ENABLING PROCESS IMPROVEMENTS THROUGH VISUAL PERFORMANCE INDICATORS

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Submitted to the Sloan School of Management and the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degrees of

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ABSTRACT

Most modern production processes automatically generate volumes of rich data, including equipment states, material presentations, labor content, and quality non-conformances. Unfortunately, much of this data is either discarded immediately, or stored in its raw form in disparate data sources for subsequent review or reporting. Accessing the data in these systems often requires time-consuming transformations, filtering for relevancy and substantial latency, rendering the potential wealth of information useless to daily decision-makers on the factory floor. Without such information, individuals on the floor rely on heuristics, experience, and intuition to inform their decisions, often resulting in inefficiency and suboptimal solutions.

This work explores the idea that decision-making can be improved through the automated transformation of data into information for real-time display on the factory floor. This thesis reviews the technology infrastructure components, evaluation metrics and presentation displays deployed at Raytheon Company that can not only characterize a current process, but also suggest opportunities for process improvement. Case studies illustrate the identification of a process issue, the investigation of root causes and improvement alternatives, and the evaluation of change efforts, all using visual performance indicators.

Work for this thesis resulted in several interactive dashboards in the Microwave area that characterize the production process in terms of schedule, cost, and quality compliance, with additional tools to investigate non-conforming processes. The tools were first leveraged to improve line coordination and reduce process times for the radar sub-assembly process, resulting in a 50% increase in throughput, 70% reduction in throughput variation, and a cost savings of over 600 hours per radar for the targeted processes. More importantly, the technological and cultural foundations for continual process evaluation and improvement were laid, which have the potential to yield far greater improvements in the future.

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1 Introduction

This thesis explores the hypothesis that decision-making in a production environment can be improved through the automated transformation of data into information for real-time display. This work explores the technological, process, and cultural challenges and changes that accompany performance measurement and improvement programs. Case studies are presented for several change initiatives launched with performance dashboards at Raytheon's Integrated Air Defense Center in Andover, MA from June 2004 to December 2004.

1.1 Burning platform for change

Most significant change efforts at Raytheon are conducted within the framework of the Raytheon Six Sigma program by first identifying a burning platform for change. Taken from the oil industry, the analogy compares critical organizational or operational issues to an oil rig fire where the issue is obvious and the need for change is imperative. The burning platform for this thesis was found in the radar subassembly area. The line had experienced dramatic variation both in daily throughput rates and processing time, contributing to uncoordinated, unpredictable and higher-cost production. Further, the high cost of data collection and the time delay in information processing masked many of these issues, making corrective action and monitoring difficult to implement. When faced with a program objective to achieve 10% cost reductions for each of the next three radars, the need for improved information management and process improvement tools became obvious and imperative, and a burning platform was identified.

1.2 Thesis organization

Chapter 1 introduces the concepts of data transformation, real-time presentation, and informed decision-making which were used to address Raytheon's production challenges, and then summarizes the remaining chapters.

We next review the background information on Raytheon, the IADC facility, and the microwave product line in Chapter 2. The chapter continues setting the stage with a summary of the Raytheon Six Sigma framework for change initiatives and the work done by previous LFM interns which spawned this project.

Chapter 3 discusses the role of information in a manufacturing environment as a prerequisite to any performance measurement or improvement program. The chapter begins with a review of the different data sources at Raytheon, continues with a review of the characteristics used to evaluate the quality of information, and concludes with a discussion of the information system architectures deployed at Raytheon. A key observation is that a reliable and responsive data warehouse foundation must be laid before any metrics or display systems can be developed.

With a proper data storage solution in place, Chapter 4 discusses the use of manufacturing information in assembling performance management systems. The chapter begins with a literature review of performance metrics programs in academia, industry, and within Raytheon itself. Various metrics for schedule, cost, and quality are discussed, along with the use of metrics for production planning and other non-measurement purposes. The key take-away is to first understand the goals and objectives of the firm or production area, and then design measurement systems which align resources and track progress towards those goals.

Chapter 5 focuses on the visual presentation of the performance metrics which were identified in the previous chapter. The chapter reviews display systems in use in various industries, and continues with a review of the metrics development and deployment environment selected for Raytheon. Examples of several dashboards developed for measurement and process investigation are provided, with suggestions for how to optimize both the density and clarity of information conveyed.

The ideas presented in the previous chapters are tested in Chapter 6 with several case studies conducted at Raytheon. The improvement process used at Raytheon is described, along with tangible results for several improvement efforts aimed at increased throughput, reduced throughput variation, and reduced process time.

Chapter 7 shifts focus slightly to discuss some of the softer issues in performance improvement efforts. The Microwave area is analyzed through the strategic, political, and cultural lenses to explore how the organizational norms and behaviors influence the performance measurement and improvement process. One of the key takeaways is that personal and organizational dynamics require an equal or greater emphasis to the technical requirements of a performance measurement and change management program.

Chapter 8 summarizes the key results of the internship, lessons learned, and provides recommendations for Raytheon as it explores a larger performance measurement deployment. The real-time displays were used to identify and improve several inefficiencies, resulting in a 50% increase in throughput, 70% reduction in throughput variation, and a cost savings of over 600 hours per radar. More importantly, the technological and cultural foundations for continual process evaluation and improvement were laid, which have the potential to yield far greater improvements in the future.

2 Raytheon Background

In this chapter, we first review Raytheon's organizational structure, and then discuss the value stream that is the context for this project. The Raytheon Six Sigma program which provides the project framework is reviewed next. Finally, previous work in prior LFM internships and their contributions in identifying this project need are summarized.

2.1 Organizational Context

Raytheon Company was founded in 1922 in Cambridge, MA to produce refrigerators, radios, and other household appliances.[1] With its significant contributions to the magnetron tube in World War II, Raytheon quickly transitioned to the design and manufacture of defense technologies which today account for the majority of the company's $18 billion in annual revenue. In 2003 the company had over 77,000 employees in its seven divisions.[2]

One of Raytheon's seven divisions, The Integrated Defense Systems' (IDS) mission is to be the premier global Mission Systems Integrator, creating partnerships to provide whole-life defense solutions for its customers. IDS employs 12,000 people in 18 locations and accounted for $2.9 billion in 2003 revenue.

A part of IDS, the Integrated Air Defense Center (IADC) is a 1.2M square foot facility in Andover, MA which was built in the 1970s to serve as the primary manufacturing center for the Patriot Missile System. While considerable Patriot operations still exist, the IADC has expanded to include support for additional IDS product lines, including Cobra Judy, DD(X), AEGIS, and the Ballistic Missile Defense Systems (BMDS, THAAD, XBR). The IADC employs over 3400 people, both union and non-union, across virtually all functional groups within Raytheon.

2.2 Microwave Value Stream

In November 2002, the IADC reorganized its operations around the customer into value streams.[3] Each value stream includes design engineers, supply chain specialists, production operators, and process engineers that team together for improved customer responsiveness.

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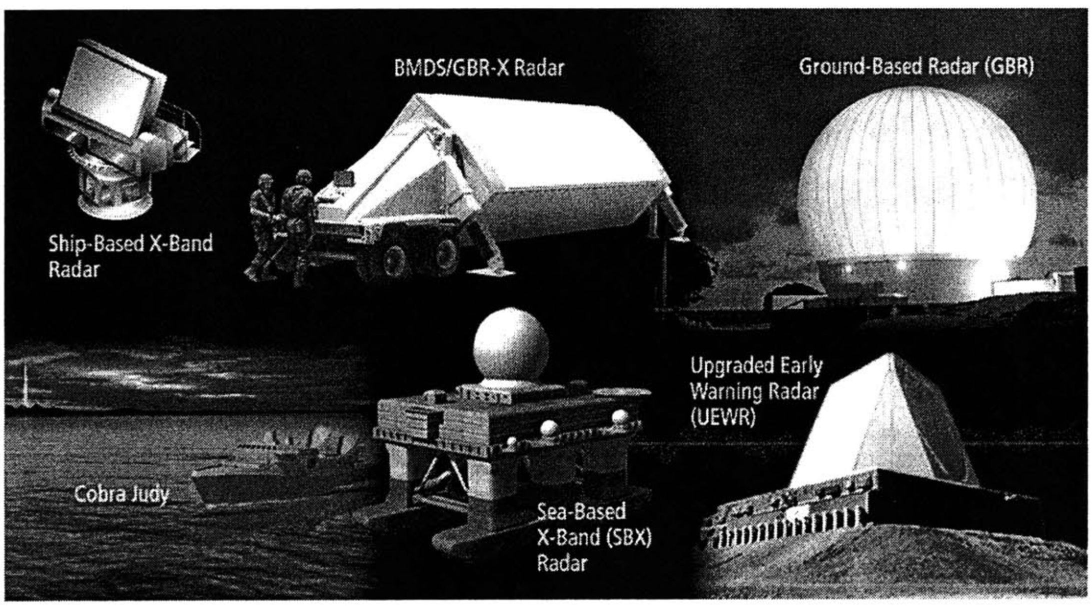
[1] www.raytheon.com
[2] Raytheon Company 2003 Annual Report
[3] Shoot for the Moon - The Manufacturer, July 2002 Vol 2 Issue 7

The microwave value stream manufactures high-volume subassemblies for the phased array radars in the ballistic missile defense products. Each radar system contains roughly 25,000 identical subassemblies which are integrated into the final product by another value stream. This thesis research was conducted in the Microwave Value Stream final assembly area, sized to build subassemblies for roughly two radars per year with a staff of almost 50 operators and support engineers. Relative to the rest of the IADC's operations, this line is fairly high volume and, due to the newness of the product line, utilizes some of the most advanced technologies at the company.

In late 2003, IDS launched the Radar Affordability Program (RAP) with the ambitious goal of a 10% cost reduction on each of the next three radars (the product family is depicted in Figure 2-1). This internship was one of several dozen projects launched toward that end.

Figure 2-1: Surface Radar Products

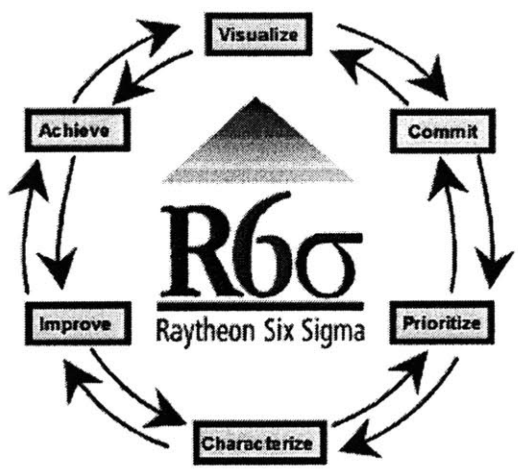


2.3 Raytheon Six Sigma Program

Raytheon launched the Raytheon Six Sigma (R6S) Program under the leadership of former CEO Dan Burnham to both increase productivity and promote a culture of continuous improvement. The program combines traditional six sigma statistical tools with lean manufacturing principles to increase value for the customer and the company. The IADC intended for 100% of its employees to be R6S trained and certified by the end of 2005.

There are two classes of six sigma projects: Specialist and Expert. Specialist projects are typically a few weeks or months in duration, while expert projects can last several years. The R6S program uses a formal six-step process to manage projects with expert coaching and required documentation in a knowledge database at each milestone. Projects are proposed by individual or teams of employees during the Visualize phase, receive manager approval in Commit, and move through Prioritize, Characterize, Improve, and ultimately Achieve as illustrated in Figure 2-2. Appendix A describes each step in more detail with examples from a specialist project to reduce the cost and errors associated with data capture.

Figure 2-2: Raytheon Six Sigma Process



The IADC had launched an expert six sigma project dubbed "The Visual Factory" nearly a year before this thesis research began. My efforts with the Microwave Value Stream were folded into this larger effort to create a pilot project to document best practices and their applicability elsewhere within the IADC.

2.4 Prior LFM Internships

The IADC has sponsored at least one or two LFM interns each year since 2001. This legacy has provided greater awareness and access for LFMs within the organization, and has also provided for continuity of research work from year to year. This thesis research resulted from the combination of recommendations for future work from the two 2004 interns. Brett Balazs highlighted poor information management systems and data accessibility issues as major hurdles in controlling and improving a manufacturing process.[4] Padmaja Vanka also identified data issues in her efforts to reduce throughput variability through line coordination.[5] My research work combines these two observations and explores ways to improve information capture and visualization to aid in line coordination and variability reduction.

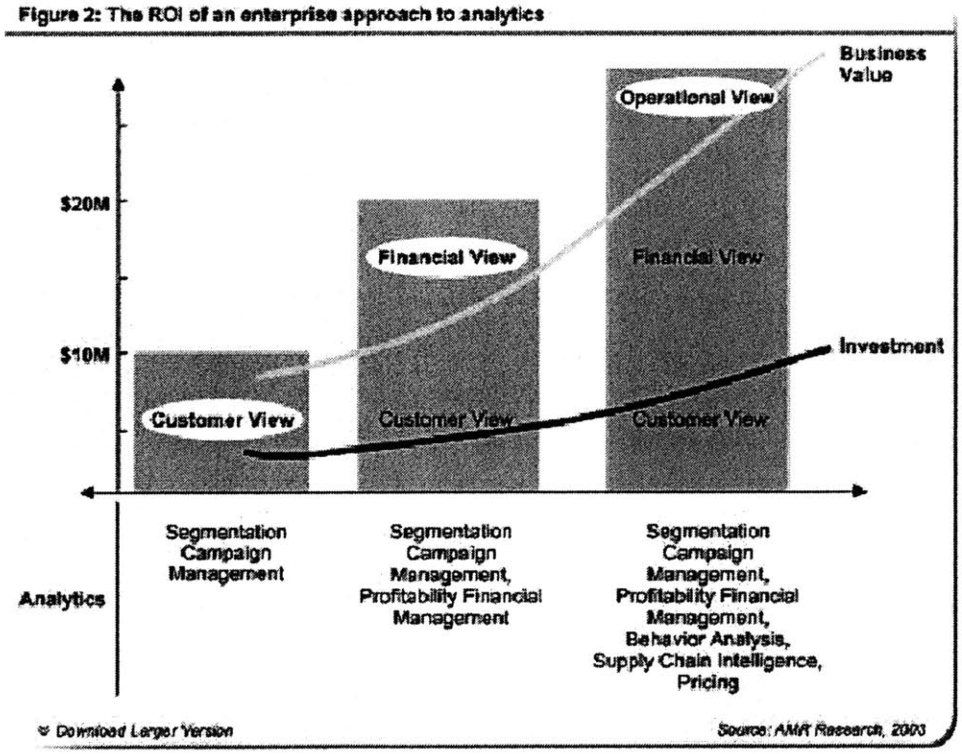
[4] Balazs, p. 17
[5] Vanka, p. 67

3 Manufacturing Information

This chapter discusses the role of information in a manufacturing environment as a prerequisite to any performance measurement or improvement program. The chapter begins with a review of the different data sources at Raytheon, continues with a review of the characteristics used to evaluate the quality of information, and concludes with a discussion of the information system architectures deployed at Raytheon.

Before any meaningful metrics or dashboards can be developed to interpret and present information, the raw underlying data must exist, be accurate, and be accessible with minimal effort. AMR Research provides the simple graphic in Figure 3-1 to show the relationship between investments in analytics systems, the types of information captured, and the business value derived for the organization.[6] As can be seen, the greatest value is achieved when enterprises can push their analytics systems down to an operational view, where analytics help inform day-to-day decisions.

Figure 3-1: ROI of Analytics



[6] Niven, p. 3

3.1 Sources of Data

Raytheon's IT infrastructure is a mix of both centralized, enterprise-wide applications and distributed, stand-alone point solutions developed for a particular functional area or business unit. This structure reflects in part Raytheon's often conflicting commitment to a "One Company" management philosophy with its decentralized organizational structure. These disparate data sources present a challenge when one requires information that resides in multiple systems, on different standards, and often controlled by different gate keepers.

3.2 Shop Floor Data Management Application (SFDM)

Fortunately, the majority of Raytheon's manufacturing facilities have standardized on a single, centralized application: Shop Floor Data Management (SFDM) to control production activities. The application was developed commercially in the 1980s, but has undergone relatively few enhancements in the years since. Raytheon's centralized IT department supports the application out of its Dallas facility. The application's broad functionality includes:

- Material release, tracking, and clearing
- Workflow management and electronic work instructions
- Electronic timesheets and labor auditing

Noticeably absent is any demand or scheduling functionality or supply chain visibility. Raytheon uses two (or more) additional applications for these purposes, which are only loosely integrated with the SFDM application.

3.3 Information Characteristics

In his thesis "Implementation of a System of Visual Indicators at Intel's D2 Fab," Erik Smith argues that traditional views of manufacturing systems which involve three inputs - material, capital, and labor – are incomplete.[7] The fourth and perhaps most crucial element of a manufacturing system is information, because it can provide performance indications which inform decision-making on how best to deploy the other three primary inputs. Therefore we will view information as a key asset for a manufacturing facility, and the process of collecting, analyzing, displaying, and acting on information as a core competency for those organizations.

