single database being used for all information?
* Are unit manufacturing cost categories understood and communicated?
* Are safety and environmental numbers at industry standards?
* Are area improvement projects completed as planned?

Category value _______ × Importance factor of 8

Overall score __________

Training Strategy

* Are specific reliability and OEE training classes available?
* Is a strategic training plan documented and communicated?
* Is a skills analysis completed for the specific work area?
* Is a certification process used to qualify roles and responsibilities?
* Are individual training plans evident (40hrs/yr or more?)
* Are key resources backed up?

Category value _______ × Importance factor of 7

Overall score __________

Basic Maintenance Assessment

* Is an equipment performance system in place?
* Is MTBF or MCBF, MTTR computed and communicated for critical equipment?

* Is a maintenance strategy defined and used for all critical equipment?
* Are critical equipment histories analyzed and used in setting maintenance strategy?
* Is a CMMS system in place and used by everyone?
* Is an effective work order system in place?
* Is a weekly work plan provided and completed as scheduled 85 percent of the time?
* Is the work order priority system understood and communicated?
* Are the following numbers available? (Record the values)
  Average mechanic 'wrench time' per shift? _______________
  Maintenance expense as a percent of
  Equipment Replacement Value (ERV)____________
  Stores expense as a percent of ERV______________
* Is maintenance work categorized into types of work? Record the percentages. (Reactive work should be less than 15 percent.)
  Reactive ___________________
  PMs ___________________
  Predictive ___________________
  Proactive or Condition Based ___________________

* Is overtime tracked and trending downward?
* Are maintenance contractor expenses audited and communicated?
* Is weekly maintenance planning and scheduling routinely completed?

Category value ________ × Importance factor of 9
Overall score ___________

Stores Strategy
* Is the storeroom clean and well managed?
* Are stores 'run like a store'? (Equal to your auto parts store?)
* Is spare part usage categorized and quantified?
* Does a random check of twenty five bins have any errors for quantity and nomenclature of spare parts?
* Is spare part quality maintained for receiving, inspection, and storing?
* If the maintenance strategy indicates a spare part should be in stores, is it available 95 percent or more of the time when it is needed?
* Are there strategic supplier alliances with specified availability goals?

Category value ________ × Importance factor of 6
Overall score ___________

Periodic Maintenance
* Are PMs completed as scheduled 95 percent or more of the time?
* Is a specific maintenance strategy used to generate PMs?

* Do PMs have comments for equipment history on completion?
* Is there a formal PM update plan based on reliability factors such as MTBF?
* Does each equipment overhaul have a start up, commissioning, and acceptance criteria?

Category value _______ × Importance factor of 7
Overall score __________

Predictive Maintenance (PdM)

* Is PdM applied to all critical equipment?
* Do predicted failures trigger conditioned-based maintenance actions?
* Is data collection defined, scheduled, and completed?
* Are expert systems used for data analysis?
* Are the following technologies used for critical equipment PdM?
    Vibration analysis?
    Oil analysis?
    Thermography?
    Ultrasonic analysis?
    Motor current diagnostics?
    Other appropriate technologies applied?
* Is statistical process control analysis used for equipment monitoring?

Category value _______ × Importance factor of 8
Overall score __________

Proactive Maintenance

* Are installation and commissioning best practices used (soft foot, precision alignment and balancing, thermal effects, vibration baseline data etc.) and startup data available?
* Is root cause failure analysis performed on all critical problems?
* Are precision alignment practices used on all rotating equipment?
* Are precision balancing practices used on all rotating equipment?
* Do critical equipment systems have in line spares?
* Are operators actively involved in monitoring and reporting on equipment status?
* Are spare part and equipment suppliers certified?
* Do purchasing practices and standards incorporate reliability information and reliability quantification testing?
* Are quick changeover methods used on repetitive maintenance tasks to shorten downtime and build in quality?
* Are lift points, access ladders and platforms, special tools, and testing equipment provided as needed for critical equipment?

Category value _______ × Importance factor of 10
Overall score __________

Operational Excellence
* Is statistical process control used for critical production processes?
* Are key process parameters identified and interactions understood?
* Is the percent of on-time, in-full, no error orders measured? Record the percentage _____________
* What is the product waste percentage for the past twelve months? Record the percentage _____________
* Are quick changeover methods used at process changeovers?
* Are real time OEE measures actively used?
* Are communications good between shifts, and with maintenance, schedule planners, vendors, and customers?
* Is process documentation (set points and operating procedures) available and applied with discipline? Confirm that off specification settings are documented and formally investigated.
* What latitude do operators have in decision making?
* Are cross-functional teams of operators, mechanics, and engineers used for problems solving and improvement projects?

Category value _______ × Importance factor of 10
Overall score __________

Safety Process Audits
* Are all employees involved and trained to conduct audits and job hazard analysis?
* Are emergency shutdown procedures and practices documented and under stood by operators and mechanics?
* Are safety issues addressed and are policies posted?
* Are pressure vessels, piping, relief valves, etc. scheduled for safety conformance PMs?
* Do the environment and employee attitudes show evidence that safety is high priority?

Category value _______ × Importance factor of 10
Overall score __________

Calibration Practices
* Are certified standards available for calibration testing?
* Are instrumentation calibration frequencies documented and is instrumentation tagged?
* Is the documentation and record keeping system formal?
* In the past two years, have there been any quality incidents that impacted the next downstream customer?
* Are there go/no go on-line automatic systems to maintain quality?

Category value _______ × Importance factor of 6
Overall score __________

Integration with Infrastructure

* Are relationships and communications good with the following departments:

(Confirm by surveying contacts in these departments.)
Upstream and downstream departments?
Purchasing?
Marketing?
Engineering?
External suppliers and shipping?
Sales, forecasting and scheduling?
Utilities?
Human resources?
Other departments and other plants?

Category value _______ × Importance factor of 7

Overall score __________

Once you've completed these questions, multiply each category score by the corresponding importance value. Add the resulting values for a total score. Work areas that perform many important things well will have a high score. By using the same benchmark criteria with similar departments in all of a company's plants, and against industry best practices, you can identify the ideal factory. Repeating the exercise over time will reveal work area improvements.

Note that in the production capability study category, the actual OEE value is not the issue. What is valued is the practice of computing true OEE and the loss categories, and using the method to drive improvement.

The benchmarking approach presented here will help you quantify the generic categories of good practices. In addition, you should benchmark both reliability and the performance of critical process steps and key equipment systems, especially if similar equipment exists within a company or factory. Just the process of visiting alternate sites or work areas with the idea of sharing best practices often surfaces new ideas and techniques of operation.

This section has focused on benchmarking reliability and maintainability of a work area. A similar focus can be developed looking at operation effectiveness and material usage. Remember that benchmarking helps you learn new operational techniques by discovering how others already do them. Breakthrough improvements can be achieved by creatively adapting new learning into existing operations.

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CHAPTER 9

A GENERAL TOOL FOR ACCEPTANCE TESTING

Because the factory is a dynamic environment, changes to equipment and processes often occur, including ones that prepare the factory for new products and better performance. This chapter focuses on one aspect of verifying proper performance prior to implementing changes to the existing system. By planning an objective test for acceptance before you start design, you can anticipate the necessary performance parameters for reliability and availability from the beginning. These reliability parameters form a part of your purchase specfications.

9.1 Reliability Quantification Testing (RQT)

Among the most important steps in providing reliable equipment are the design and fabrication stages. Many frustrations could be avoided if a crystal ball could predict, before acceptance, how well the new system would operate six months after bringing it online. New equipment performance is often an important parameter that impacts OEE and the total factory output if it fails to meet expectations. This is the very reason to make sure that the right results happen.

All projects, structured or unstructured, have a defining moment when the equipment is configured and turned on for its first production run. Unstructured approaches often have many surprises and struggle to meet expectations. Even structured methods, such as Front End Loading (FEL), need to demonstrate their start-up functionality.

One of the more helpful tools is a testing formula that involves Mean Time Between Failures (MTBF). Used by Intel Corporation when working with its vendors, this formula is the Reliability Quantification Formula (RQT)[1]. It would be my own first choice when setting general acceptance standards for equipment suppliers of typical production equipment. For highly critical, dangerous, or life dependent systems, for which confidence levels of more than 80 percent are required, even more extensively designed experiments should be carried out.

RQT can be used for new installations as well as new subsystems proposed for existing equipment lines, undoubtedly the more frequent occurrence for maintenance organizations. One of the first steps for proposed sub-systems is quantifying the existing performance by using ongoing data collection. A reliability block diagram of the operation is needed, with at least one block outlining the specific subsystem. MTBF should be generated for each block. This information quantifies the current status and helps set standards for the new subsystem.

Expectations for the proposed subsystem need to be part of the requirements document. Suppliers need to understand the assumptions and share the same goals. The purchase order should address potential outcomes of the acceptance test. In addition, the project timeline needs to account for the testing time, as well as possible re-testing.

The RQT test provides an objective way of determining, with high confidence, that the new system is either acceptable or needs further improvement. Furthermore, this determination can be made before the new system impacts current operations. RQT is an appropriate test for a supplier to run before shipping, but after initial trials.

If you have the ability to immediately convert back to the previous equipment configuration, you can run RQT with the new system in line. When you have multiple lines of identical equipment, RQT provides an objective test plan for one line's upgrade, before you carry the changes to the remaining lines.

The RQT equation helps solve for MTBF. It can also help determine required test time, given an expected MTBF. The formula is

$$\text{MTBF} = \frac{2(T)}{X^2_{\alpha\ 2r+2}}$$

where T is time and $X^2_{\alpha,2r+2}$ is chi-squared.

Chi-squared is a statistical value obtained from a standard table. It can easily be found using EXCEL® or another similar spreadsheet program. The two parameters you need to find the proper X^2 value are alpha, α, and the degrees of freedom, DF. I recommend you use 80 percent as the desired confidence level for typical production equipment. Therefore, alpha, α, will be 0.2. The degrees of freedom, DF, is determined by solving the equation:

$$\text{Degrees of Freedom} = 2\ (r) + 2$$

where r is the number of failures.

If you use EXCEL®, click on the function wizard, fx. Choose the statistical category, then the **CHIINV** function. After you click **NEXT**, the function wizard will ask for probability and degrees of freedom. The chi-squared value will show in the value box as soon as you enter α, (0.2 for the typical RQT) and DF. Let's look at two ways of using the RQT formula. The first way provides an MTBF value from known data about the number of failures for a given test time. Suppose your existing subsystem ran for 480 hours and, during that time, failed seven times. The degrees of freedom, then, is

$$DF = 2(7) + 2 = 16$$

With $\alpha = 0.2$ and DF = 16, you can calculate chi-squared using the method just described.

$$X^2 = 20.47$$

Now you can solve the RQT formula for MTBF.

$$\text{MTBF} = \frac{2(T)}{X^2_{\alpha\ 2r+2}} = \frac{2(480)}{20.47} = 47 \text{ hours MTBF}$$

You can say with 80 percent confidence that the MTBF for the existing system is 47 hours or more.

You can now require the proposed subsystem to be at that level or better without significantly impacting the factory flow. By properly evaluating the functional block diagram of the overall system, the influence of the subsystem can be quantified. If the new system is improved, the benefit for the overall system can also be estimated.

You can also use the formula to determine the test time. Assume that you have determined the new subsystem is required to perform with 120 hours MTBF. To determine the test time and failure expectations, first solve the RQT formula for time, T.

$$T = \frac{MTBF \times X^2_{\alpha\ 2r+2}}{2}$$

You can now develop an acceptance test table, such as the one in figure 9-1, by solving for T, given various numbers of failures which generates different values of chi-squared.

