

Process Management Principles for Increasing the Energy Efficiency of Manufacturing Operations

by

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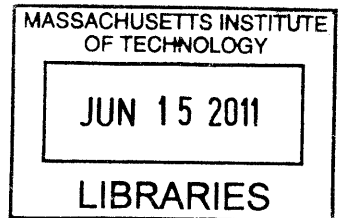
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Abstract

Energy usage is a significant operating cost for manufacturing facilities in the United States, and interest in energy management has been rising of late[1, 2, 3]. One approach, recommended by the Environmental Protection Agency (EPA), is to piggyback off of an existing lean program to reduce energy waste in manufacturing processes[4]. Just such a pilot program has recently been launched in a major manufacturing facility at Raytheon, where approximately 48% of the facilities' total energy is used on manufacturing processes. The program focuses on proven process management approaches and rides the coattails of the existing lean program at a major manufacturing facility by creating a pull for continuous improvement ideas[1].

The goal this thesis was to increase the efficacy of the existing program, and to develop a practical roadmap to guide energy managers seeking to execute such programs in manufacturing on the shop floor. We investigated three methods to enhance the program. One was to apply the Design, Measure, Analyze, Improve, Control (DMAIC) method, made popular in Six Sigma literature, to the energy waste reduction efforts of a manufacturing area. By shifting focus to more energy intensive equipment, the area quadrupled the amount of energy savings per improvement, and is in line to achieve a 10% reduction in electricity usage[5, 4].

The second method was to provide real-time feedback on electricity usage of energy intensive equipment to workers in a manufacturing cell. During an experimental period, we found that feedback ultimately engaged area operations managers who instituted an auditing program that reduced waste by 43% (or a 26% total reduction in usage) over a short period of time[6, 7, 8, 9].

The third method was to right-size equipment based on customer demand. An analysis of this approach based on field experience revealed that major savings (50% or more reduction in electricity usage) on targeted systems can be expected as companies remove "monument" equipment in supporting smaller and more responsive process flows such as true cellular manufacturing[3, 4].

In summary, we found that application of continuous improvement principles can positively impact energy efficiency programs at manufacturing facilities. In addition the three methods are different in cost and longevity, with the DMAIC and feedback at low cost and immediate impact (but potentially fading effectiveness), and right-sizing at higher cost, but producing longer term and potentially more durable savings.

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Chapter 1

Introduction

1.1 Motivation

In general, companies have two broad motivations for increasing their energy efficiency, defined as the volume of energy consumed per unit (or per dollar value): reducing cost in internal operations and external strategic considerations.

1.1.1 Reducing cost in internal operations

The energy costs for industrial operations in the United States are large and growing. In 2010, the industrial sector consumed 29.9 quadrillion BTUs of energy, or 32% of all energy in the United States, more than any other sector[10]. Consumption in this sector is expected to rise to 34.7 quadrillion BTUs by 2020, or about 0.5% per year. Current industrial energy costs depend on the source, as shown in Figure 1-1, with oil and electricity costing significantly more per BTU than coal or natural gas. In terms of percentage of overall industry-wide BTUs, natural gas is the most heavily used energy source, followed by electricity, oil and coal.

Energy costs vary widely across industries in terms of the proportion of costs attributable to support and process functions as well as energy intensity. Industrial energy support systems consist of steam systems, motor systems (i.e. pumps, fans, and air compressors) and building infrastructure (i.e. lighting and Heating Ventilation and Air Conditioning (HVAC)). Processes include all specialized manufacturing processes including industrial heating and cooling, machine drive, electrochemical processes, and office and workbench equipment. Over all industries, two-thirds of energy is consumed by processes, while one-third is consumed by support systems, though this ratio varies significantly by industry[3, 11].¹From an energy intensity perspective, figures range from 52.3 BTUs

¹Although energy consumed by support systems may contribute more to fixed costs, and energy consumed by processes may contribute more to variable costs, most manufacturing companies allocate all energy use, and its

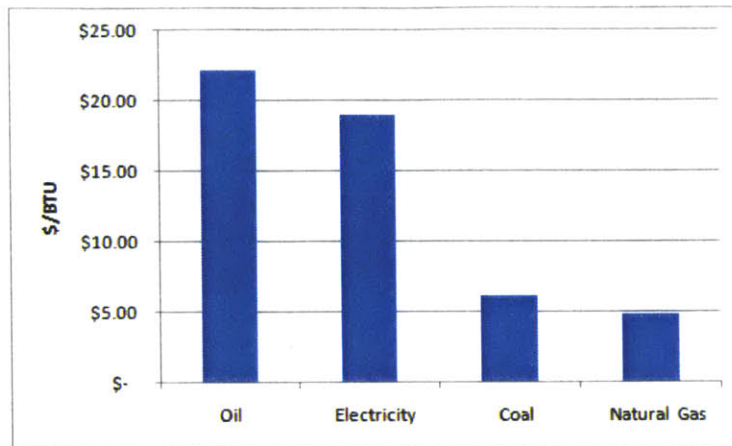


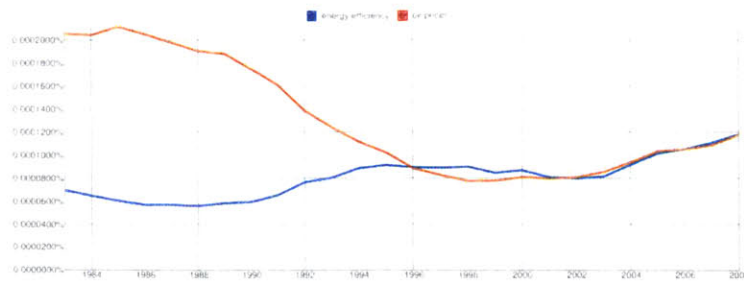
Figure 1-1: Average energy prices by source for industrial customers in 2010.

per dollar of value added in cement production to 0.4 BTUs per dollar of value added in computer assembly. Despite the low energy intensity, the percentage of overall energy used in low-intensity industry processes is still estimated at 25% of industry total, or 8% of total U.S. energy usage because of the sheer number of domestic plants in this category[3]².