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[7] Smith, p. 15

3.3.1 Data vs. Information

Volumes of data exist in all functional groups in all organizations, yet many managers still make decisions based on intuition. This is because data in its rawest form is difficult to use. To be valuable, that data must be collected, interpreted, and transformed into higher-order information that can then inform decision making. If the costs of collection, interpretation, or transformation are too high in terms of time of effort, managers will fall back on intuition, experience, or heuristics. Therefore organizations should strive not to be data-rich, but information-rich.

3.3.2 Timeliness of Information

The clockspeed of information collection and transformation must match that of the decisions which it informs. For instance, if a Statistical Process Control (SPC) chart can only identify excursions several days after they occur, the effort has little or negative value when the probability of an excursion over that period is relatively high. Managers would again rely on their intuition or downstream processes to predict or identify this condition in a more-timely manner. Of course there is always a trade-off. To detect excursions sooner with SPC, there is often a higher cost associated with sampling more frequently and preparing the control charts – which traditionally has meant manually plotting points by hand and posting a revised chart to the "Quality Wall". This thesis argues for the elimination of the marginal cost of preparation by implementing automated charting tools, where data is effortlessly transformed to information and presented in real-time. Once the obstacle of chart preparation is overcome, efforts can be focused on reducing the cost of sampling to improve the timeliness of the information.

3.3.3 Information Quality

In order for managers and operators to replace intuition with data-informed decisions, they must trust the quality of the data. Typical problems occur when users circumvent information systems (e.g. fix defects without reporting them in the tracking tool), overload fields in IT systems to serve multiple purposes, source data from different systems without synchronizing it (time delays, "units" being pieces vs. cases), etc. Therefore one of the first steps to implementing an information management system should be to analyze the data sources and clean or translate the data as needed, correcting for any errors found.

3.3.4 Universal Access Throughout the Organization

The greatest benefit can be gained from information management systems and metrics when they are available to everyone in the organization. As the cost of data acquisition and information transformation is reduced, more and different types of information can be made available. No longer should just the executive team be privy to an organization's performance information; division heads should also have metrics that they manage towards which then get rolled-up into the executive metrics; likewise functional groups should have metrics that contribute to their division metrics. This hierarchy of nested metrics can continue all the way down to an individual employee. This pervasiveness serves two primary purposes: all employees are working toward known, shared goals; each employee feels both empowerment and responsibility towards meeting those goals. A final benefit to this system is reduced supervision and overhead costs. If each employee has the means to understand his or her objectives and the tools to resolve his or her own issues, there is less need for people to play the non-value-added role of information gate-keeper.

3.4 The Three Dimensions of Information

Transforming data to information is insufficient; organizations should also be concerned with the utility of the information they capture and present. I came to think of information as possessing up to three dimensions, where the utility increases with each dimension added.

1D: Information presented in the first dimension is akin to scalars in mathematical terms – they are simply quantities without direction or scale. Metrics in the first-dimension have little value as stand-alone numbers without additional knowledge about the organization or process. Examples include measures like net income or total defects. One's conclusions about a company reporting net income of $10 million are very different if the organization has 100,000 employees and a market cap of $50 billion, vs. an organization with 100 employees and a $50 million market cap. A report of 50 defects has different meaning if 100 or 100,000 parts were produced.

2D: Like vectors in math, the second dimension adds scale or direction to the data, and is often presented as a ratio. Examples include earnings / share, defects / unit, or yield. By adding a second dimension to the data one can scale the data to benchmark across different product lines or organizations, and the data become insulated against certain variables like volume or time.

3D: The richness of a 2D metric can be enhanced by considering additional variables like time or process station. By plotting earnings / share or defects / unit over time, one can now assess the health of the organization or process. Is it improving? Are there days of the week or quarters in the year that always under-perform? By adding station to the defects / unit metric (now defects / unit / station) one can identify performance differences across stations that might be due to training or tooling issues.

3.5 Data Warehouse System Architectures

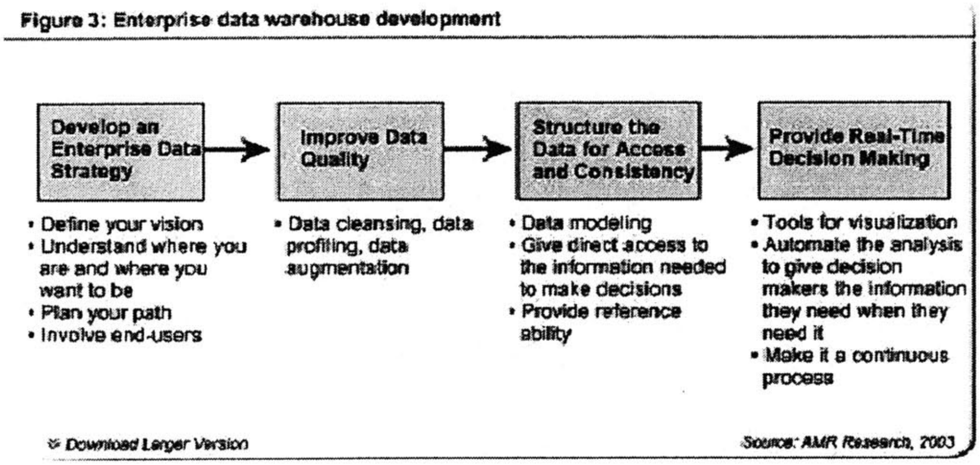
A prerequisite for a metrics or analytics program is a data source with timely, accurate, accessible, and relevant information. In discussing the enabling role of Information Technology in reengineering efforts, Hammer discusses three types of disruptive technologies, all common to enterprise data warehouse systems and performance measurement programs:

> "*Old Rule:* Information can appear in only one place at a time
> *Disruptive Technology:* shared databases
> *New rule:* Information can appear simultaneously in as many places as it is needed
>
> *Old Rule:* Only experts can perform complex work
> *Disruptive Technology:* expert systems
> *New rule:* A generalist can do the work of an expert
>
> *Old Rule:* Managers make all decisions
> *Disruptive Technology:* Decision support tools (database access, modeling software)
> *New rule:* Decision making is part of everyone's job."[8]

AMR Research defines four high-level steps to implementing a data warehouse solution, as illustrated in Figure 3-2.[9]

[8] Hammer, p. 96-9
[9] Niven, p. 4

Figure 3-2: Data Warehouse Implementation Process

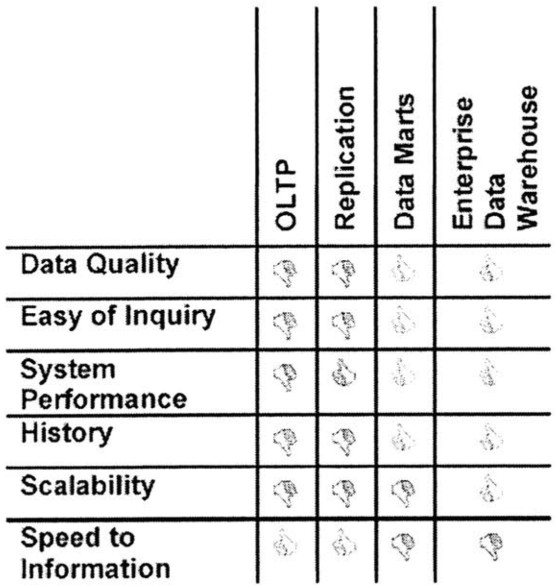


There are several tradeoffs to be considered when choosing the appropriate data source(s) for a metrics program. There are four broad classes of data sources:

- **OLTP:** or Online Transaction Processing systems. This is the primary data source that is used for daily operations in a functional area. Examples include ERP, CRM, or Financial systems. In Raytheon's case, the SFDM application is the OLTP system.
- **Replication:** A replicated system is one that mirrors the primary OLTP system's structure, but has been copied so that expensive queries are done offline without affecting the performance of the primary system.
- **Data Mart or OLAP:** A data mart (or Online Analytical Processing system - OLAP) takes an OLTP system and transforms or augments the data so that it is structured for better performance for generating reports or expensive queries. Table hierarchies can be flattened and proprietary codes in the OLTP system can be translated into more generic terms. Typically a data mart still just includes data from one information source (operations, financials, etc.).
- **Enterprise Data Warehouse:** An enterprise data warehouse combines all the information from all data sources in the company into a single location, optimized for computationally expensive queries and reports. This structure allows users to execute queries that combine information from multiple functional areas like financials and operations. Nexus Consulting Group evaluates each of these systems for data quality,

ease of inquiry, performance, age of historical records, scalability, and speed, as summarized in Figure 3-3.[10]

Figure 3-3: Database System Characteristics



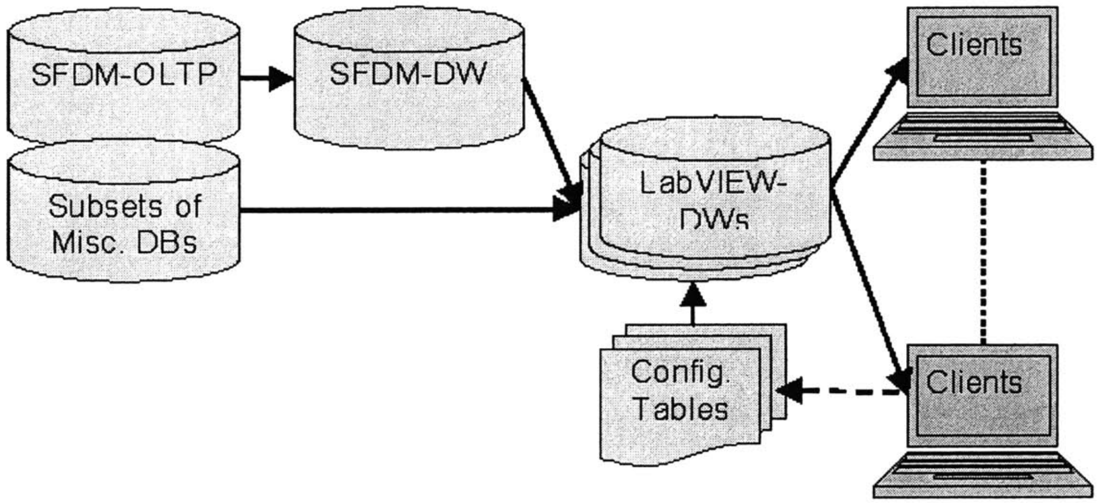
Since visual performance dashboards require high quality, easy inquiry, and quick speed to information, no system is best suited for these requirements and trade-offs must be made.

3.6 Raytheon's System Architecture

The Visual Factory team decided to implement data marts to support the metrics and dashboards deployed on the factory floor. One data mart was established for each manufacturing area in the IADC (roughly ten) to allow customization by area and improved scalability. Each data mart is populated from an existing SFDM data warehouse (more accurately a replication of the OLTP SFDM application). There is a 10 minute latency between the two SFDM applications, and then an additional 10 minutes between the replicated SFDM system and the LabVIEW data marts. Configuration tables also exist in the LabVIEW data marts to enter additional information like daily goals or to control the default appearance of dashboards. Each client PC connects directly to the data mart for their particular manufacturing area. This system architecture is illustrated in Figure 3-4.

[10] Nexus Consulting Group, p. 7

Figure 3-4: Raytheon's System Architecture



4 Manufacturing Performance Metrics

With a proper data storage solution in place, this chapter discusses the use of manufacturing information in assembling performance management systems. The chapter begins with a literature review of performance metrics programs in academia, industry, and within Raytheon itself. Various metrics for schedule, cost, and quality are discussed, along with the use of metrics for production planning and other non-measurement purposes. The key take-away is to first understand the goals and objectives of the firm or production area, and then design measurement systems which align resources and track progress towards those goals.

There is no holy grail for performance metrics; what is most effective for one organization will almost certainly not be optimal for another. The three most important factors to consider when designing metrics are:

Audience: The metrics for a CEO, plant manager, and operator will all be different. A CEO is concerned with metrics like gross margin, net income, and customer satisfaction. A plant manager might be concerned with metrics that contribute to those global metrics like asset utilization, employee absenteeism, on time delivery, etc. The metrics for an operator should be even more granular: yield at a specific workstation, scrap rates, takt time, etc.

Decision Making Time Horizon: Similar to the audience, metrics will be designed differently if the decision-making time horizon is minutes versus months. SPC charts on a factory floor are designed to identify out-of-control processes as quickly as possible. Asset utilization metrics, on the other hand, should be designed to dampen noise considerably: one would not decide to divest a plant based on poor utilization numbers for a day.

Desired Outcome: Metrics don't exist for their own sake: their value is only in the information they convey and the decisions they inform. Each metric should be designed with a purpose: process control, budget planning, service level agreements, etc.

4.1 Literature Review

Volumes of high-level, industry-neutral financial metrics are available in the literature, including gross margin, return on assets, inventory turns, etc. Far fewer operational metrics exist in the literature, because they are often industry or firm-specific. However, many organizations have published guidelines for what defines a good metric, along with lists of the operational characteristics that should be measured. Here we review a variety of these frameworks and recommendations.

4.1.1 Key Performance Indicators

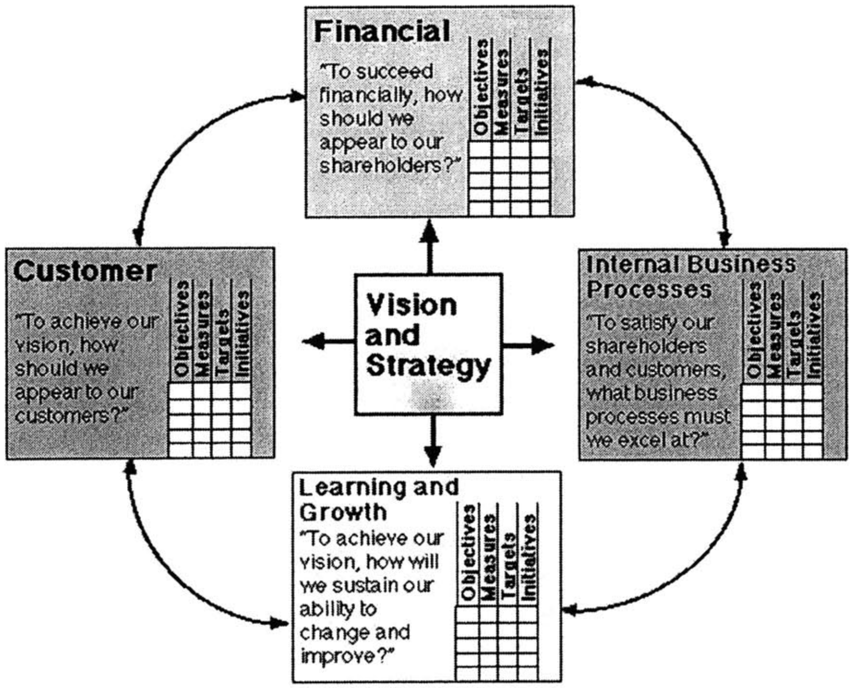
As the name suggests, key performance indicators are a set of high-level metrics used to measure an organization's performance. There are typically no more than a half-dozen "key" metrics for an organization, but they can be influenced by hundreds of lower-level metrics. Politano writes, "In my book, Chief Performance Officer, the theme is 'measure what matters, manage what can be measured.' This is the essence of the KPI. It must be measured. It must matter. It must be manageable."[11] The typical audience for KPIs is the executive management team and, as such, KPIs would be inappropriate for the microwave area. However, the more granular metrics implemented in the area could eventually be incorporated into aggregated KPIs for the IADC plant, IDS, or even Raytheon corporate.

4.1.2 The Balanced Scorecard Framework

In 1992 Robert Kaplan and David Norton proposed the balanced scorecard framework as a way to manage organizations using more than just financial measures.[12] The management framework suggests first articulating a business strategy and vision, then defining metrics that will measure achievement against that vision from four perspectives: Financial, Customer, Business Process, and Learning and Growth. The diagram in **Error! Reference source not found.** shows how these perspectives interface with one another.[13] Like KPIs, the Balanced Scorecard Framework takes a more enterprise-wide, holistic view to performance metrics and would be inappropriate for the microwave area, although the emphasis on non-financial metrics should be replicated.

[11] http://www.businessintelligence.com/ex/asp/code.83/xe/article.htm
[12] Kaplan
[13] http://www.balancedscorecard.org/basics/bsc1.html

Figure 4-1: Balanced Scorecard Model



4.1.3 SMART framework

Many resources on the design of metrics suggest the SMART acronym as a good framework for evaluating the effectiveness of any metric.[14]

- **S = Specific:** must be specific and targeted to avoid misinterpretation or dilution.
- **M = Measurable:** must be able to collect quantifiable, measurable data.
- **A = Attainable/Actionable:** must be reasonably attainable so that the workforce isn't discouraged. Metrics must also provide an indication for when action is necessary.
- **R = Realistic/Relevant:** must be cost-effective to capture, and must measure things that are relevant to the business.
- **T=Timely:** The time-horizon of data capture must match that of the ability to respond.

The last three characteristics are particularly important for the decision-making metrics deployed on a factory floor. The metrics must be relevant and lead to timely actions to be "smart" enough to influence the day-to-day operations.