MTBF	α	# failures	DF	X^2	Time
120	0.2	0	2	3.22	193
120	0.2	1	4	5.99	359
120	0.2	2	6	8.56	513
120	0.2	3	8	11.03	662
120	0.2	4	10	13.44	807
120	0.2	5	12	15.81	949

Figure 9-1 Acceptance Test Table

The results in the time column are the expected successful run hours relative to the number of failures of the system for the specified MTBF.

Using the table above, you could specify the acceptance test in the purchase order. For example, you could specify to run a 513 hour performance test requiring no more than 2 failures for acceptance.

To make the test relevant, you must reproduce actual factory conditions. Doing so may require creativity. Materials, environment, utilities, performance rates, and waste rates need to be replicated as if the system were in future production. However, these conditions may be difficult to replicate, especially at the supplier's site. They also need to be prioritized relative to the critical nature of the proposed system. I know of several projects that had serious difficulty because the test was run with substitute materials and ideal conditions. Do not discount any factor without carefully weighing the impact of that condition.

Resolve not to accept or go forward with compromised equipment. The project's business case performance levels could be unattainable if the original design, fabrication, and assembly are not capable.

In summary, equipment changes are a part of every operating area. They need to be recognized as opportunities for improvement. The RQT formula provides a simple way of bringing some objectivity to bear on making the right things happen for a successful transition to new equipment systems. If demonstration RQT testing is run with thoughtful creativity, then successful transitions should result.

9.2 Implementing RQT

RQT improves confidence that equipment systems will either operate as expected when implemented into existing systems or be capable of a square start when implemented into new systems. This confidence assumes that the RQT is valid and that *test conditions replicate actual usage.* The second assumption is sometimes compromised in testing and can be the downfall of a successful project.

In the following situations, the original equipment already existed. Projects were initiated to address maintenance and reliability problems. Reliability and RQT were introduced to improve future reliability.

Case 1. Barrel Dumper Project

A material handling improvement project called for replacing heavy movable barrel dumpers that were used to dump ingredients into stainless steel tanks for processing. The material ranged from liquid to a nearly solidified gelatin. Each tank was to have its own dedicated barrel dumper, thereby avoiding the time and effort needed to reposition the moveable dumpers. Another requirement was eliminating the waste and mess of the existing system. In that system, when barrels of ingredients were dumped, final liquid portions curved around the down-turned lip of the barrel and dribbled down the front of the tanks.

Engineering design developed a prototype for review. Conceptually, the design met the requirements, as understood by the engineer. On closer inspection, the operators challenged the size of the prototype. They explained that the proposed size and fixed position for the dumpers would prevent other types of equipment in the room from passing. Therefore, a new design was required. The lesson: Include all requirements for design up front. Start by using tape or markings to define the acceptable boundaries or volume of the new equipment. Complete a full production cycle to assess the impact on all operations.

The first redesigned prototype was fabricated and, per the purchase order, tested at the manufacturing site. The system design provided for the barrel lip to be closer to the center of the tank before tipping; spillage would then be avoided. The testing was satisfactory both for number of cycles and liquid spillage.

At this point, projects are often given the green light. The remaining items are then mass produced to meet a tight timeline. Fortunately, in this case, the next step was to use the prototype in full production before fabricating the remaining fixed dumpers. What do you think was wrong with the prototype dumper design?

Everything worked well for nearly all the usual operating conditions. However, when materials were assembled 72 hours in advance of production schedules, or when rearranged schedules caused delays, the material would solidify to a gelatin form. The material would then exit the barrel as a cylinder. The highest portion of the material would overshoot the far lip of the tank and be sliced off, falling down the other side of the tank.

In short, one problem was traded for another. The problem was not revealed during the acceptance test at the fabricating site because the full range of conditions was not replicated. The lesson: The final test can only be completed in place under full operating conditions and material variations. Implement only the first of several similar modifications to verify that all expectations are met, before committing to the rest.

Case 2. Computer System Upgrade

An important computer upgrade was planned for an extremely important production machine. If the equipment system failed to produce, all product lines for the factory would stop. The computer system controlled the logic and timing of sequences throughout a long, complex process, including many semi-automatic interfaces for new material starts and stops.

The existing system was obsolete. The master file was still based on computer cards. If a card was damaged, no card punch or material was available to replace it. The sequence program was locked in so that no improvement upgrades could be made.

The company had two alternative strategies, one twice the cost of the other. The less expensive strategy was to develop a new program offline. Then, at some designated shutdown, the company would remove the old system and tie in the new. The more expensive alternative was to build a system parallel to the existing one. The new system could then monitor, or shadow, the existing system. Offline checks would verify logic steps. A series of eight-to-ten designed experiments would bring the new system into primary control to prove that the logic was fully capable. The new system would then be certified as operational. However, the resources needed, both in programmers' time and money, was such that corporate approval was needed for the more expensive strategy.

Which alternative do you think was championed and submitted for corporate approval? Which alternative provides an environment of no-surprises?

The more expensive project approach was chosen to submit. Its asset life cycle costs (LCC) were known and it was considered to have lower overall cost with less risk.

The less expensive project brought with it too high of a possibility of a total plant shutdown. Once the new system was started, the old system could not be reinstated. The potential of very high business losses and the threat of an interrupted supply chain were not acceptable.

Selling the more expensive strategy at the corporate level was not easy. The decision-makers were not familiar with the details within the factory. The potential risks defined in the proposal were hypothetical. The proposal was reviewed many times and required the strong support of both the plant manager and the business manager. Finally, the strategy was approved.

It proved to be very successful. Furthermore, several unexpected discoveries of unique but necessary logic steps were uncovered in the old system as the project moved along. These steps would have been unknown in the alternative design. Final implementation was so transparent that most users would not have known anything was different unless they were told that the new system was now in control.

Case 3. Material Handling Wheels

A company used special containers to move production materials several hundred feet from storage to production. The original style wheels for these containers were found to be too difficult to push; they were also classified as ergonomically unacceptable. A project was initiated to replace the wheels with ones that were easier to push.

A wide selection of wheels was investigated. Only one tested model met the design requirements. This choice turned out to be very costly to the project. If these wheels were purchased, the project would overrun its budgeted guidelines. With cost and time constraints facing the engineer, the supplier was asked about other less expensive choices. A substitute wheel model was suggested as being nearly equivalent. A simplified push-pull test using equipment with the alternate wheels demonstrated that the forces were just within the allowable limits. The decision was made to incorporate the substitute wheels.

In the end, the wheels quickly degraded in normal production. They became much more difficult to move than expected. Maintenance costs were far higher than expected. The higher-priced, more reliable wheels were soon purchased for all of the containers. The lesson: Do not compromise full testing. Check out all alternatives. Recall the classic question, "Why is it that we never have time to do it right the first time, but always have time to do it the second time?"

Case 4. Automatic Core Loading

The last case looks at a process with long cylindrical cores used for winding up web at the end of a conveyance machine. The process of automatically loading these cores was designed to use a large robot. The original concept provided for a taping station, a position where double stick tape was applied for new roll starts if necessary. With this design, the core was oriented parallel to the machine axis.

The robot sequence had several steps. The robot moved along a rail system to position A, extended its arm to pick up the core, retracted from the taping station, and then rotated 90 degrees so that the core was perpendicular to the machine axis. The robot, with the core, then moved on the rail system to position B. There, the robot arm rotated vertically to provide a small elevation change. The robot extended the core into the wind-up assembly where it was carefully positioned to be transferred to the machine wind-up system. Once the core was transferred, the robot arm retracted and rotated downward. The robot then turned back 90 degrees, returning to position A to start the process again. The size of the equipment and cores was very large. The interface between the robot and the machine needed to be quite accurate.

The automatic core taping process was found to be unnecessary and that process step was eliminated. Even then the core loading robot experienced high maintenance and a failure rate of one-to-two times per month. Whenever the alignment varied, the cone-shaped interface to the core applied large forces that pushed against the robot equipment, causing high wear and failure of resisting parts. Keeping accurate alignment of large mobile interfacing equipment was time consuming. It caused significant technical downtime with each failure. As you may have guessed, this original equipment system did not go through an extensive reliability review prior to fabrication. Nor did RQT take place.

A replacement project was generated to address the reliability and maintenance costs. The engineer quickly determined that the existing system was too complex and complicated to satisfy location tolerances with high reliability. He redesigned the various functions, using proven material handling techniques in separate steps. The cores were conveyed a longer distance—the original core conveyance was highly reliable—and a simple rotation table re-oriented the cores 90 degrees. They were then perpendicular to the machine axis and raised to the machine load height. A short conveyor moved the core to a position directly centered with the machine. It used solid positive stops to maintain accuracy. Finally, a simple fixed-distance piston-like stroke moved the final core support carriage into the machine where the core was presented for machine pickup at the same exact location.

With this project, system reliability specifications were included in the purchase order for the outside design contractor. A lot of industry experience existed with the proposed simple material handling functions. Therefore, the design was viewed as very low risk relative to providing the expected outcomes. Full-scale testing at the contractor site was not undertaken. However, final payment was contingent on actual production use and failure rate for a certain number of cores. As a result, all entities worked together to achieve high reliability. A few adjustments were made shortly after start up. Afterwards, the first year's use had only two short failures, down from twenty or more failures experienced the previous year.

In this case, converting an integrated complex process into a series of simple steps using proven technology brought success. By rewriting the system requirements and clearly stating expectations in the purchase order, the supplier and the company worked together toward common goals.

These examples demonstrate the practical application of this book's recommendations and principles when approaching either new projects or modifications to existing systems. Remember to be data driven and creative when you verify the reliability of new systems. If you have other stories of failures or successes to share, please send them to me for inclusion in future editions of this book.

References:

1. Hansen, R. "A General Tool for Acceptance Testing," *Maintenance Technology,* Volume 11/number 7 (July-August 1998): pages 35-36.

APPENDIX 1

RECOMMENDED BOOKS TO READ

A book that unveils most of the unwritten rules of business politics and human diversity is Coleman, Harvey. *Empowering Yourself.* Dubuque, Iowa: Kendall/Hunt Publishing Co., 1996.

A powerful book on applying Theory of Constraints into manufacturing systems is Cox III, J., Spencer, M. *The Constraints Management Handbook.* Boca Raton, Florida: The St. Lucie Press, 1998.

My first choice for understanding interaction, communication, and action principles and skills is Covey, Stephen. *Seven Habits of Highly Effective People.* Rockefeller Center, New York, New York: Fireside, 1989.

This book helps understanding the of Theory of Constraints and manufacturing objectives for all companies is Goldratt, Eli, Cox, J. *The Goal: A Process of Ongoing Improvement.* 2nd Edition, Great Barrington, Massachusetts: The North River Press, 1992.

A profound book with an exciting new project management approach using the application of Theory of Constraints is Goldratt, Eli. *Critical Chain.* Great Barrington, Massachusetts: The North River Press, 1997.

A good shop floor handbook for all manufacturing work areas is Ishikawa, K. *Guide to Quality Control.* White Plains, New York: Quality Resources, Asian Productivity Organization, 1991.

A paper with new methodology for breakthrough thinking using the principle of abstraction is Kaplan, Stan. An Introduction to *TRIZ The Russian Theory of Inventive Problem Solving.*

http:\\www.ideationtriz.com, Ideation International, Inc., 1996.

An excellent book that brings OEE and business concepts together in models for practical application is Moore, Ron. *MAKING COMMON SENSE COMMON PRACTICE models for manufacturing excellence.* Houston, Texas: Gulf Publishing Company, 1999.

A recognized equipment reliability strategy book is Moubray, John. *Reliability-centered Maintenance.* 2nd Edition, New York, New York: Industrial Press, 1997.