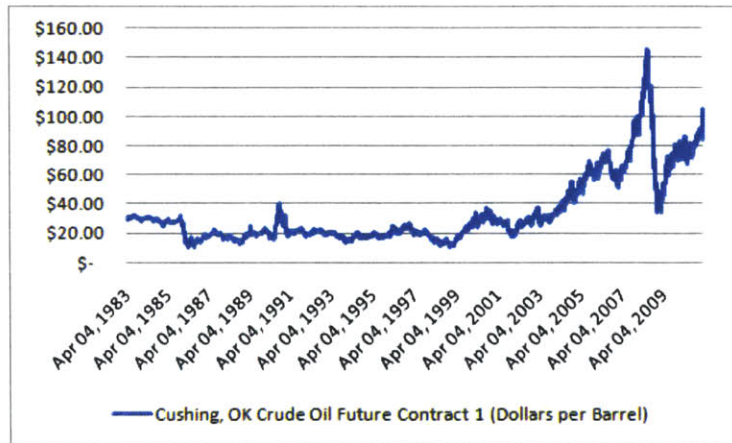
High industrial energy costs lead directly to focusing on energy efficiency. Since the mid 1990's, oil prices have been highly positively correlated with interest in energy efficiency, as shown by Figure 1-2. Although the U.S. government projects that oil prices to industrial customers are only expected to rise 1.7% in inflation adjusted dollars between 2009 and 2035, and electricity prices are actually expected to modestly decline, recent events in the Middle East have underscored the high level of short-term volatility in energy prices[10]. High energy prices are reflected in the results of a survey of over 230 energy management executives who were asked for reasons why their companies were attempting to better manage their energy demand. The top driver, cited by 80% of respondents, was the need to reduce their manufacturing costs[14]. In fact, there is ample opportunity to decrease costs through energy efficiency; it has been estimated that 18% of the industrial sector's baseline forecasted consumption in 2020 can be eliminated using proven techniques to achieve greater energy efficiency, corresponding to industry-wide savings of \$47 billion per year.[3]. Furthermore, these cost reductions can have a direct impact on profits. For example, although energy typically only comprises 5% of overall operating costs for manufacturing companies, a company with a 5% net profit margin will experience a profit increase from 5% to 6% with a 20% reduction in energy use - or a 20% profit increase.

associated costs, into overhead or facility budgets, essentially making them hidden from direct production costs[4].

²Low-energy intensive industries were defined as those with less than 10 BTUs of energy per dollar value added



(a) Google Books ngram for the phrases “energy efficiency” (blue) and “oil prices” (red) between the years 1983 and 2008 (the most current data available). The y-axis shows the normalized rate of occurrence of those phrases in the Google American English corpus of books published in any given year[12].



(b) Daily Cushing, OK Crude Oil Future Contract 1 prices in dollars per barrel between April 4, 1983 and March 7th 2011[13].

Figure 1-2: Data on actual oil prices and cultural interest in oil prices and energy efficiency. Subfigure (a) shows cultural interest and Subfigure (b) shows actual oil prices (not adjusted for inflation).

1.1.2 External strategic considerations

Companies also have an increasing number of external strategic considerations that motivate increasing energy efficiency and reducing emissions. The labor market, investors, customers and government regulators are all increasing scrutiny on industry usage of energy and more generally on reducing their greenhouse gas emissions[1, 15]. These external forces can impact company revenue, investment and costs. While these forces are not discussed in depth in this paper, they are increasingly driving decision making regarding increasing energy efficiency.

1.1.3 Barriers

It has been a difficult problem to increase process energy efficiency. On top of the usual barriers that confront energy efficiency programs in manufacturing settings (see Appendix A), there are additional barriers to improving the energy efficiency of manufacturing processes:

- **No standards:** Unlike support systems, it may be difficult and not cost-effective to impose standards on specialized process equipment given the very specific ways they are utilized in different plants for different products and industries.
- **Necessity for cross-functional collaboration:** Unlike support systems where most of the work could be done within the facilities organization, an engineer seeking to improve the efficiency of process equipment has to work with manufacturing employees, process engineers, and facilities employees to execute the project.

In addition, while a large corpus of literature has focused on improving energy efficiency through capital improvements, only recently have efforts been made to research process management approaches specifically designed to improve energy efficiency of manufacturing processes[1]. The two main advantages of process management approaches is that they are relatively low-cost and also solicit employee engagement, addressing two barriers commonly cited to energy efficiency programs[3].

Despite the promise and the recent progress, the process management approach to increasing energy efficiency of manufacturing processes needs further development. Specifically, while there has been a variety of tools and high-level frameworks proposed, most of which are covered in Chapter 2.1, best practices and detailed action plans for executing such an approach at the manufacturing cell level have not been described, especially in terms of how to best incorporate energy data and/or energy managers within an operations improvement context[1]. While high-level frameworks are important to set an overall vision and to aid inter-industry communication, the nature of the problem requires the development of a practical, repeatable and flexible approach that will work within the constraints and context of modern manufacturing environments. Ideally, these approaches should also support participation from senior operations managers, whose collective lack of attention to energy efficiency concerns is known to be an additional major barrier to successful program execution and yet is still an unsolved problem.