[14] http://www.prosci.com/metrics.htm, TRADE p. 1-54

4.1.4 Lagging vs. Leading indicators

Performance metrics are often classified as either lagging or leading. A lagging indicator is one that is reflective of past performance and is often used to measure an organization's progress against strategic goals. These metrics are often common across organizations and the set is fairly static from year to year, like Gross Margin, EBIT, and Return on Invested Capital.[15] Leading indicators, in contrast, attempt to predict a firm's future performance towards strategic goals. Examples might include communication efficiency, employee turnover, or invested capital (a predictor for return on invested capital). These metrics often vary from organization to organization and year to year, because they are closely tied to the strategy the firm employs to reach those goals. For example, if two companies share the goal of growing revenue 20% (measured with the lagging indicator of annual revenue growth), one company might implement this strategy by focusing on product quality, whereas the other might attempt to improve customer service. The product-based strategy might use predicted months between failures as a leading indicator, whereas the service strategy might look at customer survey results or average wait times to predict future performance.

Perhaps the most important distinction between the two metrics is that leading indicators can more actively be influenced or controlled. Therefore managers should implement leading indicators on the factory floor where possible because the employees can and will strive to improve them. Figure 4-2 shows several metrics on the continuum from lagging to leading across different functional areas.[16]

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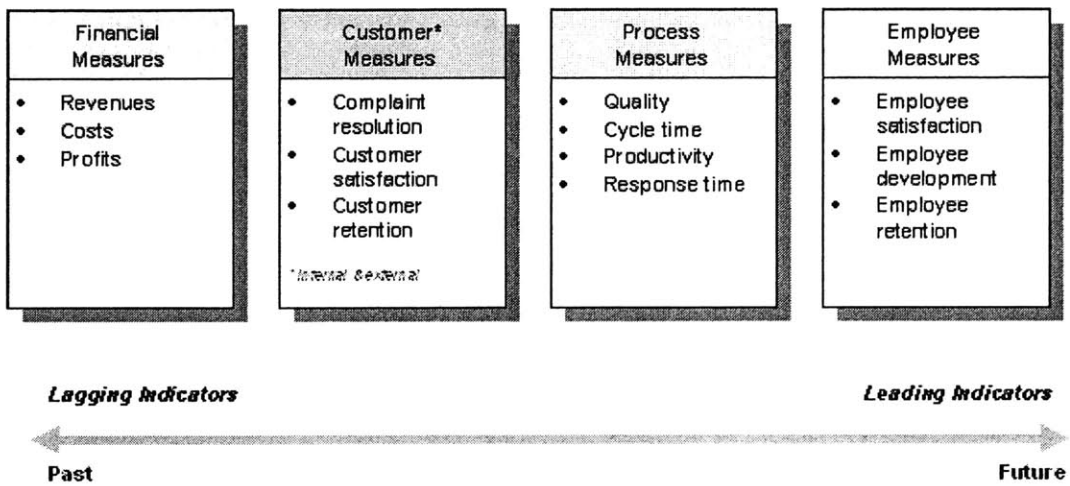
[15] http://www.som.cranfield.ac.uk/som/research/centres/cbp/pma/DR_LeadingIndicators.pdf
[16] http://www.thelgroup.com/p_TheLetter/15.asp

Figure 4-2: Lagging vs. Leading Indicators



4.1.5 University of California Laboratories

In coordination with the U.S. Department of Energy and the National Institute of Standards and Technology, the University of California has published an introductory guide on developing performance metrics. As a framework, the guide suggests that all metrics should be designed for gains in one of three principle areas: customer satisfaction, organizational performance, and workforce excellence. To meet these three objectives, they suggest metrics that measure nine attributes[17]:

- Alignment with organizational mission
- Quality of product
- Timely delivery
- Cost reduction and/or avoidance
- Cycle time reduction
- Customer satisfaction
- Meeting [customer] requirements
- Meeting commitments

The University of California provides the following eleven questions to measure the quality of a metric[18]:

1. "Is the metric objectively measurable?
2. Does the metric include a clear statement of the end results expected?

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[17] TRADE, p. 1-53
[18] TRADE, p. 1-55

3. Does the metric support customer requirements, including compliance issues where appropriate?
4. Does the metric focus on effectiveness and/or efficiency of the system being measured?
5. Does the metric allow for meaningful trend or statistical analysis?
6. Have appropriate industry or other external standards been applied?
7. Does the metric include milestones and/or indicators to express qualitative criteria?
8. Are the metrics challenging but at the same time attainable?
9. Are assumptions and definitions specified for what constitutes satisfactory performance?
10. Have those who are responsible for the performance being measured been fully involved in the development of this metric?
11. Has the metric been mutually agreed upon by you and your customers?"

The University of California also provides a nice classification of performance metrics, as summarized in Table 4-1.

Table 4-1: University of California Performance Measures

Measure of...	Measures...	Expressed as ratio of...
Efficiency	Ability of an organization to perform a task	Actual input/ planned input
Effectiveness	Ability of an organization to plan for output from its processes	Actual output/ planned output
Quality	Whether a unit of work was done correctly. Criteria to define "correctness" are established by the customer(s).	Number of units produced correctly/total number of units produced.
Timeliness	Whether a unit of work was done on time. Criteria to define "on-time" are established by the customer(s).	Number of units produced on time/total number of units produced.
Productivity	The amount of a resource used to produce a unit of work	Outputs/inputs

These attributes, questions, and classifications reinforce the connection between customer expectations and the design of metrics, at a time when Raytheon is trying to be more customer-centric as described in Chapter 7. These questions also highlight the importance of involving those being measured in the design of the metrics, also discussed in Chapter 7.

4.1.6 Juran Quality Handbook

Dr. J.M. Juran proposed the following ten recommendations to evaluate the effectiveness of a measurement system:[19]

1. "Manage measurement as an overall system, including its relationships with other systems of the organization.
2. Understand who makes decisions and how they make them.
3. Make decisions and measurements as close to the activities they impact as possible.
4. Select a parsimonious set of measurements and ensure it covers what goes on "between functions."
5. Define plans for data storage and analyses / syntheses / recommendations / presentations in advance.
6. Seek simplicity in measurement, recommendation, and presentation.
7. Define and document the measurement protocol and the data quality program.
8. Continually evolve and improve the measurement system.
9. Help decision makers learn to manage their processes and areas of responsibility instead of the measurement system.
10. Recognize that all measurement systems have limitations."

One common theme among these recommendations is that measurement systems are simply one tool to aid decision-makers and even the simplest, best-designed tools will still have limitations. Decision-makers should continually test whether they're correctly managing the underlying process, or falling into the trap of managing the measurement system proxy for the process.

4.1.7 Goal-Question-Metric framework

The software industry has popularized another framework for developing measurement systems to evaluate software quality.[20]

Goals – Conceptual: The first step is to articulate the desired product, process, or resource objectives. The goal defines the purpose and focus of an analysis, and why it is important to the organization.

Question – Operational: The next step is to generate a list of questions that must be answered to determine if the goal has been achieved.

Metric – Quantitative: Finally, metrics are devised from the data gathered to answer each question. The metrics provide quantitative means to detect process improvements.

[19] Juran, ch. 9
[20] http://www.cs.umd.edu/users/mvz/handouts/gqm.pdf

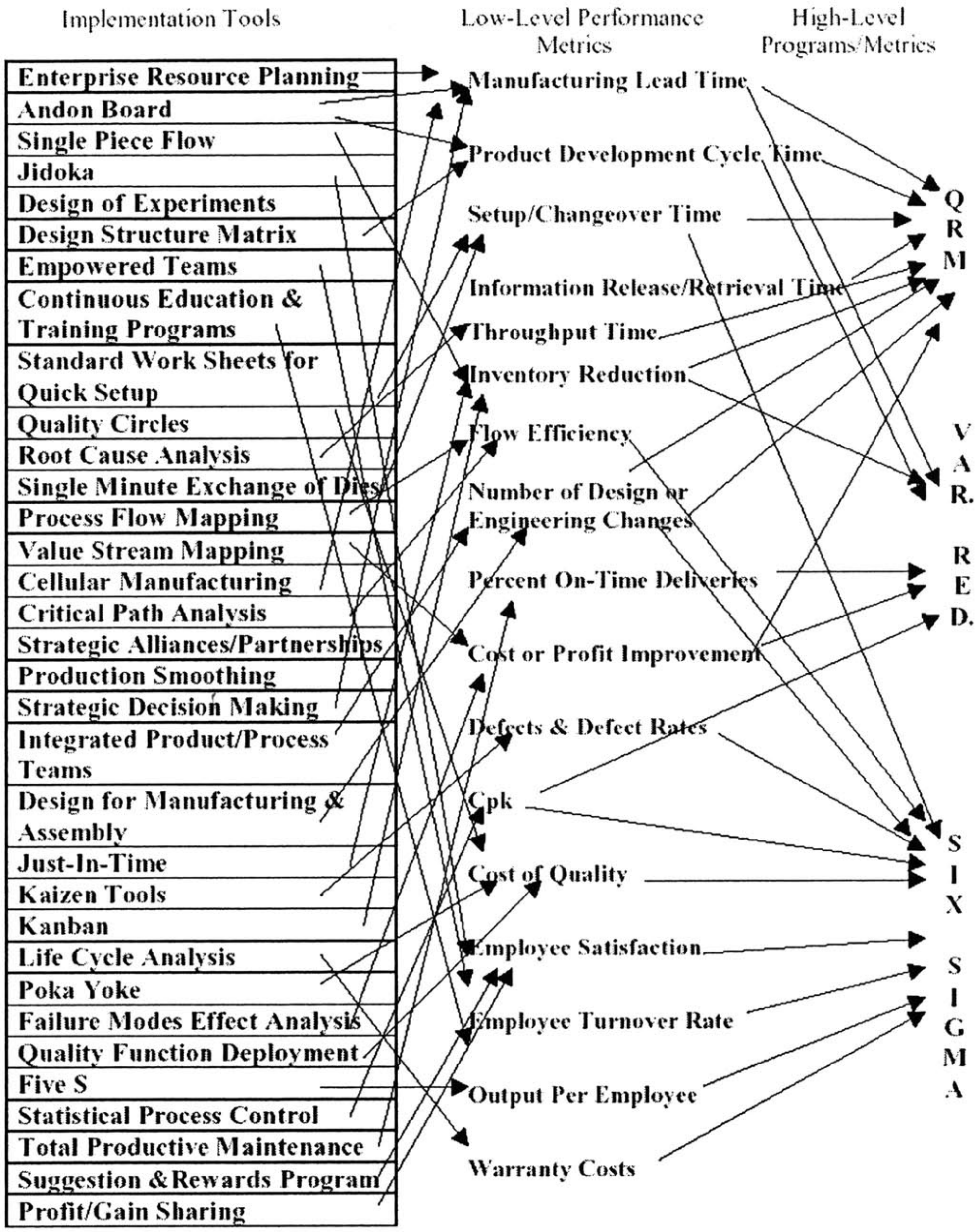
This simple framework nicely ties the conceptual goals of an organization to the quantitative metrics to measure progress through a set of operational questions. This intermediate step links or translates the language and ideas of executive management to the language on the shop floor to facilitate communication and organizational alignment.

4.1.8 Implementation Tools and Metrics

Khusrow Uzair's SDM thesis at MIT explored the relationships between the seven most popular process improvement programs and the tools and metrics used to implement each program. There are dozens of performance improvement tools that can be utilized in each program, but a smaller set of metrics can be used to evaluate the effectiveness of each tool. Figure 4-3 shows the relationships between the tools, metrics, and improvement programs, and represents the author's suggested toolkit for the most-effective performance measurement metrics.[21] This list also suggests that other management or manufacturing practices often accompany performance measurement programs as tools to help achieve the desired measure. As Raytheon identifies its goals and designs metrics to measure compliance with those goals, it should expect to introduce additional implementation tools to improve the metrics and help realize its goals.

[21] Uzair, p. 53

Figure 4-3: Implementation Tools and Metrics Relationships



4.1.9 Alternative Control Mechanisms

It should be noted that some organizations have devised control mechanisms that make certain metrics obsolete. For example, while Work In Process is a significant measure for Raytheon and other batch-oriented, discontinuous manufacturers, the measure is meaningless for manufacturers with single-piece, continuous flow: the amount of Work In Process in known a priori by the design of the system.

4.2 Legacy of Metrics at Raytheon

Raytheon has a strong culture supporting performance measurement. Two examples show Raytheon's willingness to embrace metrics across different areas of the organization, with the first focusing on concurrent engineering metrics for product development. The second example emphasizes the importance of financial metrics for each Raytheon division, and the incentive programs that have been developed to tie pay to performance.

4.2.1 Metrics for Concurrent Engineering in Surface Radar

Catherine Tedesco, an LFM from the class of 2001, researched and implemented hundreds of metrics to measure the effectiveness of the new concurrent engineering processes being implemented at the time.[22] One of her principle conclusions was that, to be effective, metrics must be easy to measure, and measured often. Like many change efforts, there was considerable initial enthusiasm and the metrics were measured frequently when they were first developed. Four years later, one could find little, if any, evidence that the metrics were still being used to evaluate concurrent engineering efforts. This suggests the implementation might have failed to address the ongoing cost of data capture and presentation.

4.2.2 Performance Sharing Program

Almost all employees should be familiar with Raytheon's Performance Sharing Program which uses Results-Based Incentive Metrics to measure the health of each individual business unit. A portion of each employee's annual bonus is based on his or her division's performance against five key financial metrics: Operating Cash Flow, Working Capital Turns, Bookings, Net Sales, and Operating Profit. Each employee has access to a Raytheon internal website that provides a dashboard with five needle-gauges showing current performance to date as a percent of target.

4.3 Quality

The Microwave area was concerned with quality at two operation types: physical inspection, and automated testing, with two goals: improve quality and reduce cost. Physical inspection involves operations like testing the torque strength of screws, the spacing of parts, or the presence of debris or cracks under magnification. These tests are typically binary (pass / fail) and are corrected immediately. Automated tests check for ribbon bond strength, signal

[22] Tedesco, p. 36

strength, and power settings and are either binary or continuous. These faults typically require a full or partial teardown, and then return to the beginning of the line. Due to the high-value of the goods, very little material is scrapped. Table 4-2 shows the advantages and disadvantages of several metrics considered for the microwave area.

Table 4-2: Quality Metrics

Metric	Advantages	Disadvantages
total defects	-immediate	-varies with volume
defects / unit	-doesn't vary with volume	-can't be calculated until part is complete (lagging indicator) -poor metric for benchmarking
Defects / million opportunities	-good for benchmarking	-"opportunity" is difficult to quantify
Yield (good units / total units)	-indicates process capability	-doesn't quantify multiple failures per unit
rework hours / unit	-measures **cost** of poor quality	-lagging indicator

Each of the metrics above was used at Raytheon at different times. For this implementation of visual dashboards, two metrics were used primarily: total defects and yield. Total defects allowed everyone on the shop floor to be aware of non-conformances as they occurred. This immediate feedback was necessary to link the defect with the upstream operation that caused it to prevent additional issues; the metric is akin to pulling the Andon cord in the Toyota Production System. Yield was also used to track performance at an operation over time, identify excursions, and set quality goals.

4.4 Manufacturing Schedule

One of Microwave's biggest concerns was making the daily production targets. The goal was two-fold: meet monthly demand numbers, and balance production from day to day, operation to operation. Table 4-3 lists the advantages and disadvantages associated with each metric devised.

Table 4-3: Schedule Metrics

Metric	Advantages	Disadvantages
completes / hour	-immediate -tangible for operators	-varies with number of operators -doesn't account for quantity differences across subassemblies
units above / below goal	-incorporates Takt time -identifies bursts and droughts	-doesn't address staffing needs -disassociated from daily goals

Completes / operator hour	-incorporates takt time -measures individual operator performance	-disassociated from daily goals
Remaining daily units	-immediate	-doesn't address staffing needs

4.5 Cost

The Microwave area's costs are driven by two main factors: material costs and labor costs. The levers that influence material costs are purchase price, inventory, and scrap. Labor costs are driven by two factors: standard work, and rework. The dashboard implementation focused initially on labor cost metrics, but Table 4-4 includes others for future consideration.