A basic OEE resource book explaining Total Productive Maintenance (TPM) is Nakajima, Seiichi. *Introduction to TPM: Total Productive Maintenance.* Cambridge, Massachusetts: Productivity Press, 1988.

A useful reliability handbook for equipment design and manufacturing analysis is Seymour, M., B. Dudley, J. Caroll, and others. *Reliability Toolkit: Commercial Practices Edition.* Rome, New York: Reliability Analysis Center, 1996.

Quick changeover information for both manufacturing managers and OEE practitioners involved with repetitive maintenance is Shingo, Shigeo. *A Revolution in Manufacturing: The SMED System*, Cambridge, Massachusetts: Productivity Press, 1985.

Everyone in manufacturing and reliability needs fundamental understanding of statistics. A good handbook on basic statistics, designed experiments, and statistical process control is Thomas, D., C. Barrett, E. Blankenstein, and others. *Statistical Quality Control Handbook,* 2nd Edition, New York, New York: The Western Electric Company, 1958.

APPENDIX 2

RAPTOR

RAPTOR (Rapid Availability Prototype Testing for Operational Readiness) simulates various Reliability Block Diagram (RBD) configurations at a basic level. First generated by the Air Force, this helpful software program should be used with caution. Unless run by an experienced reliability engineer, it should be used only for preliminary analysis. A reliability engineer or statistician should verify appropriate input choices (e.g., failure, repair, and spare part curves), model configuration, and results before applying it to critical projects. However, RAPTOR can help you roughly analyze alternate designs (redundancy) and roughly project your input model's availability and reliability parameters.

RAPTOR can currently be downloaded as free shareware at http://www.logisticsworld.com/download.asp. This site also provides a tutorial that can be downloaded as your user manual.

Onscreen menus for each RBD block require you to define your failure curve, repair curve, and spare part information.

I use the following approach to start exploring redundancy choices.

Unless there is data to the contrary, assume that randomness and a normal distribution failure curve applies. Be aware that this approach ignores infant mortality, which may be a serious factor if the repair, spare part, or installation is compromised. Selecting "normal" for the failure distribution choice will apply standard statistical curves.

Next, select the component or subsystem to be studied and research its expected Mean Time To Failure (MTTF). Appendix 4 and online tables available from http://www.barringer1.com provide this information for many common equipment components.

To validate your research, ask yourself what the MTTF would be if you had one thousand of these units in your operating environment. This number is your input for mean.

Unless a standard deviation (σ) is known, use

$$\sigma = \frac{\text{MTBF}}{2}$$

This will flatten your normal failure curve, yet 68 percent of the failures will occur at plus or minus one standard deviation and 95 percent will occur at plus or minus two standard deviations. RAPTOR's simulation program may tell you that a negative value exists. Choose "yes" or "yes for all" to round the value to zero, then continue.

An example of the above approach would be: Assume you expect a car to run an average of 10,000 units (miles or hours) between failures, and you have a fleet of 1000 cars.

Determine standard deviation as indicated above.

$$\sigma = \frac{\text{MTBF}}{2} = \frac{10000}{2} = 5000 \text{ units}$$

With a normal failure curve and a standard deviation of 5,000 units, 680 or 68 percent of the cars are expected to fail between 5,000 and 15,000 units, with the highest frequency of failures ending around 10,000 units. In turn, 950 or 95 percent of the cars should fail between 0 and 20,000 units. This is a very flat failure curve similar to patterns reported in the "Reliability-centered Maintenance"[1] book representing over 80 percent of actual failure types.

Other input screens for each block allow you to select spare part information and cost information. Without specific information, the program will default to values of infinite spares and unit costs of 1. If your equipment is always repairable, an infinite spare is appropriate.

Once you have input the various reliability and maintenance data for your blocks, run a simulation for your system. Click on "File" and select "Simulation". Input the desired simulation hours and number of runs. I recommend using ten-year simulations (87,600 hours) and four to ten runs for normal manufacturing equipment. This gives you long term results.

RAPTOR can be used to examine:

- ❑ Redundancy strategies and alternate redundancy systems.
- ❑ Overall system availability for different improvement projects.
- ❑ Levels of maintenance efforts between alternatives.
- ❑ Number of system failures for the simulation time.
- ❑ Spare part strategies.
- ❑ Cost information based on input choices.

Reference:

1. Moubray, John. *Reliability-centered Maintenance.* 2nd Edition, New York, New York: Industrial Press, 1997.

APPENDIX 3

REDUNDANCY EQUATIONS

This appendix introduces redundancy equations for approximating the time to first failure of six different redundancy situations. Equations 1, 2, and 3 are for systems with repair whereas Equations 4, 5, and 6 are for systems without repair or delayed repair.

These equations may look intimidating at first. However, by working through the following example of a common problem, you can better understand their components. Assume the following information is already available.

- ❑ A motor-pump assembly provides cooling liquid for a critical step in a continuous manufacturing process. Whenever a failure occurs, significant waste is experienced and a quality incident is reported.
- ❑ This assembly has a history of failing once per month with a Mean Time To Restore of 45 minutes.

- Currently a similar assembly in spare parts is used to rotate into position whenever the online system fails, keeping the Mean Time To Restore (MTTR) to 45 minutes.

Suppose another spare assembly is purchased. Then, one of the two spare assemblies is installed parallel to the existing system and controlled so that the liquid supply is automatically switched to the spare pump whenever the online assembly fails. What happens to the frequency of the process failures?

First, determine the existing failure frequency. Mean Time Between Failures (MTBF) is

$$\text{MTBF} = \frac{\text{(One month - 0.75 hrs)}}{1.0} = 719.3 \text{ hours MTBF}$$

Mean Time To Repair (MTTR) is 0.75 hours. The repair rate μ is the inverse of MTTR, or

$$\mu = \frac{1}{0.75} = 1.333 \text{ repairs/hour.}$$

According to this strategy, when a failure occurs, the process switches automatically and the repair is implemented immediately (just as it is currently). The proposed redundant system has two equal units in parallel. One of the two is needed for continuing the manufacturing process.

Figure A3-1 lists a series of redundancy equations. Select the appropriate formula for this situation.

Equation 3 is the appropriate choice. It matches the scenario of having a standby off-line unit, with repair. You can use this equation to approximate the effective failure rate for the redundant system. Note that the equation summary states "off-line spare assumed to have zero failure rate."

n, the number of on-line units for success, is one
λ, the failure rate of an individual online unit in failures per hour, is

$$\lambda = \frac{1}{719.3} = 0.0013902 \text{ failures/hour}$$

Prepresents the probability that the switching mechanism will operate properly when needed. A value of 1.0 means perfect switching. Because the off-line spare does have a failure rate,

EFFECTIVE FAILURE RATE EQUATION APPROXIMATIONS
RAC REDUNDANCY EQUATIONS

All units are active on-line with equal unit failure rates. (n-q) out of n required for success.

EQUATION 1 with repair

$$\lambda_{(n-q)/n} = \frac{n!(\lambda)^{q+1}}{(n-q-1)!(\mu)^q}$$

EQUATION 4 without repair

$$\lambda_{(n-q)/n} = \frac{(\lambda)}{\sum_{i=n-q}^{n} \frac{1}{i}}$$

Two active on-line units with different failure and repair rates. One of two required for success.

EQUATION 2 with repair

$$\lambda_{1/2} = \frac{\lambda_A \lambda_B[(\mu_A+\mu_B)+(\lambda_A+\lambda_B)]}{(\mu_A)(\mu_B)+(\mu_A+\mu_B)(\lambda_A+\lambda_B)}$$

EQUATION 5 without repair

$$\lambda_{1/2} = \frac{\lambda_A^2\lambda_B+\lambda_A\lambda_B^2}{\lambda_A^2+\lambda_B^2+\lambda_A\lambda_B}$$

One standby off-line unit with n active on-line units required for success. Off-line spare assumed to have zero failure rate. On-line units have equal failure rates.

EQUATION 3 with repair

$$\lambda_{n/n+1} = \frac{n[n\lambda+(1-P)\mu]\lambda}{\mu + n(P+1)\lambda}$$

EQUATION 6 without repair

$$\lambda_{n/n+1} = \frac{n\lambda}{P+1}$$

Key:

λ_{xy} is the effective failure rate of the redundant configuration where x of y units are required for success.

n = number of active on-line units. n! is n factorial (e.g. 4!=4x3x2x1= 24, 0!=1)

λ = failure rate of an individual on-line unit (failures/hour)

q = number of on-line active units which can fail without system failure

μ = repair rate ($\mu=1/M_{ct}$ M_{ct} is the mean corrective maintenance time in hours)

p = probability switching mechanism will operate properly when needed.
(P=1 with perfect switching)

NOTES:

1. Assumes all units are functional at start.
2. The approximations represent time to first failure.
3. CAUTION: Redundancy equations for repairable systems should not be used if delayed maintenance is used.

Figure A3-1 Redundancy Formulas 1

and the switching mechanism cannot be perfect, you will need to use your judgment to determine this variable. If necessary, compute the formula using both optimistic and conservative probabilities that demonstrate the sensitivity of this parameter. For this example, assume the automatic switching (and pump start up) of the assembly is 98 times out of 100. Thus,

$$P = 0.98$$

$$\mu = 1.333$$

$$\lambda_{n/n+1} = \frac{n\left[n\lambda + (1 - P)\mu\right]\lambda}{\mu + n(P + 1)\lambda}$$

$$\lambda_{1/2} = \frac{1\left[(1\text{x}0.0013902) + (1 - 0.98)1.333\right]0.0013902}{1.333 + 1(0.98 + 1)0.0013902}$$

$$= \frac{1\left[0.028050\right]0.0013902}{1.333 + 0.0027526} = \frac{0.000038995}{1.3358}$$

Failure Rate $\lambda_{1/2}$ = 0.00002919 failures/hour.

Figure A3-2 Completed Redundancy Formula

You can now compute the formula. See figure A3-2.

The failure frequency—the inverse of 0.00002919 failures per hour—is once every 34,364 hours, approximately once every four years. This information could be valuable when putting together a business case for providing redundancy.

Avoiding nearly twelve significant waste and quality issues every year is a step in the right direction.

A one-time installation expense for the second pump and controls provides about a dozen fewer surprises each year, as well as less waste and eight additional production hours per year. In this case, the maintenance efforts remain about the same. A motor-pump assembly needs repair about once per month.

Sometimes, when confronted with the original situation, the decision is made to search for a more reliable pump and motor. As this example demonstrates, redundancy may be the better choice.

Reference:

1. Seymour, M., B. Dudley, J. Caroll, and others. *Reliability Toolkit: Commercial Practices Edition.* Rome, New York: Reliability Analysis Center, 1996.

APPENDIX 4

GENERIC FAILURE RATE FOR COMMON EQUIPMENT

This appendix presents two data tables. The first table (figure A4-1) demonstrates the range of component failure rates attributable to the environment in which the components are used. The second data table (figure A4-2) combines two similar sets of data from different time frames: 1991 and 1995. Variations in the data demonstrate either reliability improvements (changes) or combined information from a larger sampling.

In both tables, the failure rate is measured in failures per 10^6 hours. The "less than" symbol, <, indicates that no failures occurred for the test period. The generic failure rate is 10^6 hours divided by the test period.

The first data table, reprinted from Reliability Analysis Center's Reliability Toolkit: Commercial Practices Edition1, shows data for three different environments. The first, GB, or Ground Benign, is similar to a computer room with controlled temperature and humidity as well as little vibration. The second, GF, or Ground Fixed, is for stationary equipment in an uncontrolled enclosure. The last, NU, or Navy Unsheltered, is similar to above-deck equipment exposed to the elements.