1.2 Problem Statement

The problem addressed in this research is to develop a practical, repeatable process management approach to increase energy efficiency at the manufacturing cell level (the “shop-floor”) that engages employees and managers and is compatible with existing continuous improvement programs. By focusing on process management techniques, we are looking primarily for approaches which do not require replacing existing machinery.

1.3 Thesis Overview

This research uses the Raytheon IADC as a model manufacturing plant. The research environment is described in more detail in Section 2.2, but it can be considered a typical manufacturing facility in the low energy intensive aerospace industry which features many of the common barriers described in Appendix A and in first paragraph of this section. However, it is important to note that although the research was conducted in a low energy intensity industry environment, the methods and conclusions are likely easily generalizable to high energy intensity industries as well because the cost incentives to increase process energy efficiency are generally more compelling.

Chapter 2 provides background for the thesis in terms of a literature review and details about the testing environment. Chapter 3 presents the hypotheses of the research. Chapter 4 details measurement methodologies and data sources used in the research. Chapter 5, which is the bulk of the document, describes two field experiments used to test the hypotheses and their results in some depth. In addition, the same chapter also provides a short treatment of “right-sizing” equipment and some data that indicates its potential impact on energy usage reduction. Finally, Chapter 6 proposes a framework on how to gradually integrate energy usage reduction goals into lean manufacturing programs and outlines management challenges in doing so. It concludes with a summary and suggestions for further research in this area.

Chapter 2

Background

2.1 Energy Management Programs

2.1.1 History - From Crisis to Continuous Improvement

“The energy crisis is real. It is worldwide. It is a clear and present danger to our Nation. These are facts and we simply must face them.” [16].

With those words, former president Jimmy Carter ushered in an era of increasing focus on energy efficiency in the United States, starting with the National Energy Act of 1978. The legislation was in response to the energy crisis of 1973, and as a result an entirely new profession of energy engineers and managers was created to assist industry in reducing their energy costs. The profession was bolstered through a multitude of industry trade groups and when most primary engineering associations, including the Institute of Electrical and Electronic Engineers (IEEE), created sub-organizations focused specifically on energy [2].

However, as energy prices declined in the mid-80's, the influence of energy managers declined as well. As the forward to the seventh edition of the “Energy Management Handbook”, the primary text of the Association of Energy Engineers (AEE), notes: “First, being an energy manager was like being a mother, John Wayne, and a slice of apple pie all in one. Everyone supported the concept, and success was around every bend. Then the mid-80's plunge in energy prices caused some to wonder ‘Do we really need to continue energy management?’” [2].

Nearly concurrent to the decline of energy management was the rise of process management techniques including the closely related concepts of lean manufacturing and six sigma. These concepts particularly emphasized pushing decision making authority down to the front line employees, and using the scientific method to make decisions. A myriad of tools and processes were created to support this general concept, with many corporations developing their own continuous improvement programs that often melded the two concepts and worked best for them [17].

While a variety of academic literature, books, and even self-help manuals have been published on lean manufacturing and six sigma, few words in those publications are devoted to the idea of reducing energy waste in operations[18]. For example, Womack, in his seminal book “Lean Thinking”, does not explicitly discuss energy waste. Spears, in his influential book “Chasing the Rabbit” has an entire chapter devoted to Alcoa, the world’s largest manufacturer in the highly energy intensive aluminum industry, but does not detail their efforts to reduce energy waste.[19, 3]. Seminal literature in six sigma shows a similar lack of attention to energy. The most cited text on six sigma, “Six Sigma: the Breakthrough Management Strategy Revolutionizing the World’s Top Corporations”, does not mention energy waste at all.

The trend in literature can be summarized in Figure 2-1, which shows a spike in interest in energy management in the late 1970s, followed by a steep decline in the 1980s through the 1990s and a more recent trend up in the early 2000’s. Almost concurrent with the nadir of interest in energy management during the 1990s, interest in lean manufacturing and six sigma increased dramatically, with lean manufacturing continuing to gain momentum in literature while interest in six sigma appears to have somewhat declined of late.

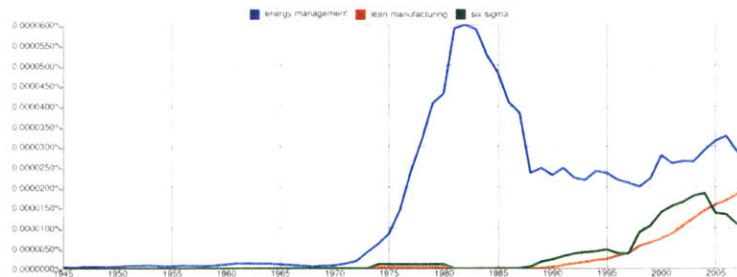


Figure 2-1: This figure shows the Google Books ngram for the phrases “energy management” (blue), “lean manufacturing” (red), and “six sigma” (green) between the years 1945 and 2008. The y-axis shows the normalized rate of occurrence of those phrases in the Google American English corpus of books over the relevant periods. In this context, the phrase “energy management” is used due to its strong use specifically within industry, rather than the more popular phrase of “energy efficiency”.²

While the reduction of other waste through the lean manufacturing and six sigma process management methodologies often leads to an indirect reduction in energy use, the recent upswing in interest in energy management, coinciding with the rise of process management methodologies, has resulted in a host of recent activity by those explicitly combining the two concepts.