Table 4-4: Cost Metrics

Metric	Advantages	Disadvantages
hours / unit	-immediate -tangible for operators -identifies bottlenecks	-standards aren't involved
Hours above / below goal	-incorporates goal	-doesn't factor in staffing
Operator efficiency	-measures individual performance	-doesn't quantify cost of quality
Units of WIP	-identifies bottlenecks	-poor for benchmarking
Hours of WIP	-supports benchmarking	-difficult to understand -varies with production rate
Units scrapped	-immediate	-doesn't consider cost of scrap
$ scrapped / hr	-includes cost of scrap	-difficult to measure (must consider all operations completed to date)
Cycle time	-considers holding costs	-lagging indicator
Dwell time	-identifies flow issues	-lagging indicator

4.6 Manage by Exception (Andon Board)

An entirely different philosophy to performance measurement is to replace the quantitative metrics like hours / unit with qualitative descriptors like "good" or "bad" that can highlight exception conditions. In the Toyota Production System these qualitative descriptors can be colored lights either above a piece of equipment or highlighting an individual work cell. For example, a light might indicate that the targeted cell's performance is sub-standard, but the operators and supervisors do not necessarily need to know the current production rate; knowing that a yellow light indicates a potential slow-down and a red light indicates a line stoppage is sufficient to identify and correct the problem. The primary advantage to this type of qualitative metric is that it is intuitive, and the underlying calculations or system support tools can change without requiring retraining for the operators or supervisors. The disadvantage to this system is that it does not provide for good historical tracking or benchmarking, and it typically requires additional management practices like one-piece flow and standardized takt times to be effective. These qualitative metrics were not appropriate for the Microwave area initially, but should be revisited in the future as the area adopts additional lean management practices and shifts from low-volume to more high-volume practices.

4.7 Implications for Production Planning

While the focus of the internship was enabling process improvements on the factory floor, one side benefit to developing metrics was to characterize the existing processes for planning purposes. Capacity planning, staffing, floor layout, and designing WIP management controls had historically been done using theoretical numbers – labor content standards, predicted yields, and so on – without consideration for variation. By developing metrics to analyze actual performance, these planning exercises were redone with actual performance numbers and actual measures of variation. The Process Model simulation package was used to run dozens of what-if scenarios to determine how the process would change with the following factors:

- Regrouping the functions performed by different operators to improve efficiency
- Changing the WIP in the system to prevent starvation
- Understanding the tradeoffs between process time variation and WIP
- Changing the floor layout to reduce material / worker travel time
- Changing the batch sizes for ovens and test stations

Ultimately this exercise allowed the area to consider the performance measured by each metric in aggregate, make trade-offs between each one, and establish goals which intended to achieve a more global optimal, rather that several local optimal solutions.

4.8 Aligning Incentives with Metrics

A key characteristic of effective performance management programs is that incentives are clearly aligned with the metrics, and the metrics are aligned with the organization's goals. That is, employees are rewarded for efforts that improve the metrics, and dissuaded from actions which negatively impact the metrics, and an improvement in the metrics helps the organization meet its goals. Therefore any efforts to install performance metrics should also be coupled with a clear organizational strategy, and a revamped incentives program.

4.9 Summary

This chapter discussed several different frameworks that can be used to design performance management metrics, and presented examples of previous performance measurement programs at Raytheon. These frameworks and past experience were then combined to define the initial set of metrics that would be deployed in the microwave area, although the expectation is that these metrics will evolve over time as the underlying processes they measure change.

5 Visual Performance Indicators

This chapter focuses on the visual presentation of the performance metrics which were identified in the previous chapter. The chapter reviews display systems in use in various industries, and continues with a review of the metrics development and deployment environment selected for Raytheon. Examples of several dashboards developed for measurement and process investigation are provided, with suggestions for how to optimize both the density and clarity of information conveyed.

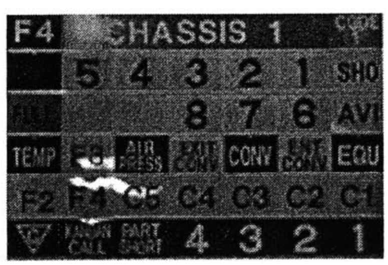
5.1 Literature Review

There are many examples in literature and industry of static visual control mechanisms on factory floors and interactive dashboards for executive management. Unfortunately, there are few examples of interactive, dynamic, information-rich dashboards for the factory floor. Several static, specific-purpose dashboards are reviewed below, with the expectation that the characteristics of good design will apply equally to multi-use or single-use displays.

5.1.1 Andon Boards

Andon boards, popularized in the Toyota Production System (TPS), are visual control mechanisms that hang on the factory floor. They typically address either current quality issues or daily throughput rates with first-dimension data. Named after the "andon cord" in the TPS system that is pulled when an operator finds a quality problem, a quality-focused andon board lights up to identify the location of the quality problem as shown in Figure 5-1 from Toyota's Georgetown plant.[23]

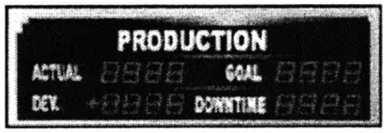
Figure 5-1: Georgetown Plant Andon Board



[23] http://www.toyotageorgetown.com/qualdex.asp

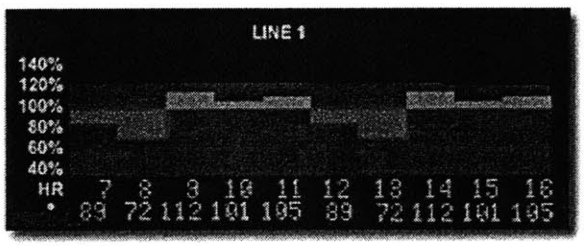
The andon board in Figure 5-2 shows current daily throughput, the daily goal, the deviation from the goal, and a running count of the system downtime – again all first or second-dimension information.[24]

Figure 5-2: Numeric Andon Board



The board in Figure 5-3 goes one step further, showing production data in three dimensions: completes as a percent of production goals over time, but the resolution and flexibility of the display still suffers.[25]

Figure 5-3: Trend Andon Board



Effective andon boards have the following characteristics: immediate process feedback, visibility from all areas of the floor, flexibility to adapt to process changes, and a clear meaning that requires no explanation or interpretation. Andon boards are also incorruptible: so long as the power is on, operators or supervisors cannot ignore them, pad or smooth reported numbers, or otherwise alter the reported measures.

5.1.2 Physical Displays

Not all production control displays are electronic. The Toyota Production System advocates physical storage bins as a way to communicate WIP levels and control production flow. If WIP is accumulating at a particular station, it becomes immediately visible. If the sized storage bin becomes full, run rules dictate that the upstream operation halts production. The Samsung Electromechanics plant in Korea uses a novel physical model to communicate

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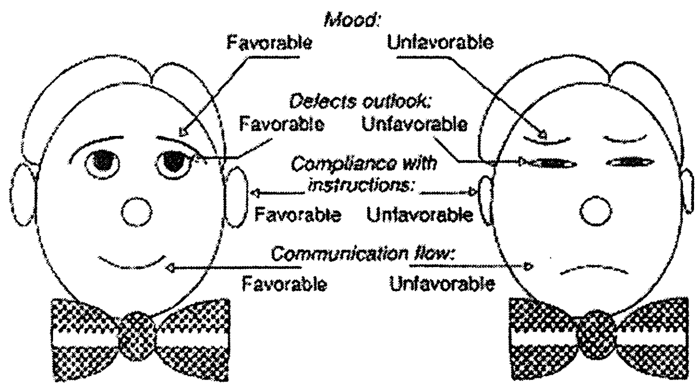
[24] http://www.ledgible.com/numeric/numeric_ppt.htm
[25] http://www.nu-mediadisplays.com/signs/bar-graph-displays.php

mood, defects, compliance, and communication metrics. The disposition of the model is physically altered to reflect the current state, as illustrated in Figure 5-4.[26]

Figure 5-4: Physical Andon Board



The most obvious disadvantages to physical models is that they require human involvement and suffer from a time-delay. Not only is this costly from a labor perspective, but it invites the opportunity for subjective interpretation and presentation of the data. It is also difficult to sustain control mechanisms that require daily or hourly input from individuals.

5.1.3 Timeliness and Flexibility

Like individual metrics, effective performance displays must provide information in a timely fashion, and must be flexible to evolve as the underlying processes that they measure evolve. Displays that show current performance aid decision-making more than metrics that show past performance, but displays that can predict future performance are better still. Likewise, displays should be designed such that changes to the underlying process require minimal effort to update the displays. For instance, as a process becomes more robust, control limits should automatically be narrowed to reflect the improved behavior. Otherwise, the metrics will loose their effectiveness as they loose currency.

5.1.4 Business Intelligence Vendors

Virtually all of the Business Intelligence or Performance Management software vendors also provide reporting tools or performance dashboards as an interface to their system. Since this internship was an extension to the existing Visual Factory Six Sigma project which had already standardized on a set of software tools, a vendor evaluation process was not conducted.

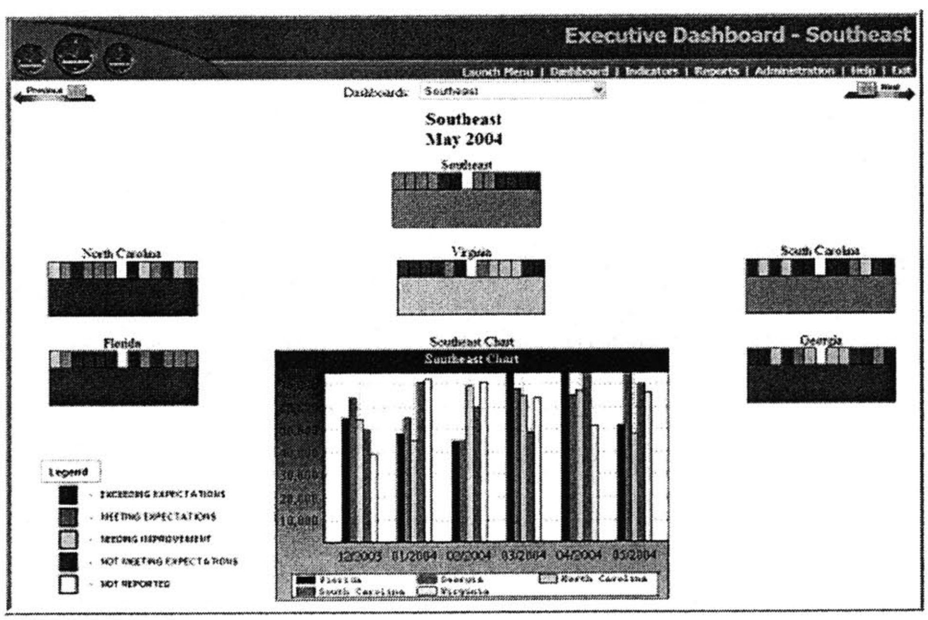
[26] Grief p. 201

However, select marketing data and screen shots are provided below to illustrate the types and quality of solutions provided, should Raytheon reconsider its technology stack in the future.

5.1.4.1 Executive Dashboard

Executive Dashboard has developed a web-based interface to their key performance indicator software that supports three-dimension information display. As seen in Figure 5-5, the display uses color coding to indicate the quality of a metric (the large colored squares), and shows both historical and predicted future performance of the metric (the small colored squares). The displays are also interactive and each metric can be expanded to get more granular details or to aid in addressing issues. "**Executive Dashboard** is a powerful web-based executive information system (EIS) that provides a consolidated view of an organization's performance, making it easy to: Take advantage of a balanced scorecard approach to management; Measure and understand an organization's key performance indicators and performance metrics. **Executive Dashboard** provides a management tool for setting expectations for every organization at every level, with easy-to-understand reporting of the status of progress throughout the year. Their executive software measures set at each level roll up to higher indicators, creating a means for gauging the status of your organizational progress."[27]

Figure 5-5: Executive Dashboard Example



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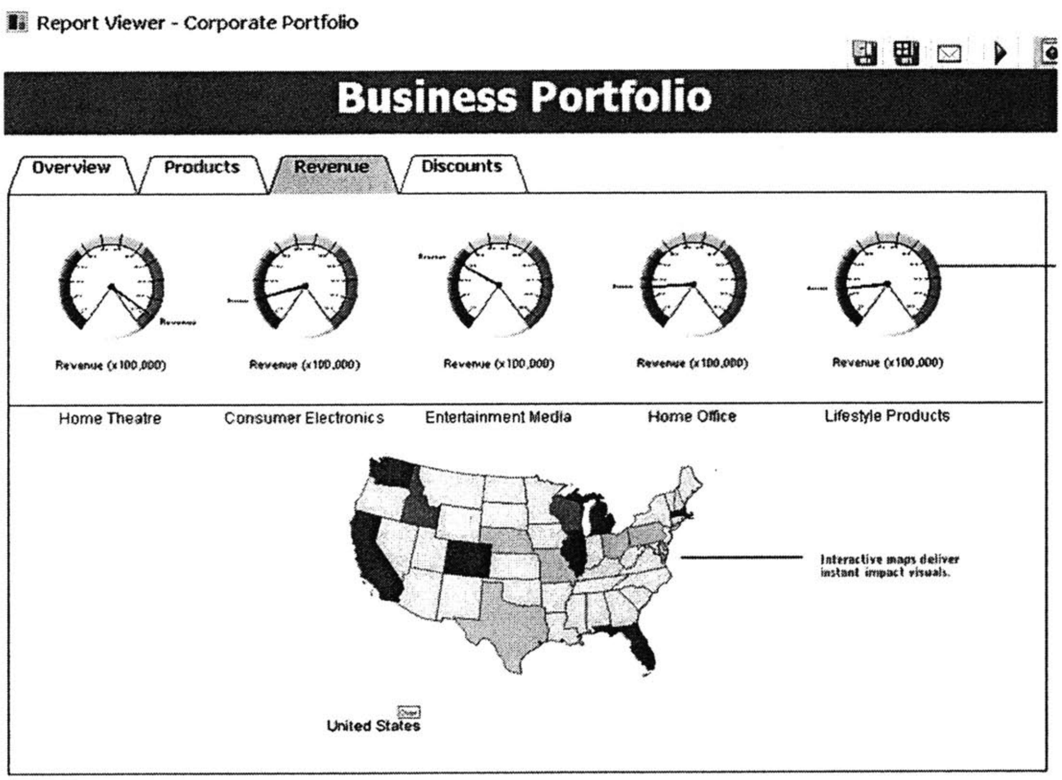
[27] http://www.iexecutivedashboard.com/overview.htm

5.1.4.2 Cognos

Cognos is one of the oldest business intelligence vendors, providing tools to support all steps in the performance management process: planning, measuring and monitoring, and ultimately reporting. The example in Figure 5-6 shows performance against revenue targets by both product line and geography, illustrating the flexibility of the application to support objects beyond simple charts and graphs. Cognos' Visualizer application provides the tools to develop interactive dashboards, supporting "swatch, value, parallel coordinate, box and whisker, gauge, histogram, thermometer, control limits, and trend charts, all fully customizable to your needs. [The application] provides one version of the truth; presents a real-world view of business as ever changing and evolving; unites data from all the core departments; supports mission-critical strategic initiatives; provides answers at a glance—for faster understanding and action by staff."[28]

Figure 5-6: Cognos Dashboard

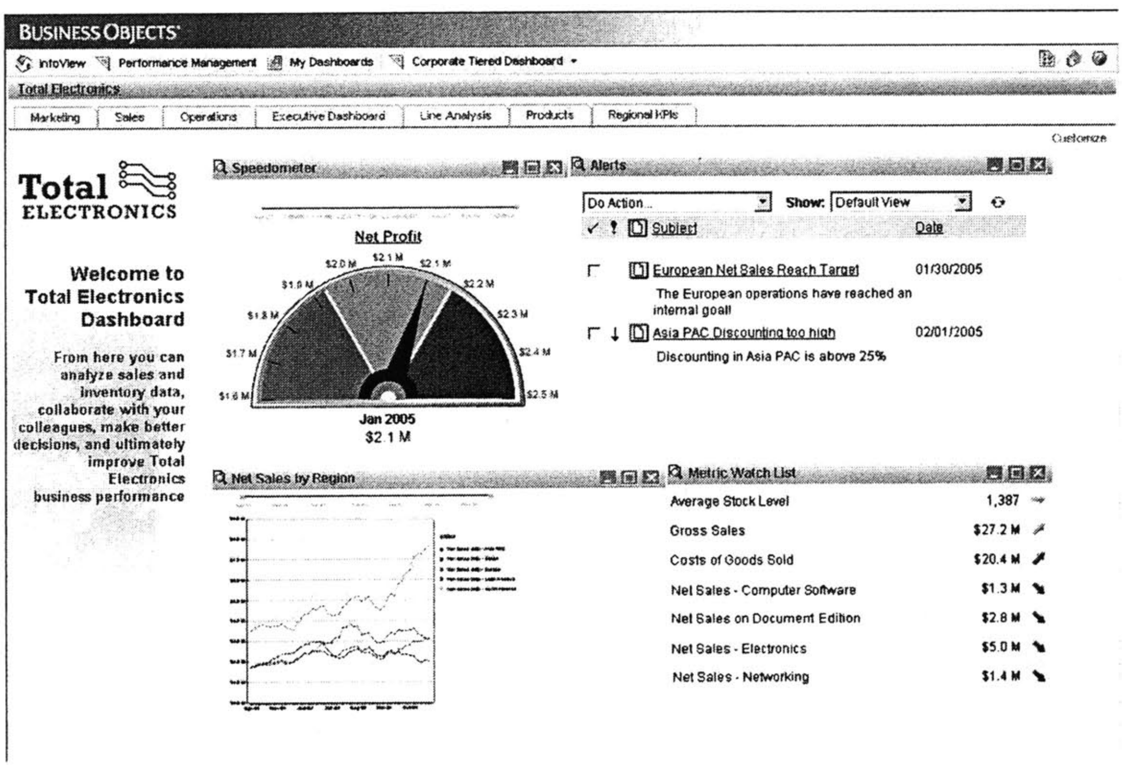


[28] http://www.cognos.com/products/business_intelligence/visualization_dashboards/features.html