The second table (figure 4A-2) combines data from Reliability Toolkit: Commercial Practices Edition and "Generic Component Failure Rates" from the Reliability Analysis Center's A RAC Quick Reference Guide. This second source uses the RAC's "Nonelectronic Parts Reliability Data 1991" (NPRD-91) as a reference. For more detailed information and a broader list of components, see the RAC's "Nonelectronic Parts Reliability Data 1995" (NPRD-95) available through:

Componenet Failure Rate by Environment

ITEM FAILURE RATE	G_B $/10^6$ hours	G_F $/10^6$ hours	N_U $/10^6$ hours
INDUCTIVE DEVICES			
Transformer, Switching	.00061	.0042	.012
Transformer, Flyback	.0058	.04	.11
Transformer, Audio	.015	.10	.29
Transformer, Power	.053	.36	1.0
Transformer, RF	.14	.96	2.7
Coil, Fixed Inductor or Choke	.000032	.00022	.00063
Coil, Variable Inductor	.00005	.00037	.001
ROTATING DEVICES			
Motors, General	6.9	6.8	8.3
Sensor Motor	27	27	33
Servo Motor	5.4	5.4	6.5
Stepper Motor	1.2	1.2	1.4
Synchros	.031	.071	.70
Resolvers	.047	.11	1.0
ELAPSED TIME METERS			
ETM-AC	10	20	180
ETM-Inverter Driver	15	30	270
ETM-Commutator DC	40	80	720
RELAYS			
General Purpose (Bal. Arm.)	.049	.12	1.9
Sensitive (Bal. Arm.)	.099	.25	3.7
Dry Reed	.059	.15	2.2
Thermal Bi-Metal	.099	.25	3.7
Magnetic Latching, (Bal. Arm.)	.049	.12	1.9
Contactor, High Current (Solenoid)	.049	.12	1.9
Solid State, All	.029	.087	.49
Switches			
Dual In-Line Package	.00012	.00036	.0035
Limit	4.3	13	1.2e+02
Microwave	1.7	5.1	49
Pushbutton	.10	.30	2.9
Reed	.0010	.0030	.029
Rocker	.023	.069	0'67
Rotary	.11	.33	3.2
Sensitive	.49	1.5	14
Thermal	.031	.093	.90
Thumbwheel	.18	.54	5.2
Toggle	.10	.30	2.9
Circuit Breaker, All	.68	1.4	18
CONNECTORS			
Circular	.0011	.0013	.018
PCB Card Edge	.044	.052	.73
Hexagonal	.16	.19	2.7
Rack and Panel	.023	.027	.38

Figure A4-1 Component Failure Rate by Environment

Rectangular	.050	.060	.84
RF Coaxial	.00045	.00053	.0075
Telephone	.0082	.0097	.14
IC Sockets (DIP< SIP< PGA)	.0035	.011	.063
CIRCUIT BOARDS			
Plated Through Hole Circuit Boards	.022	.045	.29
Surface Mount Tech. Circuit Boards	.0025	.37	42
SINGLE CONNECTIONS			
Hand Solder, w/o Wrapping	.0013	.0026	.014
Hand Solder, w/ Wrapping	7.0e-05	.00014	.00077
Crimp	.00026	.00052	.0029
Weld	1.5e-05	3.0e-05	.00017
Solderless Wrap	6.8e-06	1.4e-05	7.5e-05
Clip termination	.00012	.00024	.0013
Reflow Solder	6.9e-05	.00014	.00076
Spring Contact	.17	.34	1.9
Terminal Block	.062	.12	.68
METERS, PANEL			
DC Ammeter or Voltmeter	.09	.36	3.2
AC Ammeter or Voltmeter	.15	.61	5.4
Quartz Crystals	.032	.096	.51
Lamps, Incandescent, AC	3.9	7.8	16
Lamps, Incandescent, DC	13	26	51
ELECTRONIC FILTERS			
Ceramic-Ferrite	.022	.044	.20
Discrete LC Comp.	.12	.24	1.1
Discrete LC & Crystal Comp.	.27	.54	2.4
FUSES			
Fuses, All	.010	.020	.11

Figure A4-1continued

Component Failure Rate by Database

* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995

ITEM FAILURE RATE	NPRD-91 /10^6 hours	ITEM FAILURE RATE	NPRD-91 /10^6 hours
Absorber, Surge	0.021	Bearing, Spherical	3.978
Accelerometer	20.32 *	Bearing, Thrust	<251.400
Accelerometer	1.30 - 5.60	Belt, General	19.72 *
Accelerometer	20.32 *	Belt, Geared	<11.140
Accumulator, Hydraulic	38.260	Belt, Positive Drive	<2.955
Accumulator, Pneumatic	0.354	Belt, V-Belt	164.000
Actuator	28.620	Blower	0.307
Actuator	25.81 *	Blower	0.53 *
Actuator, Electrical	29.550	Blower, Centrifical	<0.221
Actuator, Hydraulic	44.530	Blower, Wheel	0.371
Actuator, Hydraulic,		Boiler, General	20.24 *
Linear	54.940	Bracket	<0.001
Actuator, Hydraulic,		Brake, Air (million miles)	3.34 *
Pnuematic	163.500	Brake, Electric	3.52 *
Actuator, Hydraulic,		Brake,	*
Rotary	87.930	Electromechanical	41.43
Actuator, Mechanical	25.810	Brake, Magnetic	176.000
Actuator, Mechanical,		Brake, Mechanical	138.600
Linear	41.730	Brush, Electrical	3.340
Actuator, Pnuematic,		Brush, Electrical	9.15 *
Linear	5.190	Bus, Connection	<0.011
Air Conditioner	508.20 *	Cable	0.627
Alarm	0.049	Cable	1.14 *
Antenna, Communication	6.66 *	Chiller, General	20.93 *
Arm, Power, Transmittal	62.320	Cam	24.400
Arrestor, Surge	2.70 *	Camera	261.200
Axle	7.830	Chain, Precision Timing	<8.860
Battery, Carbon Zinc	0.60 *	Circuit Breaker	3.150
Battery, Lead Acid	0.440	Circuit Breaker	1.79 *
Battery, Lead Acid	1.95 *	Circuit Breaker, Current	
Battery, Mercury	1.32 *	Trip	5.260
Battery, Rechargeable	5.360	Circuit Breaker, Voltage	
Bearing	3.111	Trip	25.030
Bearing, Ball	1.603	Circuit Breaker, Magnetic	903.000

Figure A4-2 Generic Component Failure Rate by Database

Component Failure Rate by Database			
* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995			
ITEM FAILURE RATE	NPRD-91 /10^6 hours	ITEM FAILURE RATE	NPRD-91 /10^6 hours
Bearing, Ball	1.64 *	Circuit Breaker, Thermal	2.110
Bearing, Roller	2.82 *	Circuit Breaker, Under	
Bearing, Sleeve	3.976	Voltage	1.855
Bearing, Sleeve	2.38 *	Circuit Card Assembly	335.900
Clamp	0.185	Clutch	5.01 *
Clamp	0.42 *	Clutch, Friction	103.500
Clutch	14.170	Clutch, Magnetic	4.070
Belt, Geared	<11.140	Coil	0.003
Belt, Positive Drive	<2.955	Coil, Bobbin	<0.001
Belt, V-Belt	164.000	Coil, Choke	0.001
Blower	0.307	Coil, Core	0.003
Blower	0.53 *	Coil, Fixed	0.027
Blower, Centrifical	<0.221	Compressor	67.830
Blower, Wheel	0.371	Compressor	16.09 *
Boiler, General	20.24 *	Condenser, General	13.88 *
Bracket	<0.001	Connector, Summary	0.655
Brake, Air (million miles)	3.34 *	Connector, Coaxial	0.173
Brake, Electric	3.52 *	Connector, Contact	0.004
Brake,	*	Connector, Plug	1.560
Electromechanical	41.43	Connector, Receptacle	7.960
Brake, Magnetic	176.000	Connector, Telephone	0.033
Brake, Mechanical	138.600	Cooler, General	25.34 *
Brush, Electrical	3.340	Cooler, Oil	384.400
Brush, Electrical	9.15 *	Cord, Electrical	2.330
Bus, Connection	<0.011	Counter, General	3.96 *
Cable	0.627	Counter/Timer	20.500
Cable	1.14 *	Coupling	8.800
Chiller, General	20.93 *	Coupling	5.54 *
Cam	24.400	Coupling, shaft	1.004
Camera	261.200	Crank	15.450
Chain, Precision Timing	<8.860	Crank, Shaft	17.22 *
Circuit Breaker	3.150	Detector, Fire	0.44 *
Circuit Breaker	1.79 *	Detector, Smoke	315.20 *
Circuit Breaker, Current		Diaphragm, General	5.16 *
Trip	5.260	Display, CRT	129.900
Circuit Breaker, Voltage		Display, Driver	0.528
Trip	25.030	Display, LED	0.055

Figure A4-2 continued

Component Failure Rate by Database			
* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995			
ITEM FAILURE RATE	**NPRD-91 /10^6 hours**	**ITEM FAILURE RATE**	**NPRD-91 /10^6 hours**
Circuit Breaker, Magnetic	903.000	Display, Liquid Crystal	<0.308
Circuit Breaker, Thermal	2.110	Drum	17.440
Circuit Breaker, Under		Duct	29.610
Voltage	1.855	Electrical Motor	11.310
Circuit Card Assembly	335.900	Electrical Motor	9.24 *
Clamp	0.185	Electrical Motor, AC	7.396
Clamp	0.42 *	Electrical Motor, DC	18.131
Clutch	14.170		
Electrical Motor,		Gauge, Strain	<38.500
Fractional HP, AC	7.550	Gauge, Tempereature	56.100
Electrical Motor,		Gear	5.670
Induction	<18.660	Gear	4.69 *
Electrical Motor, Stepper	1.410	Gear, Antirotation	526.300
Electrical Motor,		Gear, Assembly	36.50 *
Synchronous	8.680	Gear, Bevel	<1.470
Electrical Motor, Torque	0.048	Gear, Helical	2.600
Engine	168.000	Gear, Hypoid	5.000
Engine, Diesel	222.000	Gear, Spur	3.220
Engine, Turbine	12.000	Gear, Train	4.300
Fan	13.230	Gear, Worm	<3.830
Fan	11.96 *	Gear Set, Matched	<0.877
Fasteners	6.540	Gearshaft	0.620
Filter	7.480	Generator, General	72.98 *
Filter, Air	0.043	Generator, AC	84.700
Filter, Gas	7.020	Genreator, DC	114.800
Filter, Hydraulic	32.600	Generator, Gas	<0.853
Filter, Hydrualic, Fuel	156.500	Generator, Pulse	0.093
Filter, Pnuematic	8.330	Generator, Turbine	28.100
Fitting	8.390	Heat Exchangers	8.290
Fitting, Hydraulic	9.350	Heat Exchangers	8.08 *
Fitting, Quick		Heat Exchangers,	
Disconnect	10.470	Coldplates	11.025
Fuse	3.390	Heat Exchangers,	
Fuse	1.10 *	Radiation	8.320
Fuse, Spark Gap	3.150	Heat Exchangers,	
Fuse, Surge Arrestor	9.260	Radiator	7.883
Fuse, Terminal Link	3.800	Heater, Electrical	5.572