2.1.2 Recent Trends and Current Frameworks

The basic engineering principles for increasing efficiency of manufacturing support systems have been well disseminated and demonstrated in the energy management literature since the late 1970s[20]. In fact, the bulk of the literature in energy management, even now, is typically dedicated to upgrading the technology of common facilities support systems, such as HVAC, boilers, lighting, and motor

compressors[1, 2, 21]. Efforts to create and install more energy efficient equipment in industry is currently supported by the the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) and their Industrial Technologies Program, and there continues to be a robust facilities engineering consulting market that dates back to the late 1970s[22]. However, only about 2% of US industrial facilities employ a full-time energy manager, and many well-documented improvement opportunities still exist in many facilities[23]. Common barriers towards improved energy management include "a series of reinforcing barriers that are institutional and behavioral, rather than technical," with the most serious problem being the "lack of a consistent organization structure within most industrial facilities to effectively manage energy use." [23]

To address these deficiencies, increasing attention of late has been paid to developing management frameworks to promote energy efficiency in industry. The EPA ENERGYSTAR program developed its highly successful energy management framework during the early 1990s and has currently signed up more than 3000 industrial partners[24]. Recently, it has focused on applying process management methodologies, particularly lean manufacturing, to reduce energy waste in manufacturing processes. For example, the EPA published the "Lean and Energy Toolkit" which outlined the ways in which manufacturers can use traditional lean concepts, such as *kaizen* and value stream mapping, to reduce energy waste[4]. The EPA and ENERGYSTAR have also sponsored research at Lawrence Berkeley National Laboratory which, while still focusing mainly on facility support systems, also includes general practices for managing energy use intended for plant managers. These practices include a general strategy for energy management programs, advice on how to conduct energy audits and set up energy teams, and efforts to increase energy awareness among employees including placement of stickers at light switches and handing out leaflets on home energy savings[21].

Another effort towards standardizing energy management is crystallizing around the ISO 50001 standard, with one of the long term goals to "foster an organizational culture of continuous improvement for energy efficiency." [23]. The international standard, currently in draft form and scheduled for release in 2011, includes a general management framework utilizing the Plan-Do-Check-Act (PDCA) cycle that is the hallmark of continuous improvement[25, 26]. The ISO 50001 standard, and the program supporting its implementation in the United States, is currently funded by the Department of Energy (DOE). In addition, some consulting firms with operations practices have, in the past year, begun to sell services, with titles such as "Green Sigma", related to increasing efficiency using lean/six sigma methods and real-time feedback, although these firms still focus primarily on support systems and datacenters[27, 28, 12, 29].

While at the time of writing it is still unclear how these high-level frameworks will ultimately work together in the United States, as both include certification processes for manufacturers, the trend to apply proven continuous improvement practices to process equipment is clear. Indeed, as Figure 2-2 shows, most of the energy by manufacturing industries in the United States overall is used

on processes, and that is generally true across industries. There has been some very recent aca-

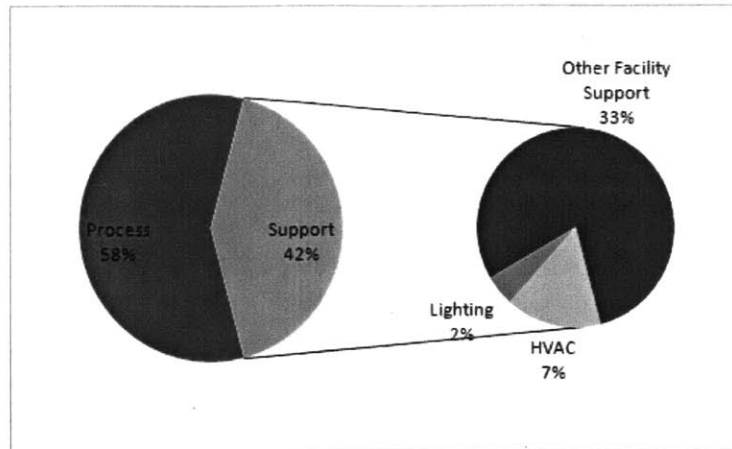


Figure 2-2: Proportion of energy used by U.S. manufacturing industries in 2006 by end function.[11]

ademic literature linking process management, specifically six sigma methods, to improving support systems in the biotechnology industry, where the primary energy expense is on heavy machinery located in central facilities[30, 31, 32]. In addition, some companies, notably Toyota and other Japanese companies, have embraced “environmentally benign manufacturing” or the closely related “green manufacturing”, which takes the approach of determining the minimum possible energy or material required to perform a given step in the manufacturing process, and then presumably making improvements to attain that goal[33, 34, 35]. However, academic literature in the subject appears to be focused more on the theoretical approach to determine the minimum energy required, rather than the process management and improvement methods which is the subject of this thesis.

In some ways, current efforts are finally fleshing out the first principles of energy management. As the first edition of the “Energy Management Handbook”, written in 1980, states: “evaluating a series of manufacturing processes for opportunities to inherently use less energy would be the logical first step before focusing on equipment” [36]. Of course, equipment and process are inexorably linked, but the concept of using existing equipment more efficiently before upgrading is a reasonable first step towards improving efficiency.

The methodology used in this thesis primarily builds on the approach promoted by the EPA and ENERYSTAR, while focusing specifically on developing effective, demonstrable, and general process management approaches front line workers and managers can use to reduce the energy waste of specialized process equipment.

2.2 Raytheon Overview

2.2.1 Raytheon Corporate Business

Raytheon is a technology provider specializing in defense, aerospace and homeland security solutions to governments throughout the world. Headquartered in Waltham, Massachusetts, Raytheon has approximately 72,000 employees and had net sales of \$25.2 billion in 2010 with a net profit margin of 7.31%. Raytheon's primary customer is the United States government, particularly the Department of Defense, for which it is a prime contractor. In 2009, approximately 88% of its sales was from the U.S. government[37]. There are six main business units within Raytheon; Integrated Defense Systems (IDS), Intelligence & Information Systems (IIS), Missile Systems (MS), Network Centric Systems (NCS), Space & Airborne Systems (SAS), and Technical Services (TS). Raytheon is most known for its manufacture of reconnaissance, targeting, and navigation systems, as well as missile systems (Patriot, Sidewinder, and Tomahawk), unmanned ground and aerial systems, sensing, and radars[37].