5.1.4.3 Business Objects

Like Cognos, Business Objects has its roots in analytics software and has extended it product suite to include performance dashboards. Figure 5-7 shows an example of one web-enabled dashboard for revenue management. The metric watch list in the lower right can be customized for each user to show current and trend performance for a selected list of metrics. "Performance management products from Business Objects help your organization align with strategy by tracking and analyzing key business metrics and goals via management dashboards, scorecards, and alerting. You can set goals around metrics and assign them to users or groups of users. Groups can then analyze information, collaborate with other stakeholders, take recommended actions, and feel confident about the decisions they make. Our performance management applications build on our core products and embed industry best practices for business analysis."[29]

Figure 5-7: Business Objects Dashboard

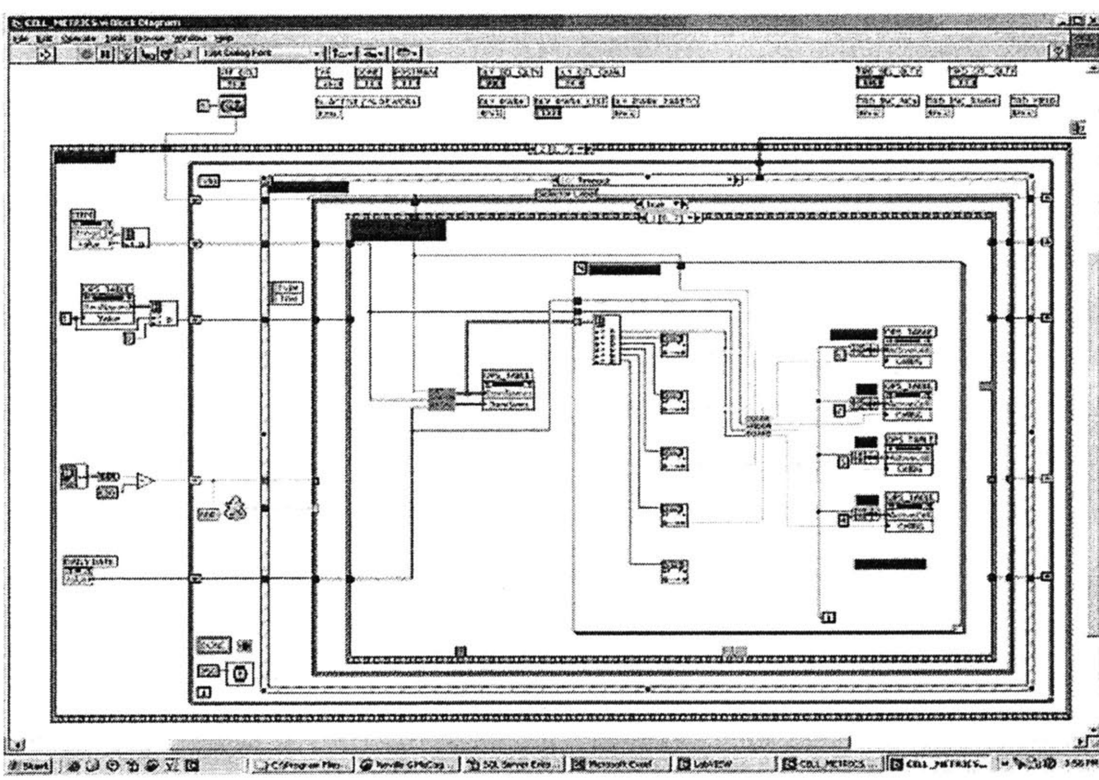


[29] http://www.businessobjects.com/products/performancemanagement/default.asp

5.2 LabVIEW Application Development

The Visual Factory project selected LabVIEW, a National Instruments product[30], as the development environment for creating visual dashboards at the IADC. LabVIEW is marketed as a graphical development tool to build control interfaces for test machines. The application provides features such as digital signal processing, robotic controls, data acquisition from instrumentation machines, and data analysis such as statistical process control. Virtual Instruments (VIs) are developed in a graphical programming language that consists primarily of controls for input (knobs, text, buttons, etc.), "wiring" to define information flows, functions to perform data manipulation, indicators to display output (tables, graphs, thermometers, etc.), and an ODBC database interface for data persistence. VIs can be embedded into other VIs, enabling efficient code-reuse and the development of super-VIs created by the compilation of several smaller VIs. The source code is compiled into stand-alone applications that run on individual PCs. Figure 5-8 provides an example of the graphical development environment.

Figure 5-8: LabVIEW Source Code Screenshot



[30] www.ni.com/labview

5.2.1 Advantages

LabVIEW provides several advantages for dashboard development:

- Raytheon has used LabVIEW for test instrumentation for years, with well over 1,000 trained users. This in-house knowledge and experience reduces the cost of implementation and development time and will facilitate rapid dissemination throughout the organization.
- The graphical user interface provides tools that are easily learned by non-programmers. This ease-of-use enables individual manufacturing areas to design and deploy their own interfaces without assistance from the IT organization.
- Simple applications can be developed and deployed quickly. This rapid development framework makes it possible to identify a particular issue on the factory floor and develop and deploy a measurement dashboard within hours. Once the problem is resolved, the dashboard can be retired.

5.2.2 Disadvantages

Since LabVIEW was not developed primarily for visual dashboards, several challenges must be overcome:

- Development and maintenance time increases exponentially with the complexity of the application. Unlike text-based languages where new logic can be inserted easily, adding logic to a VI involves "freeing real estate", reconnecting wires, and decomposing logic into sub-VIs. It also becomes difficult to separate data when dozens of different streams (wires) are used, and comments are difficult and time-consuming to insert.
- The application does not scale well to an enterprise-wide solution. Since LabVIEW is used primarily to connect a PC to a single test instrument, there is not the middleware support found in enterprise solutions like connection pooling or distributed data caches.

- There are no out-of-the-box user authentication utilities or other developer frameworks. This increases the level of development effort when access control needs to be restricted for security or privacy.

5.3 Measurement dashboards

The dashboards deployed in the microwave area serve three purposes: production monitoring and control, process improvement, and communication. As such, the dashboards are designed to be interactive, not passive, and provide functionality to drill-down into details and to lead to corrective action on the floor. Another objective was to make the dashboards as intuitive as possible. One means towards that end was designing each dashboard with a common interface and common convention. For instance, the following color scheme is repeated throughout the dashboards: dark green is good, red is bad, yellow is a warning condition, and lime green represents the goal for a given metric.

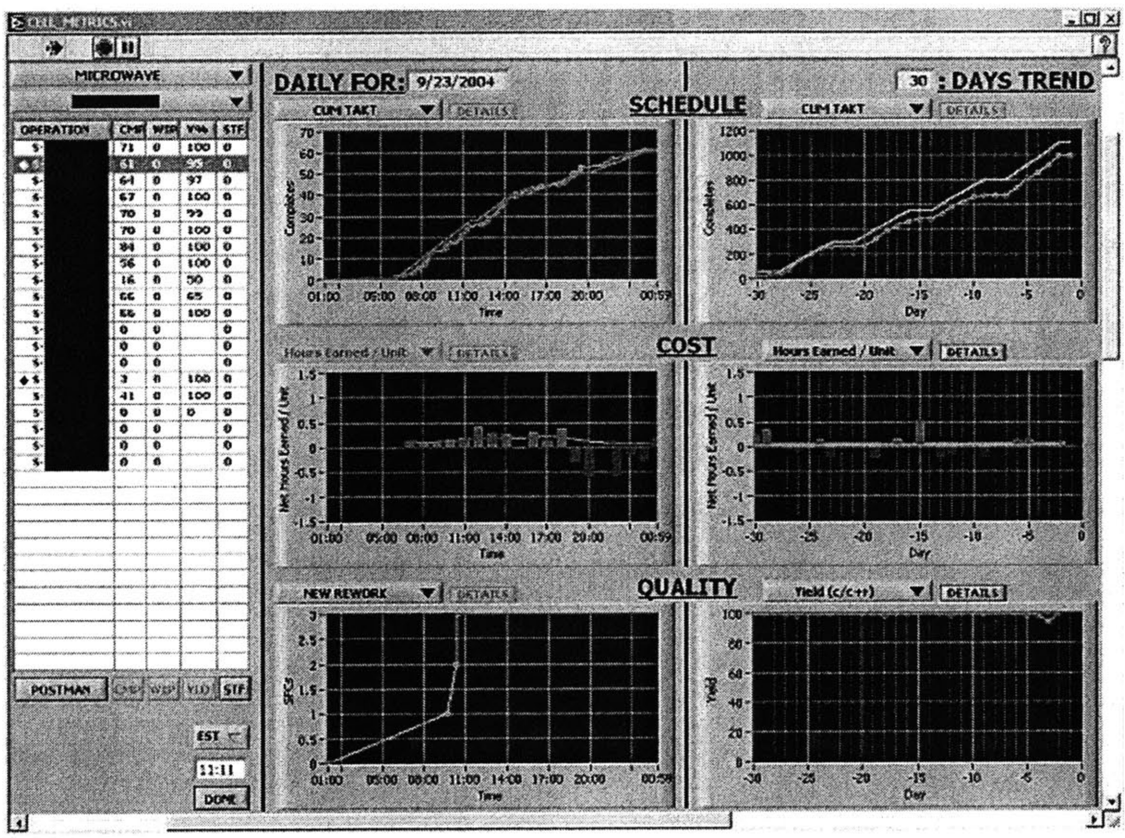
5.3.1 Area Metrics

The visual factory team is in the process of deploying area metric dashboards across the IADC. Designed with a common interface, these dashboards are meant to give passers-by the high-level performance of the area at a glance. Each dashboard displays up to eight key performance indicators for the area using a needle gauge. One needle points to the current value of the metric for the day, while another provides a historical value for the metric so that one can determine if the process is improving or deteriorating. The scale of each gauge is color coded (red, yellow, green) to provide for intuitive interpretation. One challenge with this dashboard has been designing metrics that are meaningful when data for all the different programs in an area are combined. For instance, an average measure of cycle time is of little value if the area includes products with a high range in cycle time values (from a day to a month). Depending on the mix of products moving through the area on a given day, this needle would bounce up and down in response to the change in mix allocation across products. If cycle time is indeed a key performance metric, measures like the percent above or below the target cycle time might be more appropriate for a high-mix area to factor out product-specific differences. Tufte, a pioneer in the field of technical data displays, also discusses the idea of information density in determining the quality of a display. In this case, each gauge only conveys two points of information: the current value and the trend value. The graduations on each scale convey very little information since they aren't normalized across all sites – the data could be represented just as easily with two numeric values. A more information-rich gauge could be a histogram or cumulative probability plot for each metric, which can also indicate the leading drivers behind the metric.

5.3.2 Cell Metrics

Cell Metrics was the primary interface designed for the Microwave area. It was so named because the granularity of data presented is appropriate for a cell team – typically three to five operators responsible for one or two operations on a given item. The dashboard shown in Figure 5-9 is deployed on a ten foot projection screen visible from virtually all stations in the Microwave area.

Figure 5-9: Cell Metrics Dashboard



The dashboard is divided into three vertical panes. The left-most pane acts as an andon board, providing current completes, WIP, cost, yield, and staffing levels for each operation for the selected item. Individual squares are highlighted in yellow and red to highlight areas that have fallen outside of the range of acceptable values. This allows operators and supervisors to see at-a-glance the areas that are in need of attention for manage-by-exception run rules. Diamonds to the left of an operation indicate that an issue has been reported and needs supervisor or engineering input.

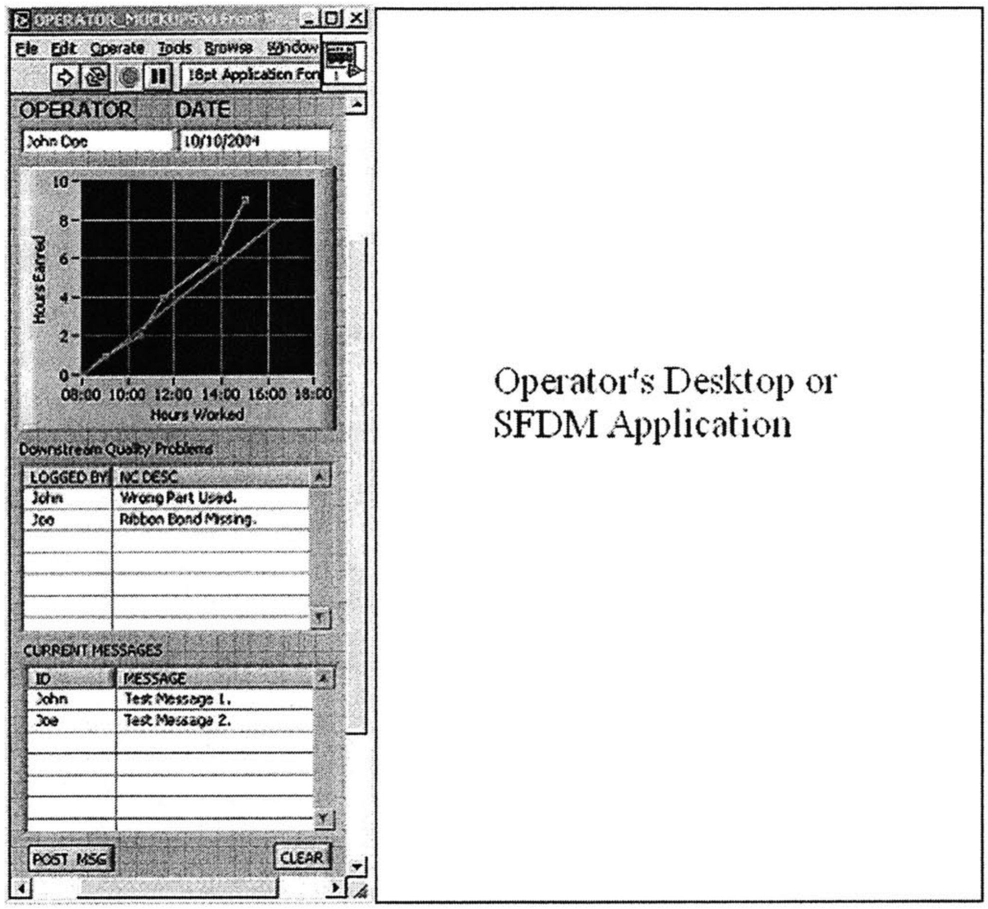
The central pane provides schedule, cost and quality data for the current day (or any day in the past). The right-most pane provides trend data for schedule, cost, and quality data over the last 30 days. The dropdown menus above each metric allow the user to vary the metric displayed, for example quality data can be toggled between total defects and yield. When issues are detected, the "details" button can be pressed to launch a popup menu with the investigative tools described below.

Padma Vanka, LFM '04, instituted a regular 9:22am meeting each day to facilitate better communication in the Microwave area (9:22am was chosen to emphasize a new attention to detail and timeliness). The Cell Metrics dashboard is now used in each morning meeting to review performance from the prior day for each item, address any outstanding issues logged, and review the goals for the current day.

5.3.3 Operator Metrics

Design was also done for a dashboard that could be deployed on each operator's station to communicate individual takt time objectives, downstream quality issues, and targeted messages. Although it was never implemented due to the high-cost of developing the necessary privacy and authentication mechanisms, the mockups are presented Figure 5-10 for illustrative purposes.

Figure 5-10: Operator's Dashboard



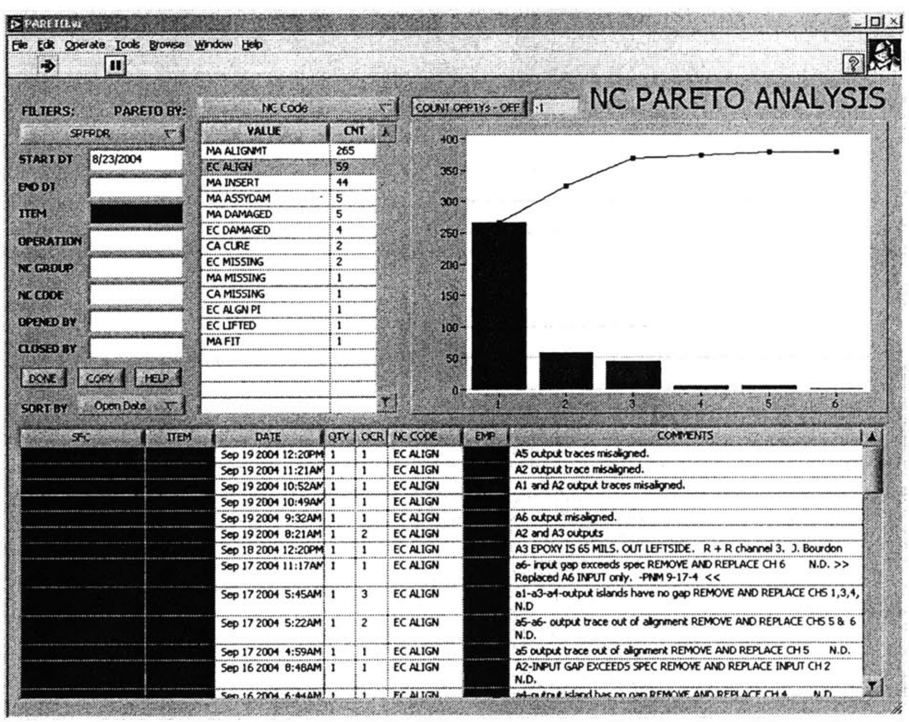
5.4 Investigative Dashboards

While the dashboards above act to measure performance and identify out-of-norm conditions, separate tools are necessary to investigate issues, find root causes, and implement corrective actions.