Figure A4-2 continued

Component Failure Rate by Database			
* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995			
ITEM FAILURE RATE	NPRD-91 /10^6 hours	ITEM FAILURE RATE	NPRD-91 /10^6 hours
Gasket	0.156	Heater, Electrical	5.21 *
Gasket	0.02 *	Heater, Gas	34.520
Gasket, Fiber	15.320	Heater, Oil	5.550
Gasket, Metal	0.574	Hose	12.900
Gasket, Rubber	0.431	Hose, Flexible	5.524
Gauge	66.500	Hose, Hydraulic	28.54 *
Gauge	44.82 *	Hose, Pnuematic	<251.383
Gauge, Fuel	79.300	Hose, Pressure	3.93 *
Gauge, Magnetic		Igniter	1.430
Sensing	88.200	Indicator, General	54.03 *
Gauge, Pressure	15.200	Indicator, Compass	148.500
Gauge, Rate of Flow	24.300	Indicator, Humidity	0.833
Insulator	<0.285	Printer, High Speed,	
Intercomm	44.300	Impact	65.300
Joystick	3.230	Printer, High Speed,	
Keyboard	21.920	Thermal	37.340
Lamp, Fiber Optic	0.207	Printer, Plotter	6.909
Lamp, Flash	20.480	Propeller	1478.500
Lamp, Incandescent	15.030	Pulley, Gear Belt	5.289
Lamp, Blub	126.300	Pulley, Grooved	4.032
Lamp, Neon	0.467	Pulley, V-Belt	12.609
Laser	49.353	Pump, General	43.65 *
Laser, Gas	8.716	Pump, Centrifugal	51.173
Laser, YAG	1366.000	Pump, Electric	134.400
Lens	12.850	Pump, Fuel	54.140
Light, Dome	6.700	Pump, Hydraulic	47.000
Magnet	0.007	Pump, Hydraulic, Piston	21.860
Meter, Ammeter	19.530	Pump, Oil	37.360
Meter, Ammeter	12.19 *	Pump, Pnuematic	41.800
Meter, Flow	24.79 *	Pump, Vacuum	62.800
Meter, Power	34.230	Recorder	18.480
Meter, Scale	2.290	Regulator	30.480
Meter, Time	10.450	Regulator	13.45 *
Meter, Voltmeter	18.380	Regulator, Electrical	42.130
Meter, Voltmeter	13.20 *	Regulator, Pnuematic	131.500
Monitor	118.260	Relay, Armature	2.370
Motor, Electric, General	2.17 *	Relay, Electomagnetic	15.770

Figure A4-2 continued

Component Failure Rate by Database			
* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995			
ITEM FAILURE RATE	**NPRD-91 /10^6 hours**	**ITEM FAILURE RATE**	**NPRD-91 /10^6 hours**
Motor Generator	19.72 *	Relay,	
Motor Generator Set	34.320	Electromechanical	33.150
Nozzle	717.900	Relay, Reed	0.786
Nut	0.434	Relay, Solenoid	20.600
Nut	0.57 *	Relay, Time Delay	3.400
Optical Encoder	20.000	Screw, General	13.96 *
Particle Separator	921.700	Seal, General	5.47 *
Pipe, Tail	1654.000	Seal, Boot	3.990
Pilot Tube	123.200	Seal, Magnetic	601.300
Power Supply	24.900	Seal, O-ring	5.160
Power Transmitter	14.700	Seal, Packing	1.187
Printed Circuit Board	0.011	Seal, Pressure	87.100
Printed Wiring Assembly	0.065	Seal, Solder	2.172
Printer, Dot Matrix	15.480	Seal, Static	<0.100
Printer, High Speed,		Seal, V-ring	<251.400
Electrostatic	506.000	Sensor, Altitude	3.39 *
Sensor, Hail	<0.590	Synchro, Resolver	9.707
Sensor, Light	4.216	Tank, Storage	1.616
Sensor, Pressure	1.72 *	Terminal Connection	0.271
Sensor, Temperature	0.107	Terminal Connection,	
Sensor, Temperature	1.83 *	Barrier Block	0.019
Sensor, Thermocouple	<0.010	Terminal Connection,	
Sensor, Torque	79.100	Lug	0.001
Sensor, Transmitter	37.260	Terminal Connection,	
Sensor, Water level	77.780	Stud	<0.001
Separator	312.100	Terminal Connection,	
Servo, General	6.98 *	Tab	<0.022
Servo, DC	7.970	Thermostat	25.300
Shaft, General	1.420	Timer, Electromechanical	148.500
Shaft, General	0.93 *	Transducer	11.120
Shock, Absorber	23.660	Transducer, Air Flow	32.950
Socket, IC	<0.002	Transducer, Temperature	41.100
Socket, Strip	0.010	Transmission	1102.000
Socket, Tube	<0.011	Tubing	2.217
Solar Cell	<3.260	Valve, Air	0.21 *
Solder Connection	<0.002	Valve, Fuel	12.341
Solenoid, General	2.970	Valve, Fuel	11.87 *

Figure A4-2 continued

Component Failure Rate by Database

* = Data is from the Reliability Toolkit: Commercial Practices Edition 1995

ITEM FAILURE RATE	NPRD-91 /10^6 hours	ITEM FAILURE RATE	NPRD-91 /10^6 hours
Solenoid, General	0.70 *	Valve, Hydraulic	8.440
Spring, General+A301	2.065	Valve, Hydraulic, Fuel	23.470
Spring, General+A301	0.61 *	Valve, Hydraulic, Mech.	
Sprinkler Head	0.619	Activated	22.140
Sprocket	3.880	Valve, Hydraulic, Servo	13.600
Starter, Engine	682.300	Valve, Hydraulic,	
Switch, Coaxial	1.065	Solenoid	23.860
Switch, DIP	0.128	Valve, Hydraulic, Spool	169.200
Switch, Float	50.820	Valve, Pnuematic	11.730
Switch, Flow	22.530	Valve, Pnuematic,	
Switch, Pressure	31.670	Bellows Diaphragm	9.765
Switch, Push Button	5.161	Valve, Relief	<15.675
Switch, Rocker	0.529	Valve, Water	7.900
Switch, Rotary	2.408	Washer, General	1.83 *
Switch, Thermal	8.986	Wire Wrap Connection	<0.001
Switch, Thermostatic	6.550		
Switch, Toggle	2.924		
Synchro, General	6.786		
Synchro, General	5.23 *		
Synchro, Differential	1.644		

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phone: 800-526-4802
web site: http://rac.iitri.org

Reference:

1. Seymour, M., B. Dudley, J. Caroll, and others. *Reliability Toolkit: Commercial Practices Edition.* Rome, New York: Reliability Analysis Center, 1996.

APPENDIX 5

MECHANICAL FAILURE MODES

Failure Mode Effects and Criticality Analysis (FMECA) begins by identifying failure modes for each equipment component, then assigning the probability of occurrence for each mode.

The decimal fractions are the proportion of all failures studied for each equipment component listed by failure mode. The sum of the fractions must total 1.00 for each equipment component.

A FMECA table needs to be adjusted in two ways when an equipment upgrade is implemented.

1. Adjust the failure rate to the improved level.
2. Re-proportion the failure mode distribution to represent the upgraded component.

The field data used to prepare the table in figure A5-1 was obtained from the Reliability Analysis Center (RAC) publication "Failure Mode/Mechanism Distributions."[1]

Reference:

1. Seymour, M., B. Dudley, J. Caroll, and others. *Reliability Toolkit: Commercial Practices Edition.* Rome, New York: Reliability Analysis Center, 1996.

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Mechanical Failure Modes

ITEM	FAILURE MODE	PROBABILITY (α)
Accumulator, Tank	Leaking	.47
	Seized	.23
	Worn	.20
	Contaminated	.10
Actuator	Spurious Position	.36
	Change	
	Binding	.27
	Leaking	.22
	Seized	.15
Alarm, Annunciator	False Indication	.48
	Failure to Operate	.29
	on Demand	
	Spurious Operation	.18
	Degraded Alarm	.05
Antenna	No Transmission	.54
	Signal Leakage	.21
	Spurious Transmission	.25
Battery, Lithium	Degraded Output	.78
	Startup Delay	.14
	Short	.06
	Open	.02
Battery, Lead Acid	Degraded Output	.70
	Short	.20
	Intermittent Output	.10
Battery, Rechargeable, Ni-Cd	Degraded Output	.72
	No Output	.28
Bearing	Binding/Sticking	.50
	Excessive Play	.43
	Contaminated	.07
Belt, General	Excessive Wear	.75
	Broken	.25
Blower Assembly	Bearing Failure	.45
	Sensor Failure	.16
	Blade Erosion	.15
	Out of Balance	.10
	Short Circuit	.07
	Switch Failure	.07
Brake	Excessive Wear	.56
	Leaking	.23
	Scored	.11
	Corroded	.05
	Loose	.05
Bushing	Excessive Wear	.85

Figure A5-1 Failure Mode Distributions

ITEM	FAILURE MODE	PROBABILITY (α)
	Loose	.11
	Cracked	.04
Cable	Short	.45
	Excessive Wear	.36
	Open	.19
Circuit Breaker	Opens Without	.51
	Stimuli	
	Does Not Open	.49
Clutch	Binding/Sticking	.56
	Slippage	.24
	No Movement	.20
Coil	Short	.42
	Open	.42
	Change in Value	.16
Connector/Connection	Open	.61
	Poor Contact/	.23
	Intermittent	
	Short	.16
Crystal, Quartz	Open	.89
	No Oscillation	.11
Diode, General	Short	.49
	Open	.36
	Parameter Change	.15
Electrical Motor, A.C.	Winding Failure	.31
	Bearing Failure	.28
	Fails to Run.	.23
	After Start	
	Fails to Start	.18
Fitting	Leaking	.90
	Contaminated	.05
	Scored	.05
Fuse	Fails to Open	.49
	Slow to Open	.43
	Premature Open	.08
Gasket/Seal	Leaking	1.00
Gear	Excessive Wear	.54
	Binding/Sticking	.46
Generator	Degraded Output	.60
	No Output	.22
	Fails to Run,	.09
	After Start	
	Loss of Control	.09
Hybrid Device	Open Circuit	.51
	Degraded Output	.26
	Short Circuit	.17
	No Output	.06
Keyboard Assembly	Spring Failure	.32

Figure A5-1 continued

ITEM	FAILURE MODE	PROBABILITY (α)
	Contact Failure	.30
	Connection Failure	.30
	Lock-up	.08
Lamp/Light	No Illumination	.67
	Loss of Illumination	.33
Liquid Crystal Display	Dim Rows	.39
	Blank Display	.22
	Flickering Rows	.20
	Missing Elements	.19
Mechanical Filter	Leaking	.67
	Clogged	.33
Meter	Faulty Indication	.51
	Unable to Adjust	.23
	Open	.14
	No Indication	.12
Microcircuit, Digital, Bipolar	Output Stuck High	.28
	Output Stuck Low	.28
	Input Open	.22
	Output Open	.22
Microcircuit, Digital, MOS	Input Open	.36
	Output Open	.36
	Supply Open	.12
	Output Stuck Low	.09
	Output Stuck High	.08
Microcircuit, Interface	Output Stuck Low	.58
	Output Open	.16
	Input Open	.16
	Supply Open	.10
Microcircuit, Linear	Improper Output	.77
	No Output	.23
Microcircuit, Memory, Bipolar	Slow Transfer of Data	.79
	Data Bit Loss	.21
Microcircuit, Memory, MOS	Data Bit Loss	.34
	Short	.26
	Open	.23
	Slow Transfer of Data	.17
Optoelectronic LED	Open	.70
	Short	.30
Optoelectronic+A198 Sensor	Open	.50
	Short	.50
Pnuematic Actuator	Spurious Closing	.54
	Spurious Opening	.46
Power Supply	No Output	.52
	Incorrect Output	.48
Printed Wiring Assembly	Open	.76
	Short	.24
Pump, Centrifigal	No Output	.67