The Integrated Defense Systems (IDS) division of Raytheon is headquartered in Tewksbury, Massachusetts and has annual revenues of approximately \$5 billion (20% of Raytheon's total revenue). IDS employs 13,500 workers spread across 11 sites globally, which combined have a facility footprint of 5.45 million square feet[1]. The IADC manufactures many of the key components for the Patriot Program, a primary product of the IDS division, and is the site in which this research was primarily conducted.

Raytheon Corporate Energy Use Program

Raytheon participates in two major industrial energy management programs sponsored by the EPA. The company is an active member in the ENERGY STAR program described in 2.1. In fact, the company has won multiple awards from ENERGY STAR, most notably, Partner of the Year honors in 2007 and Sustained Excellence honors in 2008, 2009 and 2010. Additionally, Raytheon is a charter member of the EPA's Climate Leaders program, a voluntary industry/government initiative that requires participating companies to set long-term greenhouse gas emission goals. Raytheon set a goal to reduce their emissions by 33% from 2002 to 2009. In fact, they achieved this goal a year early, reducing their emissions by 38% by 2008. As a result, their current goal is to reduce total greenhouse gas emissions 10% by 2015, with a baseline year of 2008[38].

Raytheon also has a formal energy management organizational structure, directed by the Enterprise Energy Team (EET). The EET is composed of facility employees and managers from each of Raytheon's six divisions. The EET reports directly to the Facilities Leadership Council (FLC), a group of facility directors from each of Raytheon's divisions. Primary activities of the EET include developing and implementing programs designed to help the corporation reduce its energy usage,

reduce its energy related operational costs and decrease their greenhouse gas emissions. The EET also helps to develop the energy reduction and greenhouse gas emission goals for the corporation and for each Raytheon division. These divisional goals are ultimately rolled down to the facility level[1].

Aside from helping to provide strategic direction for the company on energy issues, each EET member is responsible for helping their specific division meet their energy goals. Each facility within a division has a liaison from the EET that works with the lead Energy Champion at that facility to implement energy saving programs. While each facility has one lead Energy Champion which coordinates the facility’s energy saving programs, it also has department level Energy Champions that coordinate energy saving initiatives at the department level. Finally, each departmental level Energy Champion works with the motivated Energy Citizens within their area to encourage energy conscious behavior. Figure 2-3 displays Raytheon’s energy management organizational structure[1].

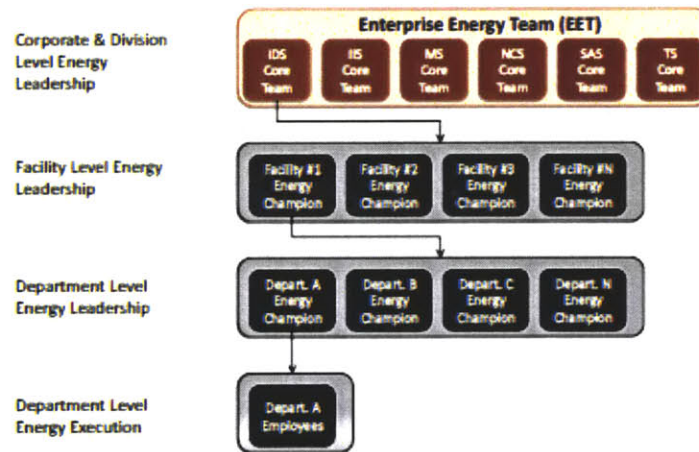


Figure 2-3: Raytheon’s energy management organizational structure[1].

While this organizational structure has provided a system that has enabled the EET to very successfully influence Raytheon’s energy strategy at both a corporate and individual facility level, its design does not currently well support increasing energy efficiency of manufacturing processes. Most notably, with the EET consisting solely of facilities employees, it is often viewed as a facilities initiative rather than a business and operations initiative[1]. Also, the majority of people involved at the individual facility level, especially the Energy Champions and Energy Citizens, work on these programs on a volunteer basis. Thus, accountability is not as strong as if it were part of their formal job responsibilities[1]. Regular energy auditing, a feature of strong energy management programs, is generally confined to support systems[15]. Finally, performance improvement goals are typically set at the division level, and tracking metrics are generally available only at the facility, rather than department or process line level.

Nonetheless, the EET represents an innovative and effective system that has attained impressive

results compared to peer organizations. It is important to note that as of 2006, only 1% of U.S. manufacturing facilities had on-site energy managers and only 2% had defined energy efficiency goals despite published results showing reduction of energy costs of 20-30% through effective energy management[11, 23]. Indeed, Raytheon's own experience has been an energy efficiency improvement of 38% since the energy management program was formalized[38]. Improvements have centered around improving facilities operations such as HVAC and technology such as more energy efficient chillers[1]. Recently, Raytheon has sponsored projects which have investigated the use of renewable energy and improved datacenter operations to reduce Raytheon's carbon footprint and improve overall business sustainability [28, 39].

2.2.2 Integrated Air Defense Center Overview

The Integrated Air Defense Center (IADC) is located in Andover, Massachusetts and is IDS's largest manufacturing facility. The IADC has a footprint of 1.2 million square feet (22% of IDS's total footprint) and has more than 4,400 employees. While the facility's primary function is manufacturing, it also has office space, two dining centers and a data center onsite[1]. The largest program supported by the facility is the Patriot Air & Missile Defense System, however, the facility also manufactures and integrates products for various land and sea based systems. The size and complexity of the products manufactured at the facility span the production of circuit cards to the final assembly of large radars used on naval ships[1].