5.4.1 Pareto Tool

The Pareto tool shown in Figure 5-11 provides a mechanism to characterize quality problems for root cause investigation. The left-most pane allows the user to define a date range and optionally select an item, operation, defect code, and/or operator associated with a non-conformance. The center dropdown titled "Pareto By" lets the user select how non-conformances are grouped for the Pareto chart. For instance, Pareto-ing by date can determine if the non-conformances were isolated to a few particular days or have been consistent across the date range selected. Pareto-ing by non-conformance code will indicate the error types with the highest frequency of occurrence, suggesting those that should be addressed first. The table at the bottom provides details for the selected group of non-conformances, including notes entered by the operator which can help in resolving the given issue.

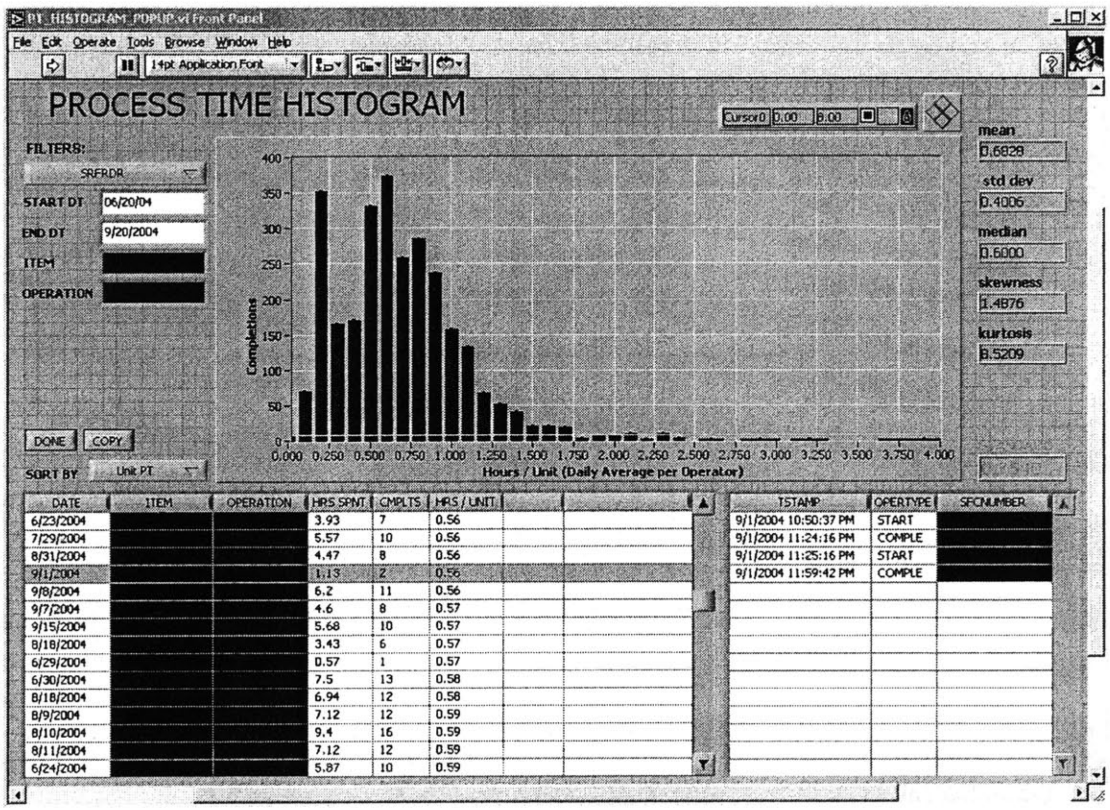
Figure 5-11: Pareto Analysis Tool



5.4.2 Process Time Histogram

As the name suggests, the Process Time Histogram tool shown in Figure 5-12 provides a histogram of the individual process times over a given period for a selected item, operation pair. The tool helps to characterize the variation observed in the process to understand any schedule or cost issues. The tables at the bottom provide the transactional data that is necessary to determine the operators, times of day, and work profiles for the selected events.

Figure 5-12: Process Time Histogram Tool



5.4.3 Communication Tools

The main dashboards provide an interface to a two-way communication tool that lets both operators and supervisors log and resolve issues. Entries might include tooling problems that need immediate attention (akin to pulling an andon cord), suggestions for process changes to resolve observed non-conformances, or simply recognition for outstanding performance. Severity levels can be selected, and time-to-resolution is calculated. As will be discussed in chapter 7, the communication tool was a big factor in winning the support of the individual operators. While it was understandable for them to feel threatened and initially resist the implementation of performance measurement tools, the communication tools were empowering, providing a way for them to improve the process and get the prompt attention of supervisors and engineers when needed. The tools also show that the new culture of measurement is not just focused on hourly workers – supervisors and engineers could now be measured on their responsiveness with metrics such as total outstanding issues, and average time to resolution.

5.4.4 Set Cell Targets

Several additional interfaces were designed to populate the control tables. This data is necessary to establish the daily goals for each metric and provide the range of acceptable limits (e.g. maximum WIP levels, +/- 10% of the daily completes goal, etc.). The area manager will regularly (weekly, at a minimum) launch this application to review the current goals and make adjustments as necessary. An automated interface to Raytheon's MRP system was investigated but not implemented for two reasons. First, the cost of building the interface wasn't justified for a single production area. If the Cell Metrics dashboards gain more widespread adoption and these costs can be allocated across several areas, it might be more economically feasible. Second, daily production plans don't necessarily follow the weekly or monthly projections identified by MRP. For instance, supervisors should have the flexibility to reduce a daily throughput target if a substantial number of employees are absent, downstream backlogs exist, or there is a material shortage. Once the problems are resolved, the supervisor can establish a new daily throughput level to meet the end-of-month requirement from MRP.

5.5 Summary

This chapter reviewed both the traditional single-use performance indicator dashboards and the more modern multi-use, dynamic dashboards being developed by business intelligence software vendors. The dashboard environment selected for Raytheon was reviewed next, followed by a summary of the specific dashboards developed for the microwave area. The next chapter will present case studies in which these dashboards were put to use to enable process improvements.

6 Process Improvement Results – Case Studies

The ideas presented in the previous chapters are tested in this chapter with several case studies conducted at Raytheon. The improvement process used at Raytheon is described, along with tangible results for several improvement efforts aimed at increased throughput, reduced throughput variation, and reduced process time.

The real benefit to measurement systems is the opportunity presented for process improvement. By establishing a process baseline, one can then identify abnormal or unpredictable behavior, compare responses to different input factors, and quantify the benefits to different change initiatives. The case studies below provide examples for how the dashboards have been used to improve several processes.

6.1 Kaizen Events

Each case study improvement effort was launched with a Kaizen blitz – a focused effort for continuous improvement. Each one-hour session involved all the operators assigned to a given process and was led by the responsible process engineer. Each session followed the Plan, Do, Check, Act cycle recommended by Shewhart and Deming.[31]

PLAN: The dashboard was first reviewed to illustrate the issue at hand and the deviation from the desired behavior. A root cause investigation was then led, with feedback solicited from each operator to try to explain the issue. Each operator was asked for suggestions for changes to improve the process, and a plan was devised.

DO: The new plan was implemented, with commitment from all the operators and support personnel to follow the plan for a specified period.

CHECK: The dashboards provided immediate feedback to check the effectiveness of the new plan. When the desired behavior was not observed, the team returned to the planning process.

ACT: Once the desired improvement was achieved and stable, the final step was to document the improvement with changes to work instructions to achieve standard work. Public

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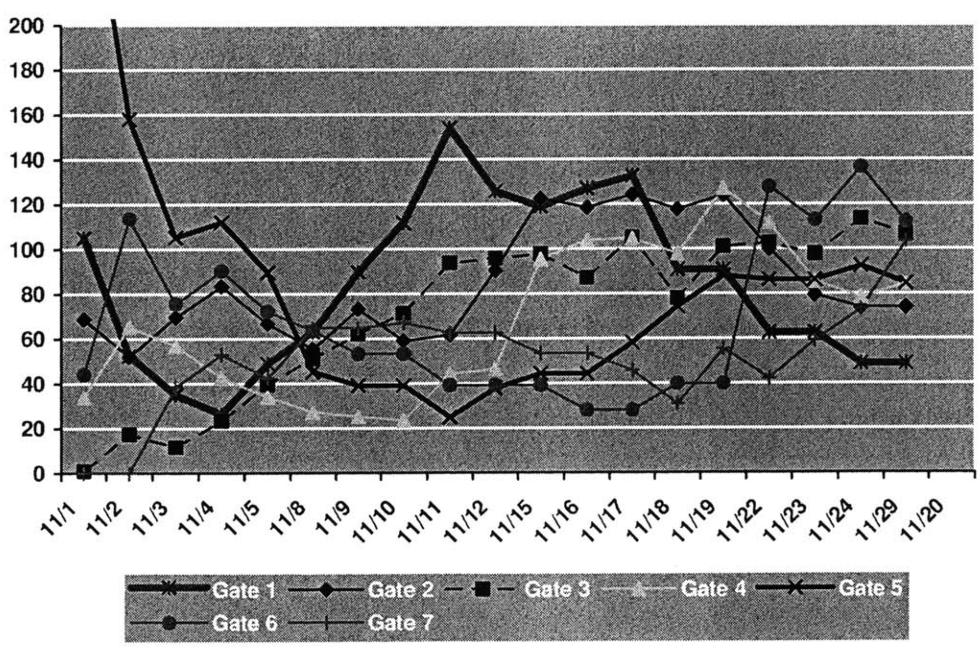
[31] Shiba, p. 82

recognition and / or financial bonuses for the team's achievement were awarded, and suggestions for further improvements were also noted.

6.2 Coordinated Production and Variation Reduction

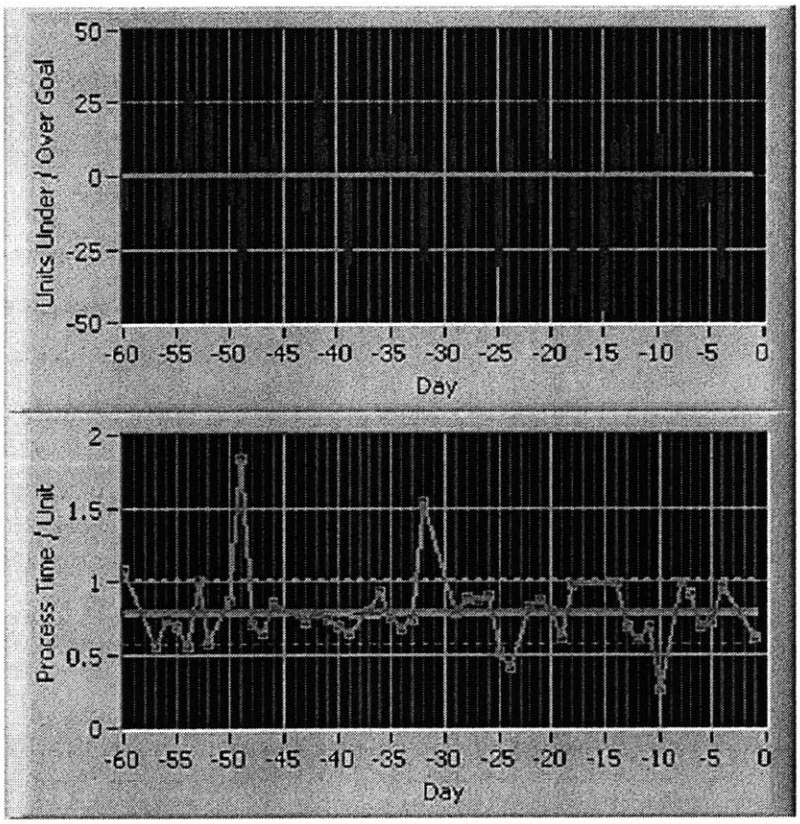
One of the Microwave area's primary goals is to coordinate production from part to part and operation to operation to achieve balanced flow – consistent level of daily output. Coordination is important to reduce WIP and cycle times, improve planning and yields, and establish predictable results. The chart in Figure 6-1 shows how the daily production for a given part at seven operations fluctuates over a three week period. The throughput at gate 1 and gate 5 shows the typical behavior: when gate 5's output is high, gate 1 is low, and vice versa. In order to meet weekly commitments through each gate, the typical behavior is to overstaff the later operations, essentially draining all WIP from the system to meet the commitment. The next morning, the lack of WIP in the system means the early operations must be overstaffed to fill the pipeline. "Feed the Beast" literally became a call to order to fill an oven which cycles twice a week. This lack of coordination has several implications: operators often aren't trained in all the necessary operations, there can be tool or workstation shortages, increased costs for poor quality, and increased inventory storage and handling costs.

Figure 6-1: Uncoordinated Production



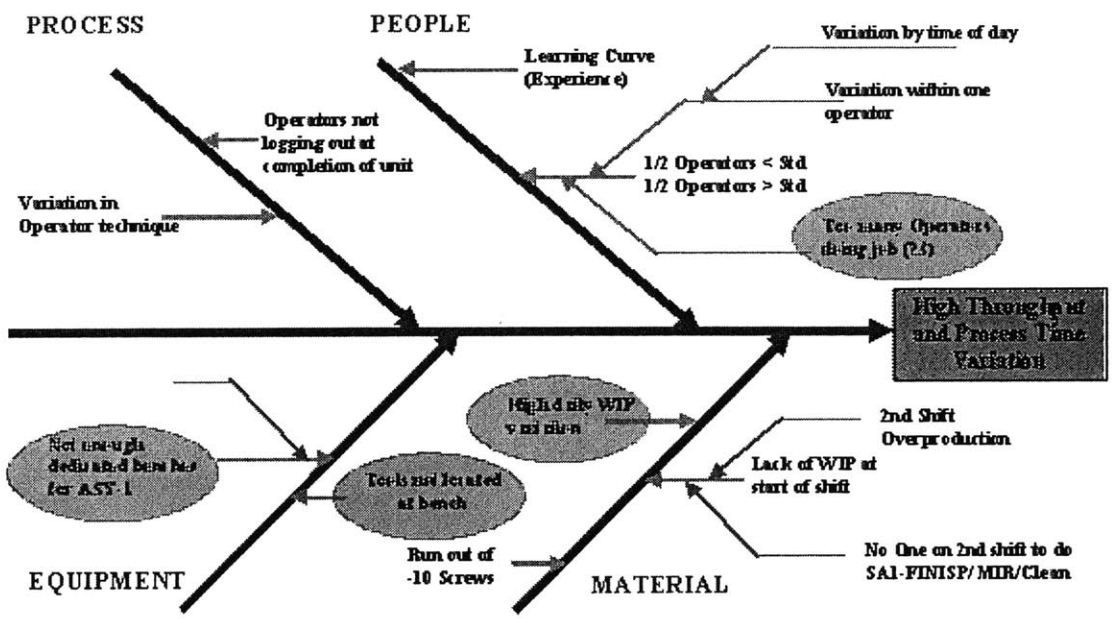
The screenshots from the Cell Metrics dashboard in Figure 6-2 show high variation for a given operation in both throughput and process time, and a correlation between the two. When the process time per unit increases beyond the standard, the area has trouble meeting the daily commitments. When process time is less than the standard, the area overproduces, although a direct causal relationship can't be deduced. A Kaizen Blitz was organized to reduce the variation in both the daily throughput rates and the process time. Once the process becomes stabilized, future blitzes will be scheduled to reduce process time.

Figure 6-2: High Variation in Throughput and Process Times



The root cause analysis in Figure 6-3 was compiled to explain the high variation. Four causes were singled out as being the most significant. First, 23 operators had worked the job over a three week period, while only three were necessary to meet target production rates. This suggests that the area is operating at a lower point on the learning curve, and that higher operator training costs are realized. Second, there is high variation in WIP. Operators explained that they are often starved for material, and the typical response is to simply "extend" the process time for the current unit until another piece of WIP arrives. Third, there often are not tools available at the bench to perform the necessary work and operators often passed a tool from station to station. Tools had historically been stored in a common tool corral. At the start of the shift, each operator would get the tools necessary for his or her station. Since operators often worked more than one station as WIP bubbles were chased through the system, operators would grab all the tools they thought they might need. One operator said, "If I don't get in early to get my tools, I'm doomed." The tool shortage problem is exacerbated when an operation is overstaffed. Finally, operators complained that there are not enough stations dedicated to each operation. Although WIP racks were located next to the assigned stations, workers would often have to work on the other side of the area and physically move WIP back and forth.