Figure A5-1 continued

ITEM	FAILURE MODE	PROBABILITY (α)
	Degraded Output	.33
Pump, Hydraulic	Leaking	.82
	Improper Flow	.12
	No Flow	.06
Regulator	Stuck Closed	.23
	Stuck Open	.23
	No Output	.22
	Leaking	.22
	Insufficient Output	.10
Relay	Fails to Trip	.55
	Spurious Trip	.26
	Short	.19
Rotary Switch	Improper Output	.53
	Contact Failure	.47
Screw	Loose	.67
	Excessive Wear	.33
Sensor	Erratic Output	.59
	Short	.20
	Open	.12
	No Output	.10
Software	Design Changes	.46
	Design Errors	.41
	User Error	.07
	Documentaion Error	.06
Solenoid	Short	.52
	Slow Movement	.43
	Open	.05
Switch, Push-button	Open	.60
	Open Sticking	.33
	Short	.07
Switch, Thermal	Parameter Change	.63
	Open	.27
	No Control	.08
	Short	.02
Switch, Toggle	Open	.65
	Sticking	.19
	Short	.16
Synchro	Winding C178Failure	.45
	Bearing Failure	.33
	Brush Failure	.22
Transducer, Sensor	Out Of Tolerance	.68
	False Reponse	.15
	Open	.12
	Short	.05
Transformer	Open	.42
	Short	.42
	Parameter Change	.16

Figure A5-1 continued

ITEM	FAILURE MODE	PROBABILITY (α)
Transistor, Bipolar	Short	.73
	Open	.27
Transistor, FET	Short	.51
	Output Low	.22
	Parameter Change	.17
	Open	.05
	Output High	.05
Transistor, GaAs FET	Open	.61
	Short	.26
	Parameter Change	.13
Transistor, RF	Parameter Change	.50
	Short	.40
	Open	.10
Tube, Electron	Change in Parameter	.53
	Open	.25
	Unstable Output	.15
	Short	.07
Tube, Traveling Wave	Reduced Output	.71
	Power	
	High Helix Current	.11
	Gun Failure	.09
	Open Helix	.09
Valve, Hydraulic	Leaking	.77
	Stuck Closed	.12
	Stuck Open	.11
Valve, Pnuematic	Leaking	.28
	Stuck Open	.20
	Stuck Closed	.20
	Spurious Opening	.16
	Spurious Closing	.16
Valve, Relief	Premature Open	.77
	Leaking	.23

Figure A5-1 continued

APPENDIX 6

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

This appendix discusses Failure Mode Effects and Criticality Analysis (FMECA), an analysis tool that can be used to prioritize different categories of failures, such as defects and downtime. As an example, it specifically addresses Failure Rate on an equipment system. Refer to section 7.6 for background information on the equipment system and reliability.

Assume that the metering bin failure rate is 0.0700 for this FMECA example. This example focuses on two of the five elements of the equipment system: the delivery pump and the metering bin. These two items were previously determined to have the largest impact on the system Mean Time Between Failures (MTBF).

A full FMECA would address every element. It would provide a summary report that combined all information in a criticality table, sorted by highest criticality number. This example combines and sorts only the two elements.

The first step is to list the equipment and carefully identify its function on the FMECA table. For our example, the two functions can be stated as follows.

Delivery Pump. Its function is to suction uniformly-mixed fruit and dough from the mixing tank, then supply the dedicated donut cutters with undamaged material at a pressure of 1 psi, a temperature of less than 90º F, and a rate of 60 standard-sized donuts per minute.

Metering Bin. Its function is, by using a gravity feed system, to continuously supply uniformly-sized dried fruit chunks or nuts to the mixing tank at a volume of 1/8 cup per standard-sized donut and a rate of 60 standard-sized donuts per minute.

At this time, also identify the specific failure rate of each item (e.g., 0.0333 failures per hour for the pump and 0.0700 failures per hour for the metering bin).

Next, set up a table for each element with the following seven columns: Failure Mode, % (of failure mode), Cause, Effect, Severity Number, Criticality Number, and Possible Actions.

1. List the various categories of Failure Mode in column 1.
2. Using historical data or industry standard data, distribute the relative percent of failures to the various Failure Modes. The numbers in column 2 should total 100 percent. (Appendix 5 lists failure modes for various components.)
3. In column 3, list the various causes for each failure mode.
4. For each cause, note the effect or consequence of that kind of failure.
5. For each effect, assign a severity number. You may use an arbitrary scale, but be consistent for all combined FMECA tables. Choose a scale that is applied throughout the plant in order to increase its use and understanding across all departments. For this example, use a scale of 0 to 100, with 100 representing a total factory shutdown, possible illness, or law suit. The 70-to-80 range would represent a half-shutdown of the factory, and 15-to-35 range various quality and waste events. Note: This scale is an important parameter. It must be agreed upon by the plant leadership team so that final results are consistent and focus is on the biggest concerns.
6. Compute the criticality number by finding the product of the failure rate, the failure mode percent, and the severity number.
7. List the possible actions—tasks you can implement to eliminate the cause or detect eminent failure in order to mitigate the situation.

Figures A6-1 and A6-2 provide the FMECA tables for the pump and metering bin respectively.

Generate a summary table by combining all the individual FMECA tables into a master table, then sorting the criticality number in descending order. For this example, only the top nine criticality numbers are listed in the summary table (figure A6-3).

The items with the greatest opportunity for improvement are listed first. In this specific example, the delivery pump items rank toward the top primarily because the delivery pump failures usually shut down portions of the factory.

Assume the leadership team chose not to shut down the factory when the metering bin failed, perhaps because all donuts could be sold, even if at discounted prices. This decision is primarily a business-driven one.

Table 1. **Pump**. The function is to suction uniformly mixed fruit and dough from the mixing tank and supply the dedicated donut cutters with undamaged material at a pressure of 1 psi, a temperature of < 90ºF and a rate of 60 standard size donuts per minute.

PUMP Failure Rate = .0333 **Criticality number** = Failure Rate x Failure mode % x Severity number.

FAILURE MODE	%	CAUSE	EFFECT	SEV	CRIT	POSSIBLE ACTION
Fails to pump	80	No power	½ Factory down + quality problem. Reset breaker	70	1.8648	Requires consistent mixture and correct pump horsepower and circuit design.
		Broken	½ Factory down + quality problem. Longer downtime	80	2.1312	Consider redundant pump system or on site quick exchange module.
		Blocked	½ Factory down + quality problem. Find/Remove blockage or bridging	75	1.9980	Provide special clean out tools and configure system with easy access ports upstream and downstream.
Pump rate is out of spec.	12	Controller Fails low	Too little (Donuts Out Of Spec. DOOS <)	30	.1199	Provide on-line SPC monitoring and manual control capability.
		Controller Fails high	DOOS > Too much material to the ovens. Causes flooding and major mess. Factory down	100	.3996	Provide pressure relief divert valve just prior to donut cutters as well as on-line SPC monitoring and manual control capability.
		Pump loses capacity	DOOS < – Donuts too small. Stop and rebuild pump to initial conditions. ½ Factory down.	75	.2997	Consider redundant pump system or on site quick exchange module.
Pump damages mixture	8	Gets too hot	Carbon specs in donuts, poor taste, quality problem	35	.0932	Consider thermal alarm on pump
		Contamination	Food violation, possible lawsuit	100	.2664	Specify sanitary system pump designed without seals
		Mashes or cuts fruit	Quality problem	20	.0533	Consider designed experiment testing prior to pump selection to eliminate this concern

Figure A6-1 FMECA Table: Delivery Pump

Table 2. **Metering Bin**. The function is to continuously supply uniformly sized dried fruit chunks to the mixing tank at a volume of 1/8 cup per standard sized donut and a rate of 60 donuts per minute using a gravity feed system.

METERING BIN Failure Rate = .0700 **Criticality number** = Failure Rate x Failure mode % x Severity number.

FAILURE MODE	%	CAUSE	EFFECT	SEV	CRIT	POSSIBLE ACTION
No Metering	55	Bridging or Blocked Broken	No fruit in donuts (DOOS<) quality problem DOOS< – cover tank fix problem quality problem.	25 30	.9625 1.1550	Consider mixer agitator to prevent bridging and blocking Consider modular equipment parts for quick replacement and quality monitoring alarms.
Meters too little	38	Speed fails slow Material stuck in metering cup	Quality problem too little fruit Quality problem too little fruit DOOS < both cases	20 20	.5320 .5320	Consider SPC alarm on equipment speed Provide positive displacement of cup material or alarm weight of empty cup
Meters too much	6	Speed fails fast	Waste problem DOOS > customers happy?	15	.0630	Consider SPC alarm on equipment speed
Mixture Damaged	1	Contamination	Metal in donuts law suit?	100	.0700	Consider collector guard under bin or offset location so moving parts are not over tank.

Figure A6-2 FMECA Table: Metering Bin

Summary Table This table combines the FMECA tables and sorts the rows by criticality number. The top 9 items are displayed with this table. A complete summary table would include all items.

FAILURE MODE	%	CAUSE	EFFECT	SEV	**CRIT**	POSSIBLE ACTION
Fails to pump	80	Broken	½ Factory down + quality problem. Longer downtime	80	**2.1312**	Consider redundant pump system or on site quick exchange module.
Fails to pump	80	Blocked	½ Factory down + quality problem. Find/Remove blockage or bridging	75	**1.9980**	Provide special clean out tools and configure system with easy access ports upstream and downstream.
Fails to pump	80	No power	½ Factory down + quality problem. Reset breaker	70	**1.8648**	Requires consistent mixture and correct pump horsepower and circuit design.
No Metering	55	Broken	DOOS< – cover tank fix problem quality problem.	30	**1.1550**	Consider modular equipment parts for quick replacement and quality monitoring alarms.
No Metering	55	Bridging or Blocked	No fruit in donuts (DOOS<) quality problem	25	**.9625**	Consider mixer agitator to prevent bridging and blocking
Meters too little	38	Speed fails slow	Quality problem too little fruit	20	**.5320**	Consider SPC alarm on equipment speed
Meters too little	38	Material stuck in metering cup	Quality problem too little fruit DOOS < both cases	20	**.5320**	Provide positive displacement of cup material or alarm weight of empty cup
Pump rate is out of spec.	12	Controller Fails high	DOOS > Too much material to the ovens. Causes flooding and major mess. Factory down	100	**.3996**	Provide pressure relief divert valve just prior to donut cutters as well as on-line SPC monitoring and manual control capability.
Pump rate is out of spec.	12	Pump loses capacity	DOOS < – Donuts too small. Stop and rebuild pump to initial conditions. ½ Factory down.	75	**.2997**	Consider redundant pump system or on site quick exchange module.

Figure A6-3 FMECA: Summary Table

The summary and individual tables help prioritize resources and targets for new and existing systems. Whenever modifications or changes in operating procedures are considered, the tables can be easily updated and re-sorted for criticality. For instance, you could easily reassign new severity numbers to the metering bin failures if agreement was reached to stop the process whenever failure occurred. The revised summary would probably show a different set of top priorities.

APPENDIX 7

PARETO CHARTS

When you construct Pareto charts from a data sheet, you start by sorting the data, then converting it into relative percentages of that data parameter's total. The data sheet in figure A7-1 comes from T. Ouvreloeil's article[1] "Pareto For Reliability Engineering." You can use it to practice constructing Pareto charts with the method that follows. After one or two charts, you will be able to construct presentation-ready charts very easily and quickly.

The steps are written for use with Microsoft Excel 97 Chart Wizard®. You will need to modify these steps as necessary for other spreadsheet programs.