Process management and continuous improvement programs

In 2001, the IADC increased its emphasis on operational excellence and began a lean transformation. After working with outside consultants, the IADC developed their own internal lean office, called the Operational Excellence Resource Center (OERC). The OERC, which is staffed by full-time industrial engineers, works directly with manufacturing departments and cells in the IADC to implement principles of lean manufacturing. Aside from using traditional lean tools such as kaizen events and value stream mapping, the OERC promotes the PDCA cycle by tracking and publicizing the number of improvement ideas generated by individual cells over time. Despite the IADC being a heavily unionized facility, and the fact that manufacturing employees do not need to participate in the lean program, it has been incredibly successful. For example, the IADC achieved a 20% cost reduction to its bottom line each year in a row between 2004 and 2008, and won the North American Shingo Silver Medallion award for operational excellence in 2008[40]. In addition, from January to September of 2009, employees implemented over 600 improvements throughout the facility[1].

The facility also participates in the corporate wide process improvement program, called Raytheon Six Sigma™. The program has derived elements from other corporate six sigma programs including the Texas Instruments Continuous Flow Manufacturing program, the Hughes Aircraft Agile

program, the Motorola Six Sigma® program, and the General Electric Six Sigma program[17]. The Raytheon Six Sigma™ process shares many principles with lean manufacturing, and on a practical level represents a company-wide channel for employees to receive training on process management, re-orient the business towards the end customer, work in cross-functional teams across sites, and get visibility for successful improvement projects.

Energy Usage at the IADC

The IADC's primary source of energy is electricity. Electricity represents 70% of its total energy usage on a BTU basis and 89% on a cost basis. The remainder of the energy comes from natural gas, and it is not considered in this study because of its relatively low cost and the fact that it is not generally used in manufacturing processes. The IADC had an annual electricity consumption of approximately 57,574 MWhs in 2009, which is the equivalent amount of electrical energy used by 5,126 average American homes[1]. The IADC's peak power during this period was 11,410kW, occurring in mid August[1]. Since the IADC is such a large user, it negotiates its rates directly with its electricity provider. However, for purposes of this thesis, we use the blended rate of \$0.135 per kWh for all cost calculations, which is the average retail price for industrial customers in Massachusetts in 2010[41]³.

Most of the electricity used at the IADC is used on manufacturing processes. Figure 2-4 shows the results of an energy audit conducted at the IADC in 1995, the last known audit of its type to be completed at the facility. The auditors indicated that 54% of electricity use at the facility was used on processes, while 46% was used on support systems. This breakdown, fairly typical in the aerospace industry, is likely more heavily skewed to process electricity use currently now that many energy efficient support system technologies has been introduced since the time of the audit[11, 42].

The electricity distribution network in the IADC can be described as a tree structure. At the root of the tree, electricity is delivered to the IADC with a voltage of 15kV at two points and then distributed to ten substations geographically spread out in the facility. As Figure 2-5 shows, these substations do not align with departments or manufacturing value streams, rather, the substations align with geographic areas of the plant. While it is preferred to have substations align with organizational departments, especially from a reporting and accountability standpoint, it is often not realistic because equipment and departments relocate over time[1]. From these substations, the electricity is stepped down to various voltages (typically 480V, 220V and 120V) and then delivered to equipment via powerplugs attached to overhead busbars (referred to as simply buses), panels, or wall outlets in offices and on the shop floor. Figure 2-6 shows a simplified version of the distribution tree. As the distribution system has evolved over time in the facility, buses have

³Massachusetts has the second highest electricity retail prices for industrial customers in the continental United States, next to Connecticut

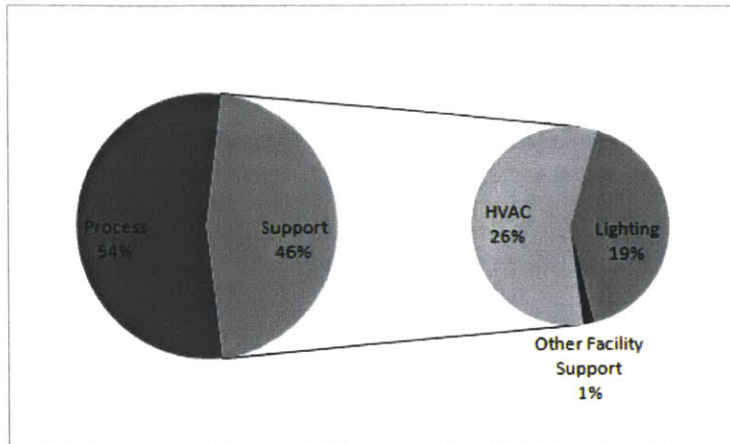


Figure 2-4: Electricity used by the IADC in 1995 by end function.[42]

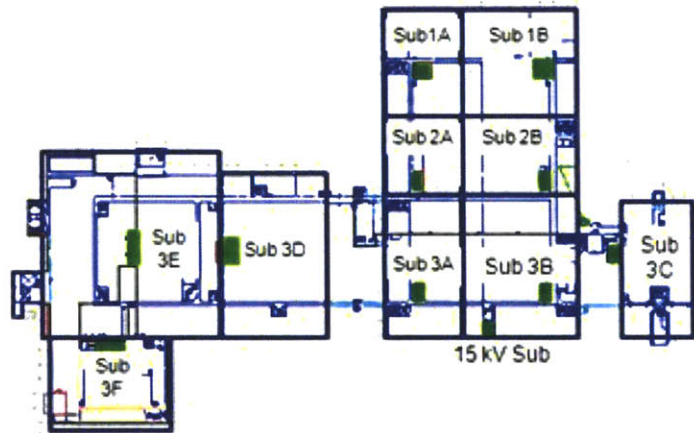


Figure 2-5: Map locations of the 10 substations at the IADC.

come to feed sub-buses, panels have come to feed sub-panels and transformers have been added at multiple points in the tree. The end result is a very complex system with multiple layers that is difficult to map on paper or electronically, let alone plan in advance.