Figure 6-3: Throughput Variation Root Cause



The following steps were implemented to improve operation:

1. The "feed the beast" behavior was identified as being counterproductive. The area's manager now prioritized consistency over meeting the weekly goal at all costs.

2. Three benches were dedicated to the operation and would be fully staffed. Each bench had its own toolbox – a foam shadowbox tray with cutouts to match each tool's shape.
3. Takt time and WIP levels would be strictly adhered to by shift. Problems often resulted from second shift over producing, leaving insufficient material for first shift the following day. These objectives are made easier because this is the first operation in the item's assembly.

The screenshots in Figure 6-4 show the results of the Kaizen event. Production levels were stabilized (the initial overproduction was necessary to put sufficient WIP into the system and the shortfalls at the end were due to supply chain issues). The process time variation was also considerably reduced, with the average process time below standard for all days following the improvement efforts. The tools proved valuable to monitor the change efforts on a daily basis, providing immediate feedback to operators and supervisors alike.

Figure 6-4: Throughput Stabilization Kaizen Event

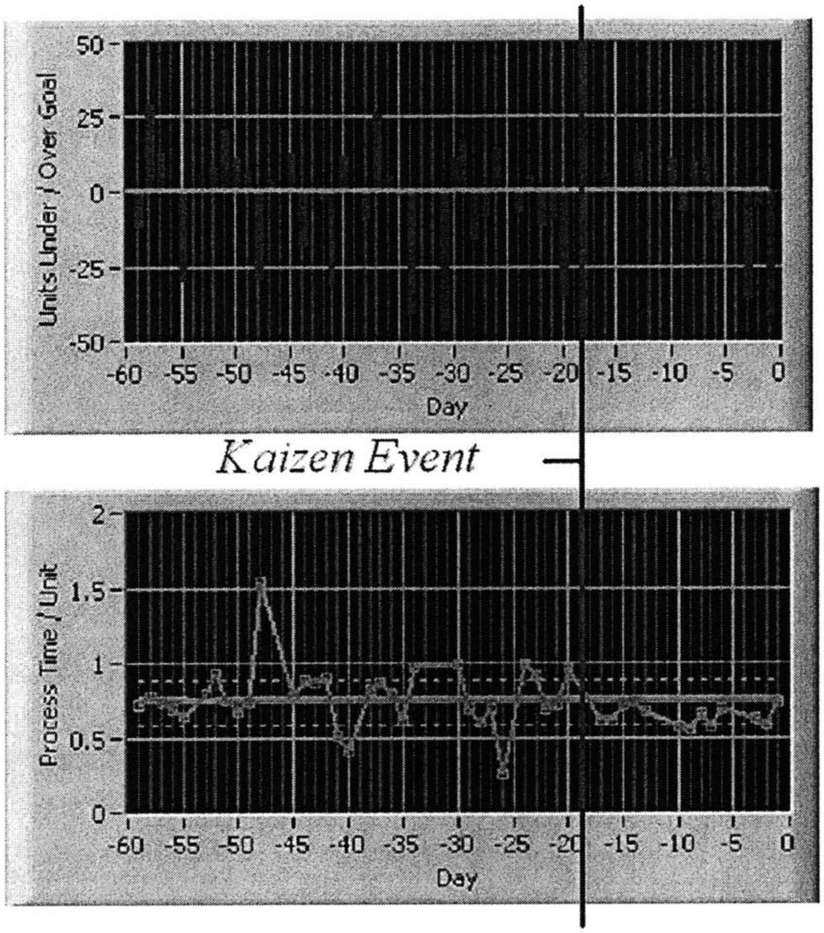
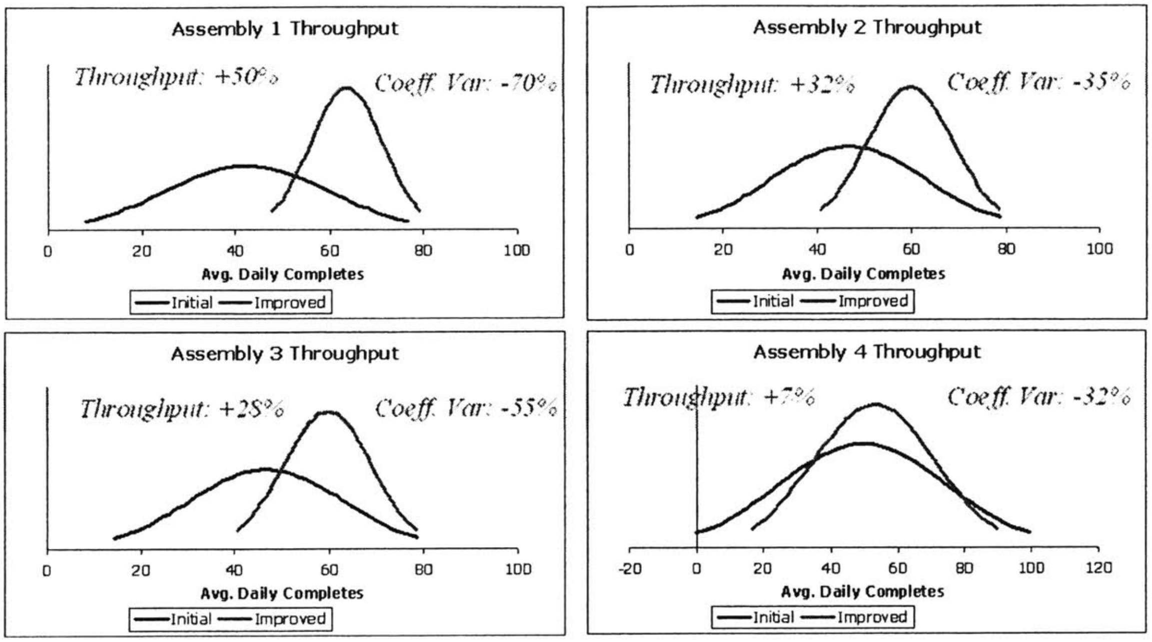


Figure 6-5 shows how throughput and variation were improved at Assembly 1: a 50% increase in daily throughput, and a 70% reduction in the coefficient of variation. The coefficient of variation is a unit-less ratio of the standard deviation to the mean of a process, and is used here to normalize the variation of the process by the mean. What was most surprising in these results was how the change effort at assembly 1 affected the rest of the system. Assembly 2, 3, and 4 (the next three operations) also realized increased throughput and reduced variation. This suggests that stabilizing the first operation is key to achieving stabilization down the line.

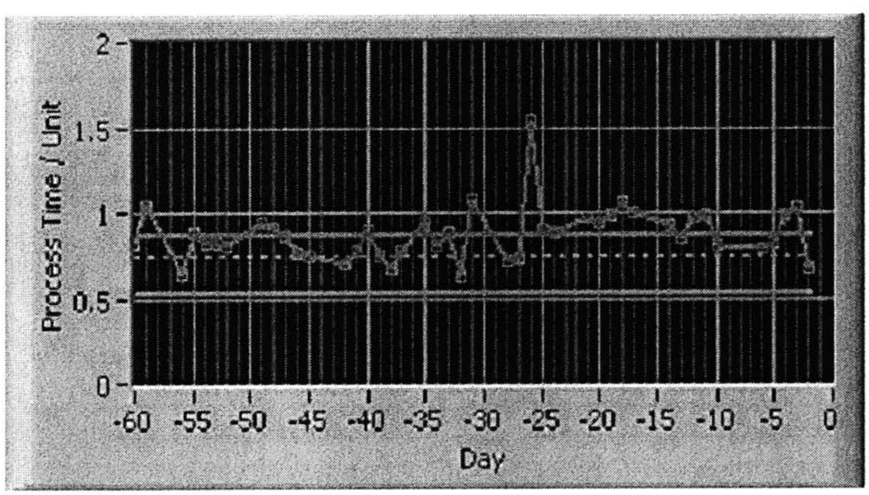
Figure 6-5: Throughput Improvements



6.3 Process Time Reduction

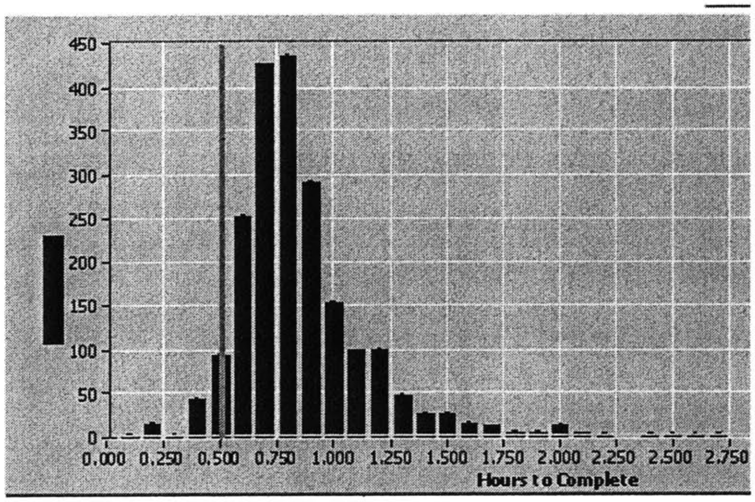
Assembly 2 experienced much less variation in process time, but the process times were consistently 170% of the budgeted goal, as shown in Figure 6-6. The objective of the change effort in this second case study was to keep the distribution tight, but shift the mean considerably.

Figure 6-6: High Process Times



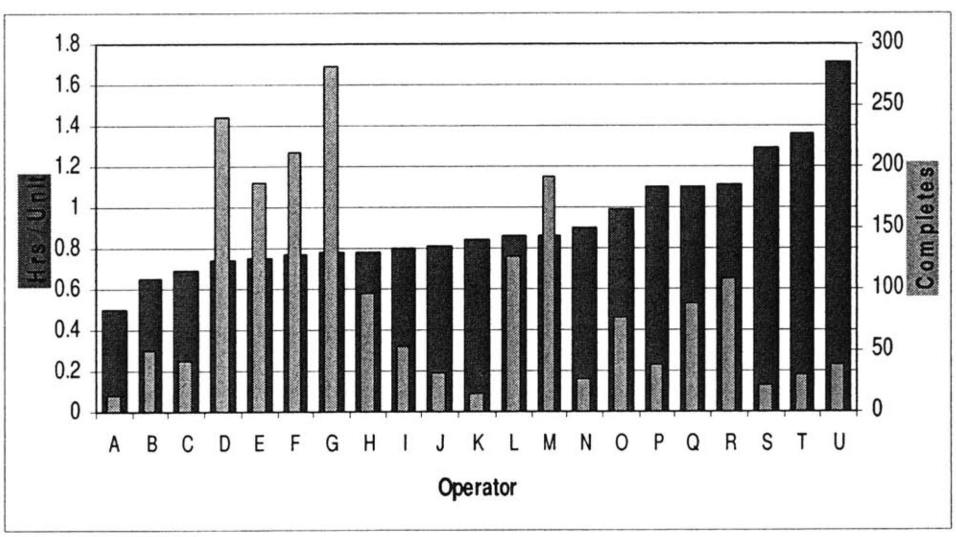
The Process Time Histogram tool was used to characterize the process. As can be seen in Figure 6-7, the distribution is fairly tight across all completes, and there are very few instances of items being completed at or below the goal.

Figure 6-7: Process Time Histogram



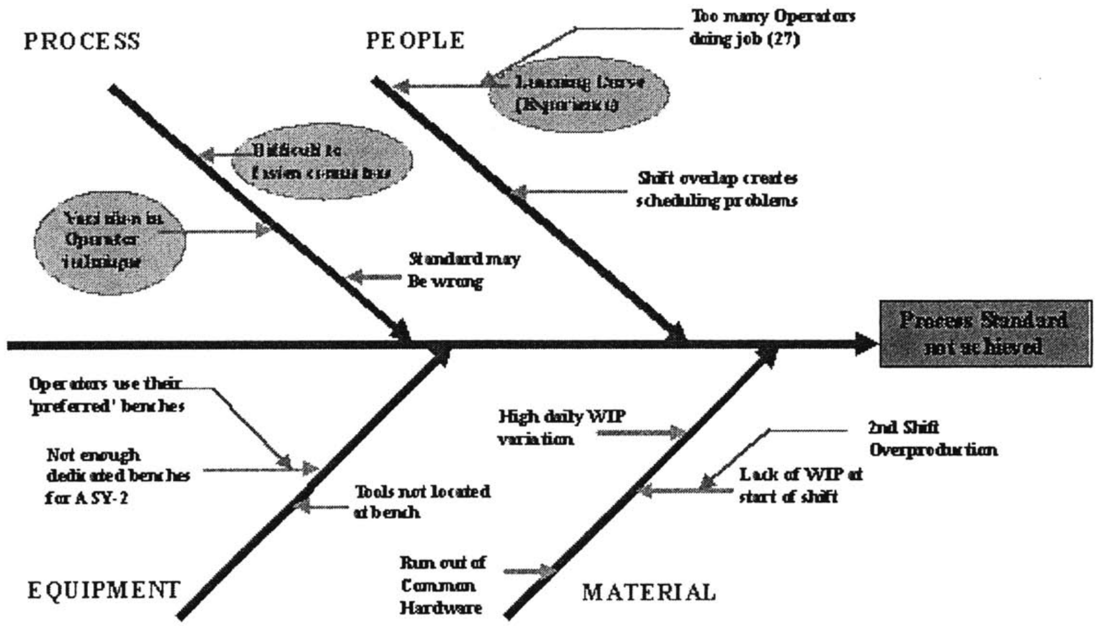
When the Process Time Histogram tool was used to understand the average process time for each operator, a correlation was observed between the number of completes and the average process time, as illustrated in Figure 6-8.

Figure 6-8: Average Process Times by Operator



Again a root cause analysis was performed as illustrated in Figure 6-9, with three leading factors identified. First, the operation involves a steep learning curve and too many different operators had worked the assembly, driving down the average process times. Second, operators noted considerable variation in technique, with little standardization. Third, operators suggested that several connectors were difficult to fasten. The process time goal was established with standard times for each fastener, but operators noted that it took four or five times as long because they could only get a quarter-turn of the wrench at a time due to tight spacing.

Figure 6-9: High Process Time Root Cause



The following changes were implemented:

1. Process Engineers designed a special tool to reduce the time required to connect the difficult cables. Each tool cost less than $1.

2. Standard work procedures were defined and strictly followed.

3. Dedicated benches and toolboxes were created.

4. Takt times and WIP levels were strictly enforced.

As a result of the changes, the process time was reduced 21%, or 11.5 minutes per subassembly. This resulted in a labor savings of roughly 600 hours per radar.

6.4 Summary

This chapter presented two case studies that illustrate how to identify opportunities for process improvement, investigate alternatives, and monitor changes with visual indicators. In the first example, the daily throughput indicator highlighted the inconsistency in daily completes, which previously had gone unnoticed because the variation was dampened in weekly or monthly summaries. In the second example, the process time per unit indicator was instrumental in identifying the operations that were consistently completed above budget. The histogram investigation tool allowed the area to search for trends in processing times by operator, by day, and by shift, and to ultimately determine the root cause was more systemic. Finally, the indicators allowed both operators and supervisors to monitor the effectiveness of their changes, a critical but often neglected step in process improvement programs.

7 Organizational Analysis

This chapter analyzes the larger organizational framework in which the change effort was implemented, noting both positive and negative influences. The approach, described by MIT professor John Carroll, analyzes the organization from three lenses: the Strategic, Political, and Cultural, to gain a better understanding of the organization.[32] Neely introduces some of these barriers to measurement and improvement programs in writing, "The real challenges for managers come once they have developed their robust measurement system, for then they must implement the measures. As soon as they seek to do so they encounter fear, politics and subversion. Individuals begin to worry that the measures might expose their shortcomings. Different people seek to undermine the credibility of the measures in different ways. Some seek to game the system. Others seek to prevent it ever being implemented."[33]

7.1 Strategic Design Lens

The strategic design lens looks at how structures, resources, and information flows are organized to make decisions to support the company's strategic goals. Raytheon historically has been organized by functional group. Recently, the company has shifted to more of a matrix organization, with employees still reporting primarily through functional groups, but also being assigned to cross-functional customer-focused teams. This new structure has helped the company be more customer-focused, shorten planning horizons, and increase efficiency. This new structure has also brought increased focus on cost. As mentioned earlier, the Radar Affordability Program was a cross-functional team organized around reducing the cost of each of the next three radars by 10%. This high-level visibility provided much needed support for the change initiatives of my internship. Despite this progress, the company still operates with a hierarchical, functional group structure where individuals are often unable or unwilling to assume responsibility or take initiative in areas outside their prescribed role. The greatest example of this functional focus is in the division of labor between union and non-union employees. The union rules and cultural biases suggest that the operators' primary role is to build the product, and support personnel are there to give direction and supervise. Many opportunities for improvement are lost because either the rules forbid certain behavior, or the

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[32] Carroll, p. 3
[33] Neely, p. 1142

cultural expectation is that it is someone else's responsibility. As an example, the team waited three days for a unionized facilities employee to adjust the dashboard's projection system – a 15 second fix that simply required adjusting one screw. In Michael Hammer's terms, this inefficiency is ripe for reengineering, and he suggests new work rules can succeed with union involvement from the beginning and a firm commitment from management.[34]

The functional separation of operations and Information Technology also presented challenges for the project. The IT organization is centralized, serving all the different Raytheon locations and functional groups. While this centralized structure helps to ensure consistency and compatibility across the organization, it is detrimental to groups that want non-standard systems support. Many areas in the IADC had actively looked for information technology solutions that could be implemented without the support of IT because they had been dissatisfied with the response times, or weren't allowed to introduce non-standard practices. This structure works to discourage innovation, or encourages secret innovation where the benefits are slow, if ever, to reach other areas of the company. A shift to a more decentralized IT organization where each functional area would have one or more dedicated IT professionals would provide for faster response time, higher satisfaction, and likely better implementations which utilize and leverage the strengths of IT, rather than trying to circumvent them.