First, copy the pulp mill data from figure A7-1 into an Excel® spreadsheet. Then, select the data column for the Pareto chart and highlight only the data numbers—including the total value. For this example, analyze the data for Number of Corrective Work Orders by Manufacturing Area.

1. In the column titled "Number of Corrective Work Orders," high light the numbers 6 through 519, and click on copy.
2. Copy this column of numbers to column A of a new spreadsheet (sheet #2 of the current Excel file) beginning at cell A3
3. Go back to the original spreadsheet, highlight the names in the "Manufacturing Area" column, from Refiner Pulp Mill through Shower Fabric.
4. Copy this column of names to column B of spreadsheet #2, starting at cell B3. Resize column B as necessary to show the full name of the manufacturing area.

5. On spreadsheet #2, highlight columns A and B, from row 3 down to the end of the manufacturing area names. Do not include the row with the total of 519.
6. Click on Data in the menu bar and select sort. This brings up a sort options table.
7. From the sort options table, select 'My list has no header row' and then chose column A as the sort parameter. Then select the option to sort in descending values. Click OK. This step will rank the data from top to bottom so that the equipment with the greatest number of corrective work orders, in this case Analyzer TRS, will be listed first.

Next, develop the relative percentages of work orders for each manufacturing area. This is done by dividing each data value by the data total, which in this example, is 519 and is located in cell A18. This location will vary when you complete other charts.

8. Click on cell C3, the third cell in column C on a data row.
9. Type the formula: = A3/A18 and click enter. A decimal value

Area No.	Equipment Description	Number of Corrective Work Orders	Maintenance Cost Dollars
1	Refiner Pulp Mill	6	45495
2	Chemi-Washer Black Clawson	25	31647
3	Kiln Line	67	917850
4	Digester Kamyr 1	101	50696
5	Digester Kamyr 2	32	40271
6	Pump Makeup Liquor	4	25123
7	Analyzer TRS	131	13425
8	Analyzer Liquor	53	7172
9	Analyzer Alkali	37	4511
10	Honeywell TDC	7	84759
11	Filter Precoat	9	25123
12	Filter Ecofilter	5	31109
13	Feeder High Pressure	2	24078
14	Doctor Roll	17	2134
15	Shower Fabric	23	2628
	TOTAL	519	1306021

Figure A7-1 Pulp Mill Data Sheet

will show in cell C3. The $ sign in front of A and 18 in this formula hold the cell location A18 constant, which in this case is the cell with the total, when you copy the formula.

10. Select cell C3 again. Then click on the percent sign in the formatting toolbar area to change the decimal value to a whole percentage. (Go to View, select toolbars and make the formatting toolbar active if the % symbol isn't already on your computer screen).
11. With cell C3 selected and showing the percent value, copy the cell. Then highlight the rest of column C adjacent to equipment names. Click on paste. This computes the relative percent of work orders for each manufacturing area into column C.

The next major step is to generate information on the accumulated percent in the column adjacent to the percent value

12. After selecting cell D3, type: = C3 and click enter.
13. With cell D4 selected, type the formula: = D3 + C4.and click enter. This step adds the percentage value of the cell above and the percentage value of the cell to the left into the selected cell.
14. Select cell D4 and click copy. Highlight the remaining cells in column D (cells D5 through D17) adjacent to data in column C. Then, click on paste. The last cell in column D should equal 100%. This step completes the information you need for the Pareto chart. The completed version of spreadsheet #2 appears in figure A7-2. You can go to cell A1 and type in the title: Pareto chart data for Corrective Work Orders

With this second spreadsheet complete, you can now construct a Pareto chart by selecting the chart wizard from the standard toolbar. (Go to View, select Toolbars and make the Standard Toolbar active if the chart wizard symbol isn't already on your computer screen).

15. Highlight the names in column B and the percentage information in columns C and D. This area would be cells B3 to D17. Then select the chart wizard from the standard toolbar menu. This program will help guide you through four steps.
16. In step one of the chart wizard, select Custom Types tab. Scroll down, select the line-column type of chart, and click Next. On the

131	Analyzer TRS	25%	25%
101	Digester Kamyr 1	19%	45%
67	Kiln Line	13%	58%
53	Analyzer Liquor	10%	68%
37	Analyzer Alkali	7%	75%
32	Digester Kamyr 2	6%	81%
25	Chemi-Washer Black Clawson	5%	86%
23	Shower Fabric	4%	90%
17	Doctor Roll	3%	94%
9	Filter Precoat	2%	95%
7	Honeywell TDC	1%	97%
6	Refiner Pulp Mill	1%	98%
5	Filter Ecofilter	1%	99%
4	Pump Makeup Liquor	1%	100%
2	Feeder High Pressure	0%	100%
519			

Figure A7-2 Sample Pareto Chart Input Spreadsheet

second step page of the chart wizard, confirm the series is columns is selected and click Next.

17. On the third step page, choose the Titles option. Click inside the Chart title box. Type your chart's title, such as "Pareto of Corrective Work Orders by Manufacturing Area."
18. Click inside the box labeled Category (X) axis. Enter a title for the information from column B, such as "Manufacturing Areas."
19. Click inside the box labeled Value (Y) axis. Enter the title for the first set of Y values, such as "Relative % of Work Orders."
20. Click inside the box labeled Second value (Y) axis. Enter the title for the second set of Y values, such as "Accumulated %."
21. On the chart wizard, select the Gridlines tab. Select to show Major gridlines for both the *x*- and *y*- axes.
22. On the chart wizard, select the Data Table tab, then click on Show data table and show legend keys. Now click Next to move to the next step.
23. On the fourth step page of the chart wizard, select the option to show the chart as a new sheet. Then click Finish. This will make the chart appear on a new sheet of the Excel spreadsheet labeled Chart 1.

You now have a completed Pareto chart. On the standard toolbar, resize the chart to 100 percent.

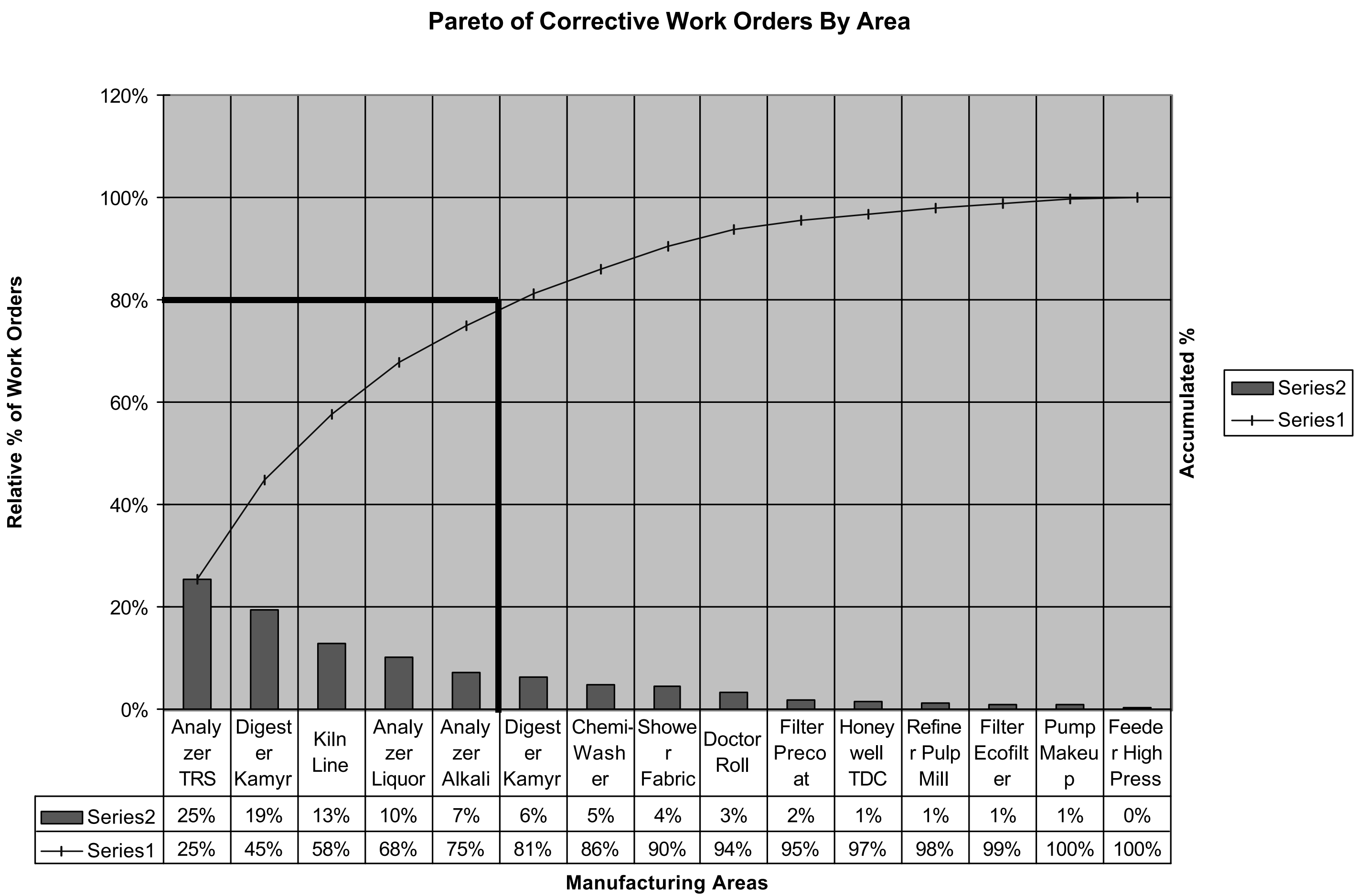
Next, enhance the information you want to display by placing a border around the accumulated 80 percent data points. This is done using the following steps.

24. If the Drawing toolbar is not already visible, select View on the menu bar, then Toolbars, and then Drawing and click it.
25. In the Drawing toolbar menu, click on the Line icon, located to the left of the arrow icon. Place the cursor, which is now a crosshair, on the 80% value of the y-axis.
26. Pressing and holding the left button of your mouse, drag the crosshair horizontally to the right until the data points representing the accumulated percent are above the 80% value line. Then move the cursor left, back to the closest vertical gridline. Release the left button. The line will overlay the 80% gridline and be bounded by a small box on each end.
27. Place the cursor on the new horizontal line until it turns into crossed arrows. Press the right mouse button to display an options menu. Click on Format AutoShape, then select the Colors and Lines tab.
28. Click on the line-style dropdown menu arrow and select the 3 pt line. Then click OK. You have now created the horizontal part of the border.

Now follow similar steps to create the vertical border.