Relative loads among substations are not evenly distributed. Figure 2-7 shows the percentage breakdown of energy used by each substation over a typical week. However, because the equipment used in different substations varies dramatically, substations with larger average loads may not necessarily be inefficient compared to their peers[1]. Typical energy users on the shop floor are ovens, environmental testing chambers, processing equipment with motors including machine tools, computerized test equipment, and work bench tools.

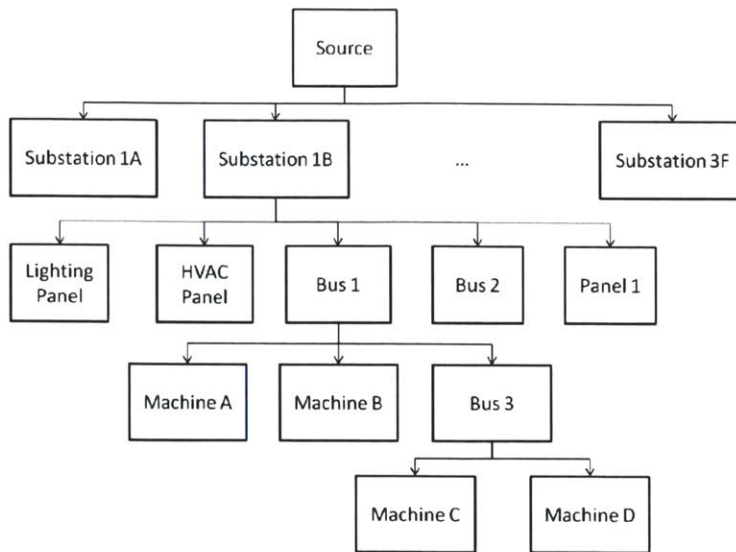


Figure 2-6: Simplified electricity distribution tree for the IADC.

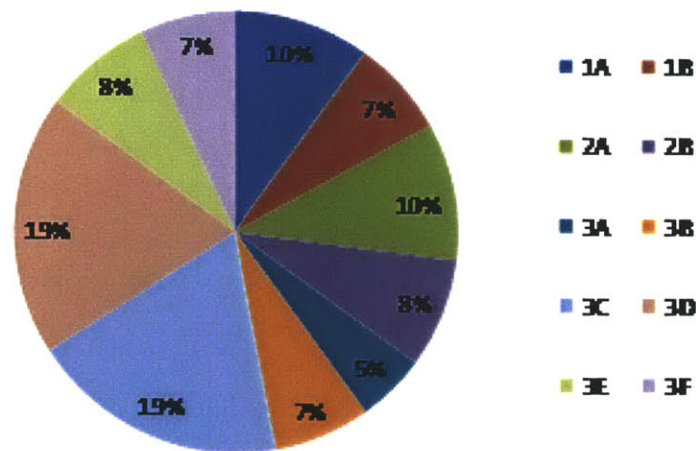


Figure 2-7: Distribution of energy used by the 10 substations in the IADC in a typical week[1].

Energy Efficiency Program at the IADC

The content and approach of the energy efficiency program at the IADC is currently undergoing a transformation. In terms of organizational structure, however, it continues to largely adhere to the corporate energy management program structure. The facility has volunteer Energy Champions and Energy Citizens who largely drive the program. More specifically, there is a facility Energy Champion, who is also a senior manager in the facilities department, and is voluntarily responsible to help the Integrated Defense Systems (IDS) division achieve its goals set by the EET. In addition, there are department-level Energy Champions who may be manufacturing employees, engineers or managers who work on multiple shifts. Finally, there is a network of Energy Citizens: employees

that have passed an on-line quiz on helpful energy habits in a given year. On a monthly basis, the Energy Champions and motivated Energy Citizens meet to review energy data from the submeters, plan energy-related events, and discuss ways to increase energy efficiency in the plant.

The IADC Energy Champions and Energy Citizens have worked to raise awareness and decrease energy usage over the past few years with success. Some of their activities include annual Energy Day events, conducting energy audits after hours to see what equipment was mistakenly left on, and starting a campaign to label which machines should be turned off every night (engineering maintenance employees do not want certain pieces of equipment turned off in fear of losing critical production parameters)[1]. However, based on anecdotal evidence, only a small contingent (about a dozen) of passionate and committed employees are consistently volunteering their time to this program at the plant.

In the summer of 2009, the EET sponsored a plant-wide initiative to increase the energy efficiency of processes at the IADC, which successfully engaged more employees at the facility, piggybacks on the existing lean manufacturing program, and focuses on operator behavior change[1]. This initiative raised participation in the Energy Citizen program from 38% to 78% of IADC employees and created a sustained “pull” for energy saving ideas from front-line employees by tying energy into the OERC “Lean Olympics” competition, an integral part of the lean manufacturing program at the IADC (see Figure 2-8) [1].