The Raytheon Six Sigma program described earlier is an excellent tool to show executive commitment to measurement and process improvement, and to include every employee in the process. The goal of 100% participation sends a clear signal that this initiative is an important part of the company's strategy. One challenge the company faces is how to most effectively share and propagate the learnings of each individual project. The Six Sigma team has developed a central knowledge database that stores all the data associated with a project, but employees are still not conditioned to search the database either formally or informally for ideas. The result is that many similar projects will be launched in different areas, each implementing slightly different solutions, where a single top-down implementation might offer a better, more consistent solution at lower cost. This issue is common to almost all knowledge management programs and will likely improve with familiarity and experience with the system.

[34] Hammer, p. 244

Finally, one of the goals of this internship was to implement more of the systems typically found in a strategic-focused organization. Measurement systems, information-informed decision-making, and formal process improvement procedures are all hallmarks of a strategic organization. Raytheon's willingness to embrace and support these initiatives indicates that the company is changing, and that strategic purpose is gaining influence within the organization.

7.2 Political Lens

The political lens views an organization as a collection of individuals, each amassing power and influence to achieve their own interests and those of their stakeholders. Power and influence have traditionally been gained through tenure and title at Raytheon. This respect for seniority is due in part to the fact that the branches of the military are Raytheon's largest customers, and that many of Raytheon's employees are veterans. Perhaps more explanatory is the fact that one of Raytheon's greatest assets is its experienced workforce, with many senior executives having worked for the firm for over thirty years. While there are signs that the organization is shifting towards more of a meritocracy, the process is slow in a 78,000 employee organization. Fortunately, the Visual Factory project had the support of the IADC's plant manager, and without this support the project certainly would have suffered. Within the Microwave area my change efforts also had the full support of the value stream lead, his direct reports, and most notably the area manager and the process engineering manager who each played a hands-on role in developing and using the performance indicators. Again, with power concentrated in management positions, this project could not have been successful without this support.

Due to the sensitive nature of Raytheon's work, U.S. government security clearances are necessary to visit many areas of the plant. These security clearances also present a source of power for different individuals. Each employee's badge is color-coded to indicate their clearance level: yellow for no clearance, blue for confidential, red for secret, and green for top secret. Because an individual's clearance dictates their level of access to information and facilities, individuals without clearance can be at a clear disadvantage.

The union also had considerable power at the IADC. Supervisors quietly complained that there was little they could do to combat absenteeism or poor performance. The Microwave

Area experienced absentee rates as high as 30% several days during the summer, with lost wages being the only management lever for discouragement. Supervisors also suggested it was easier to "hide" underperformers than to take disciplinary action due to the union regulations. As a result many teams were formed by grouping two or three star performers with one or two underperformers in the hopes that their collective performance would balance out at the standard levels. The measurement dashboards now provide a tool that lets supervisors review an individual's performance in an objective manner, and the hope is that the area will shift from "hiding" underperformers, to identifying performance issues and working together to find ways to improve that performance.

7.3 Cultural Lens

The cultural lens views an organization from the collective history, attitudes and beliefs of an organization, and how these factors affect decision-making. Like all defense contractors, Raytheon had operated for decades with many of their contracts being cost-plus: the cost of time and materials, plus a reasonable profit margin for Raytheon. Further, once many of the contracts were secured, there was little or no external competition until the contract expired. So long as Raytheon met the terms of the contract, the revenue stream was all but guaranteed. These contracts contributed to a culture that lacked competitiveness and cost-consciousness. The culture at the IADC was also primarily low-volume. Operators were accustomed to building high-value, low-volume parts in a job-shop fashion. Therefore concepts like standardized work, continuous improvement, and metrics-driven decision-making were relatively novel.

The visual factory project had significant symbolic meaning at the IADC. Operators initially viewed the tools as a threat – a way to "crack the whip" harder to get higher levels of productivity. Management saw the tools as a necessary means to understand their processes and improve them to generate more value for both Raytheon and the customer. The tools were framed as a way to help the organization work smarter, not harder. Operators and managers alike were frustrated with the amount of rework and non-value-added work content in each part. There were two key breakthroughs that helped secure operator support for the tools. First, the initial emphasis was placed on achieving improvements as a team, and not on measurement and individual evaluation. When areas were not meeting the stated objectives, no individuals were singled out as cause. The area was consulted as a group, and the entire area was involved in the improvement. In the case of the assembly 2 process time reductions, operators realized that their jobs were made easier, AND the throughput levels increased – a win for both operators and supervisors. Second, the dashboards included a communication tool that allowed for two-way communication. This single act of empowering the individual operators was a significant step in challenging the belief that communication was one-way, from management to operators. While much work is still needed, changes are underway to improve management and union relations towards more of a team approach. One of the ultimate goals of the project was to push decision-making down to a lower level, empowering operators to take the initiative to self-manage, reducing the need for supervision.

The low-volume culture that pervades the IADC also has an aspect of individuality and operator autonomy associated with it. In one Kaizen blitz, supervisors suggested changing the layout of the work center to group all similar operations together, and to arrange the workbenches so that material would flow more smoothly. The operators quickly rejected this suggestion, claiming their productivity would be higher by working benches grouped by the strength of interpersonal relationships, not the material flow. The power of the operators was evident because the suggestion was not implemented, despite the fact that it would have reduced both operator and material travel times. The IADC benefits greatly from the positive relationships between management and the union, and among the long-tenured union employees themselves, and the modest cycle time reductions from this change were not worth jeopardizing the balance of power that has proven successful over time. This issue also illustrates the power of precedent in company cultures: because operators had become accustomed to autonomy in their workspace, changing the rules mid-program was far more difficult than changing the rules at the beginning of the next program.

7.4 Summary

Selecting data management systems, metrics, and display technologies is often the easiest part of a performance measurement program. The strategic, political, and cultural forces within an organization can present far greater challenges and should be evaluated and consulted throughout the design and implementation process to improve both the quality and level of acceptance of the program.

8 Conclusion

This work explores the idea that decision-making can be improved through the automated transformation of data into information for real-time display on the factory floor. This thesis reviews the technology infrastructure components, evaluation metrics and presentation displays deployed at Raytheon Company that can not only characterize a current process, but also suggest opportunities for process improvement. Several case study examples illustrate the identification of a process issue, the investigation of root causes and improvement alternatives, and the evaluation of change efforts, all using visual performance indicators.

Work for this thesis resulted in several interactive dashboards in the Microwave area that characterize the production process in terms of schedule, cost, and quality compliance, with additional tools to investigate non-conforming processes. The tools were first leveraged to improve line coordination and reduce process times for the radar sub-assembly process, resulting in a 50% increase in throughput, 70% reduction in throughput variation, and a cost savings of over 600 hours per radar for the targeted processes. More importantly, the technological and cultural foundations for continual process evaluation and improvement were laid, which have the potential to yield far greater improvements in the future.

8.1 Lessons Learned

Several key lessons were learned in the application of performance metrics in the microwave area which can be of benefit to future Raytheon performance management programs.

- The benefits of visual performance metrics are most pronounced when coupled with strong management support and communication.
- All metrics influence behavior, so metrics must be chosen wisely to elicit the desired response.
- Do not underestimate the resistance to performance measurement and change efforts. While all change initiatives undoubtedly face resistance, performance measurement changes can be particularly difficult if individuals perceive that the primary objective is performance measurement, not improvement.

- Operators should be included in the process of identifying opportunities for improvement, proposing alternatives, and owning the path to resolution to increase the acceptance of the changes, but more importantly, to improve the quality of the solutions themselves.
- Users can quickly become desensitized to information displays if they are not timely, accurate, and straightforward.

8.2 Recommendations

The following list provides recommendations for both the Microwave area, and Raytheon Company in general, to further leverage the work done to date to improve the effectiveness of their performance management programs.

- Establish target performance objectives early in each program lifecycle. Significant resistance to performance measures could have been avoided had the measures been established early, in consultation with both management and operators.
- Investigate an enterprise-wide data warehouse strategy. Both the quality of the data and the breadth of data available to each area would be improved with a comprehensive data warehouse installation.
- Investigate alternative display technologies. While LabVIEW was sufficient for point solutions in the Microwave area, it lacks the infrastructure and flexibility necessary for an enterprise-wide performance management program.
- Leverage the tools developed for the Microwave area to other IADC areas as well as other facilities. The tools developed for the Microwave area can easily be extended to support production processes and products in other areas.
- Implement additional visual tools like stacked bar charts and overlaid throughput data. These tools would help managers assess the performance for a given item across all operations at a single time, simplifying bottleneck identification.

- Revamp incentives to align with metrics. Some of the cultural obstacles faced during implementation can be overcome by changing the incentive structures for both managers and operators to encourage actions that improve metrics to help meet area goals.

This work shows some of the benefits that can be realized from a concerted effort to use information in daily decision-making in a production environment. By eliminating or substantially reducing the costs of data collection, synthesis, and presentation, visual performance indicators empower both operators and supervisors with information and provide an objective means to identify issues, communicate goals, and monitor the progress of improvement efforts.

Appendix A: Radar Subassembly Barcode R6S Project

This appendix is provided both to show the Raytheon Six Sigma process in use, as well as to provide an example for some of the data integrity issues that must be addressed before performance metrics can be accurately deployed. In many cases, data is manually entered into SFDM by operators. Not only is this labor intensive, it presents data quality challenges to downstream consumers. In the Microwave area, each radar subassembly is assembled with several transmit / receive modules, and the serial number from each module had been manually entered into SFDM and associated with its parent subassembly to facilitate lot tracking and in-field servicing. Early in the internship a Raytheon Six Sigma project was formed to correct the two short-comings of this system: the unnecessarily high cost of data acquisition, and the quality of the data entered.

Step 1: Visualize

The project had a clear burning platform: over 250 hours / radar were spent manually entering configuration data into SFDM, and the downstream error rate was estimated at 5%. The vision for the future was twofold: automated a manual process to reduce the labor content per radar, and improve the accuracy of serial numbers in the system to 100%.

Step 2: Commit

With funding secured from the project sponsor, we formed a multidisciplinary team including process engineers, IT staff, and procurement managers with transmit / receive module contacts in Dallas. We set two clear goals for the project: reduce data entry time by 90-100%, and eliminate configuration data errors.

Step 3: Prioritize

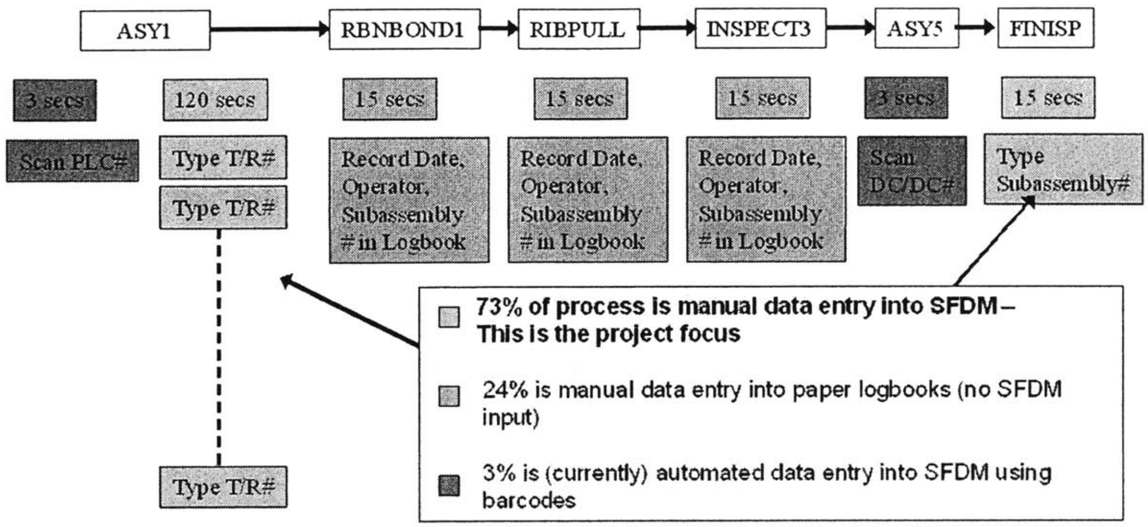
Consistent with Raytheon's customer-focus culture, we first completed a value stream assessment to understand the potential benefits of the change efforts. The team planned to first address data entry inefficiencies with transmit / receive modules in subassembly operations, then in follow-on phases address data entry with other components and in other operations, primarily test. The team targeted a completion data of September, 2004.

Step 4: Characterize

In the characterize step the team performed a time study to analyze all data entry steps in the radar subassembly final assembly process. As shown in Figure A-1, data entry consumes

186 seconds per subassembly, with 120 seconds being the manual entry of transmit / receive module serial numbers.

Figure A-1: Data Entry Process Times



The team next researched different implementation options to reduce the process time. The three most promising options are summarized in Table A-1.

Table A-1: Process Time Reduction Alternatives

Solution	Time Reduction	Traceability	Cost
Handheld Barcode Scanners	80%	100%	~$1,500
Lanco Optical Scanner	97%	100%	~$50,000
Eliminate S/N Capture Operation	100%	0%	$0

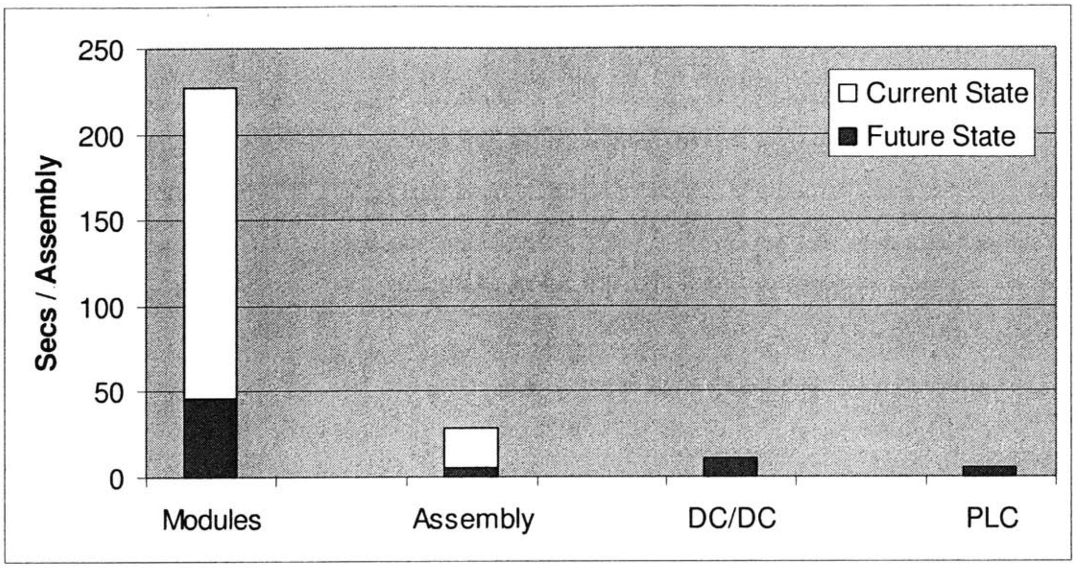
Step 5: Improve

The implementation plan required four primary steps:

1. Issue an Electronic Change Notice to the transmit / receive module supplier (a Raytheon division in Dallas) to begin printing serial number barcodes on the module covers.
2. Order six Intermec Scanplus 1800 handheld barcode scanners.
3. Configure scanners for code-128, test, and install at Assembly 1 and Final Inspection stations.
4. Train operators on new procedures and update process instructions.

The final step was to measure the improvements in process time realized from the change effort. Figure A-2 quantifies the improvements made.

Figure A-2: Process Time Improvements



Step 6: Achieve

The new process was embedded with the first module order for the following radar system. The target of reducing data entry time by 90-100% was not achieved because no affordable solution could ensure 100% traceability of transmit / receive modules. An 80% process time reduction was achieved, however, with 100% accuracy of configuration data. Additional processing time gains can be achieved in the future by converting the ribbonbond logbook to an electronic format.

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