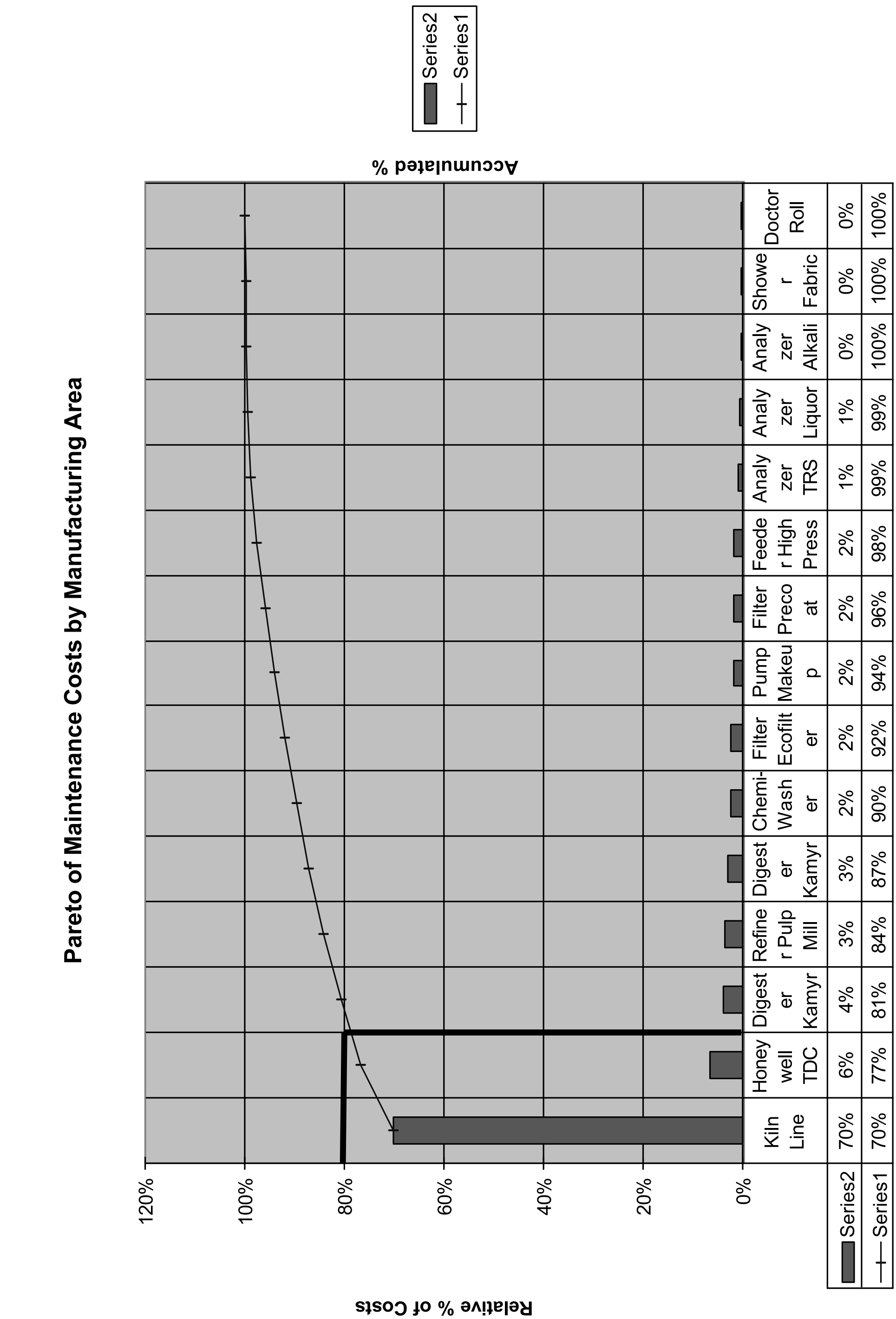
29. Choose the Line option from the Drawing toolbar. Place the crosshair at the right end of your new 3 pt line. You should also be on a major vertical gridline. Pressing and holding the left button, drag the crosshair down the gridline to the x-axis. Release the left button. Your line should overlay the vertical gridline and be bounded by a small box at each end.
30. Repeat steps 27 and 28 so that you have a vertical line.

You have now constructed a Pareto chart of the corrective work orders by manufacturing area. Save the chart as a separate sheet for printing and presentation. A copy appears in figure A7-3. You may wish to abbreviate the manufacturing area names so that the chart format is clean-



	Analyzer TRS	Digester Kamyr	Kiln Line	Analyzer Liquor	Analyzer Alkali	Digester Kamyr	Chemi-Washer	Shower Fabric	Doctor Roll	Filter Precoat	Honeywell TDC	Refiner Pulp Mill	Filter Ecofilter	Pump Makeup	Feeder High Press
Series2	25%	19%	13%	10%	7%	6%	5%	4%	3%	2%	1%	1%	1%	1%	0%
Series1	25%	45%	58%	68%	75%	81%	86%	90%	94%	95%	97%	98%	99%	100%	100%

Figure A7-3 Pareto Chart of Corrective Work Orders By Manufacturing Area



	Kiln Line	Honeywell TDC	Digester Kamyr	Refiner Pulp Mill	Digester Kamyr	Chemi-Washer	Filter Ecofilter	Pump Makeup	Filter Precoat	Feeder High Press	Analyzer TRS	Analyzer Liquor	Analyzer Alkali	Shower Fabric	Doctor Roll
Series2	70%	6%	4%	3%	3%	2%	2%	2%	2%	2%	1%	1%	0%	0%	0%
Series1	70%	77%	81%	84%	87%	90%	92%	94%	96%	98%	99%	99%	100%	100%	100%

Figure A7-4 Pareto Chart of Maintenance Costs by Manufacturing Area er. Going to the Pareto chart data sheet (figure A7-2) and changing the manufacturing area names does this.

In this example, the five left manufacturing areas make up 80% of the work orders identified in the original data table. They are listed in descending order of significance for this parameter.

Now that you have learned to construct a Pareto chart, go back to the original spreadsheet and construct a second chart using the data for maintenance costs.

The completed chart appears in figure A7-4. With very little practice, Pareto charts can be made easily and quickly (in less than ten minutes).

Using the information from these two charts, a Pareto analysis would rank the Kiln Line as a priority target because it appears in the 80 percent box in both Pareto charts.

Reference:

1. Ouvreloeil, Tita. "Pareto for Reliability Engineering." *Maintenance Technology,* Volume 14, No. 5 (May 2001): pages 26-28.

Appendix 8

Preserving Failure Data

I first found this important root cause failure analysis article on the web at www.maintenancerecourses.com. Parts of this article are reprinted by permission of the Reliability Center at www.Reliability.com and by Reliability, magazine where the original article is published in the November 1994 issue.

Scott Broussard, a reliability engineer, encourages everyone to "Become An Equipment Reliability Detective Preserve Failure Data"[1] in order to successfully solve root cause failure problems.

It is amazing how quickly failure data can disappear after a sporadic failure has occurred. Following such an incident there is sometimes a lot of confusion…. All everyone knows is, "We better get this process or piece of equipment back on line." This paradigm drives the operations, maintenance and technical people at the failure scene. Oftentimes in the chaotic activities that follow, a wealth of failure data can be destroyed or altered. Failed parts are marred, discarded or taken to a shop and forgotten; lubrications and other fluids are mopped up; valve and instrument positions are changed in preparation for startup; distributive control systems start to average live data; shifts change and operation and maintenance personnel are replaced with people who were not present at the time of failure. Along with the disappearance of all this data, go the chances of uncovering the true root causes of the incident.

I often ask …."Would you expect a homicide detective to be able to solve a murder without any clues?" …. Drawing the parallel between being a homicide detective and a failure analyst is an effective analogy. Consider that the investigating officer's sole responsibility at the scene of a homicide is to "FREEZE" the scene and collect as much data as possible for later analysis. How does he or she "FREEZE" the scene? They:

- ❑ Take photographs of everything before anything is disturbed.
- ❑ Bag and tag any items which may yield information (murder weapon, hair, clothing, fibers, etc).
- ❑ Dust for fingerprints.
- ❑ Interview people (neighbors, friends, colleagues, etc.).
- ❑ Map the position of the body relative to its surroundings.
- ❑ Review available documents.

As failure analysts we can learn a lot from homicide detectives. When a failure occurs, we should treat it as if a homicide has occurred and develop the appropriate strategies to "PRESERVE THE FAILURE DATA." If the failure analyst is to be successful, he or she must collect data from each of the 5 P's which are simply memory joggers that stand for:

- ❑ **PARTS**
- ❑ **POSITION**
- ❑ **PAPER**
- ❑ **PEOPLE**
- ❑ **PARADIGMS**

Failure data from each of these categories must be collected to ensure a successful Root Cause Failure Investigation. Let's briefly review each classification.

PART: Any failed components such as bearings, seals, shafts, valves, nozzles, lubricants, chemicals from spills, and gases from leaks.

POSITION: Where were things at the time of failure? Was the valve open or closed? What are the instrument's settings? Position of parts?

PAPER: Operating conditions prior to, during, and after the incident (temperatures, pressures, levels, etc.), vibration monitoring results, equipment histories, operating procedures, manufacturing procedures and equipment specifications.

PEOPLE: Who was there, where were they, and what did they see, hear, feel or smell prior to, during, and after the incident? Was anything unusual being done around the time of failure? What was their perception of the sequence of events?

PARADIGMS: What are the cultural norms of the organization? What do people accept as a way of doing business, such as communication between units or shifts? What repetitive remarks were made during the interview that indicate beliefs, values or deep-seated convictions?

Data needs to be collected from each of the five P's as quickly as possible following the failure. Obviously, the principle failure analyst cannot be at the manufacturing facility 24 hours a day; therefore, provisions have to be made to train several people on each shift to be failure data collectors. These people should function much like the fire brigade at a plant. Each member is assigned a certain task, and when called into action should perform that task until the failure analyst or analysts can arrive and direct the effort in more detail.

Getting to the failure data before it becomes corrupted is a key to effective Root Cause Failure Analysis. In addition, there is a definitive pecking order for collecting the 5 P's because some data is more fragile than others. The most fragile data (data that becomes distorted and easiest) are **Position** and **People** data. The fact that **Position** data is fragile makes sense to most people. In order to "FREEZE" the failure scene, I often suggest to students that the failure response team be equipped with brightly colored boundary tape so that they can "rope off" the area, and a video camera to make a photographic account of the scene. (Note: Use the video camera only after the area is cleared of flammable materials.) This photographic data can be invaluable as the failure analyst tries to understand what caused the failure.

The fact that **People** data is extremely fragile often surprises would-be investigators. Due to this perception, valuable failure data is lost. The problem is that as time passes following an incident, the raw sensory data that was taken in by people who were at or around the failure scene starts to become distorted. People start to evaluate what they heard, saw, smelled or felt and draw conclusions based upon this input. If something they sensed doesn't fit their mental models of what the scene should contain, they may discount it and only inform the failure analysts of their conclusions about what happened as opposed to providing the failure analysts with the raw data. It is imperative that the people who were at the scene be debriefed prior to their leaving the facility. At the very least, they should fill out a generic failure data collection sheet documenting what they sensed at the time of failure and anything unusual that was being done at the time of the incident. Preferably, each person should spend 15-20 minutes being debriefed by a failure analyst. This provides the failure analyst with much more meaningful data because he gathers it firsthand.

Following **Position** and **People,** Parts should be bagged and tagged and taken to a secured area for later analysis. **Paper** data (which includes electronic data which might be distorted or disappear) such as Distributive Control System data, should be gathered and stored for later review. Finally, **Paradigm** data is the least fragile of the 5 P's. The fact of the matter is that they are deeply ingrained within the organization… Paradigms are uncovered as people are interviewed and later through interaction with the failure analysis team. Failure analysts should always be on the lookout for restraining paradigms that may have contributed to the failure. These restraining paradigms are considered latent root causes.

Doing a good job of "PRESERVING FAILURE DATA" is a key step in conducting Root Cause Failure Analysis. Unfortunately, it is also the step that is usually second in priority to getting the process or the piece of equipment back on line as quickly as possible. There is no better way to avoid future incidents than to learn from past mistakes. That is why Root Cause Failure Analysis is such a powerful tool. However, effective Root Cause Failure Analysis cannot be conducted without DATA, and to get the DATA manufacturing facilities must do a good job of PRESERVING it.

Reference:

1. Broussard, S., "Become An Equipment Reliability Detective Preserve Failure Data", Reliability magazine, *Industrial Communications, Inc.*, Knoxville, TN. November/December 1994.

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