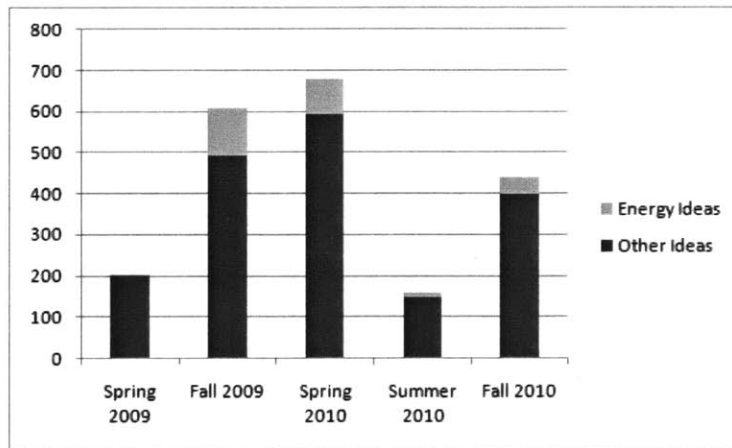


Figure 2-8: Number of continuous improvement ideas generated for the IADC “Lean Olympics”. An energy idea category was introduced in Fall 2009.

While the initiative achieved its primary goals of engaging employees and generating more improvement ideas in process energy efficiency, it encountered some challenges in terms of its ultimate impact on improving efficiency in the plant for several reasons. First, the ability to measure process energy savings was difficult, even with the extensive metering system, for reasons discussed previously in this chapter. Secondly, the initiative focused on mainly on improving “leading metrics” such

as increasing employee engagement (as measured by the proportion of employees who took an electronic quiz on energy) and increasing the number of ideas submitted to the Lean Olympics, rather than on the magnitude of energy saved by those ideas. The focus on leading metrics was appropriate given the conditions at the time of the research, and the desire to begin by promoting the concept of “a million one dollar ideas” central to continuous improvement. Finally, it was observed that the processes which cells actually used to generate improvements did not utilize process management best practices, and that more disciplined approaches may result in better improvements[1].

With the success of the first phase of the initiative, the Raytheon EET sought to leverage its momentum by continuing to develop methodologies to increase the energy efficiency of manufacturing processes at the IADC. Specifically, it sought to discover and spread practical and easily reproduced best practices, compatible with the existing lean manufacturing and process management programs, at the manufacturing cell level.

2.3 Chapter Summary

This chapter has outlined the background of the research, namely the history and recent trends of energy management programs in industry and a broad introduction to Raytheon, its energy management program and the manufacturing plant where field experiments and study was conducted. We described the trend of energy management programs dovetailing with the process management programs in the near future, and identified the need for further research into specific approaches that can work at the manufacturing cell level. We presented Raytheon as a good example of a U.S. company on the leading edge of this type of research, and described the state of the energy efficiency program in one of its major manufacturing facilities encountered at the beginning of the research period.

The next chapter will propose our research hypothesis, and provide an argument as to why proving the hypotheses will help address the problem of developing a practical, repeatable process management approach to increase energy efficiency at the manufacturing cell level.

Chapter 3

Hypothesis

It is hypothesized that programs focused on improving the energy efficiency of manufacturing processes, included as part of a general lean manufacturing program, can reduce operational cost without impact on production schedules. Moreover, these programs can be enhanced using the following process management best practices:

1. Measuring energy usage of individual equipment as part of team-based continuous improvement projects.
2. Providing continuous, real-time data on energy use to operators.
3. Right-sizing equipment.

The first two approaches are of particular interest because:

- They do not explicitly rely on additional capital allocation, which is a barrier to energy efficiency programs.
- They are in the spirit of focusing on employee behavior change, which was the vision of the initial pilot project sponsored by the EET at the IADC and elsewhere.

However, the third approach was included in the hypothesis because it is also in the spirit of lean manufacturing, though it explicitly involves the acquisition of equipment.

The three approaches were tested using two field experiments and one analytical study. The two field experiments, testing the first two approaches, were conducted in different manufacturing cells at the IADC and included an implementation of each approach and a measurement of the impact of the implementation based on an appropriate set of control data. The analytical study was conducted to assess the potential impact of right-sizing equipment, and was based primarily on data collected at the IADC.

The next chapter gives more detail on the study design, and will describe the specific methodology taken to test these hypotheses.

Chapter 4

Methodology

4.1 Study Design

Each component of the hypothesis was tested in the field at the IADC, and the overall study included two field experiments and a more analytical approach conducted over a six month period from February to August, 2010.

The first field experiment involved conducting team based continuous improvement projects incorporating energy data on individual manufacturing equipment. This experiment was done in a manufacturing area that had participated in the first phase of the initiative, but had not previously used best practice approaches. In addition, the experiment was performed within the confines of a “season” of the Lean Olympics. In this way, we were able to assess the effect of introducing best practices while controlling for team members, equipment and study duration. While there may have been learning effects based on the previous phase of research within the group (conducted in Fall 2009), these effects are assumed to be counterbalanced by the fact that the subjects were unable to submit ideas based on previously identified “low-hanging fruit”. Additional details of this study environment can be found in Section 5.1.

The second field experiment, measuring the impact of introducing real-time feedback, proceeded in several phases within a different manufacturing cell in the IADC. As explained in more detail in Section 5.2, the cell had been chosen based on willingness to participate, along with the relatively high level of energy intensity in their process and its relative process simplicity.¹ The field experiment design for real-time feedback consisted of a control period of eight weeks with no feedback, followed by the introduction of three experimental conditions which occurred in serial order over a period of eight weeks. The first condition was the introduction of a highly visible form of feedback to operators with accompanying training, with the hypothesis that it would reduce energy waste through increased

¹Energy intensity is defined here as energy per unit produced

operator experimentation. The second condition was introducing the same feedback to operations managers with accompanying training, with the hypothesis that it would reduce energy waste even more than what was observed in the first phase. The third condition was reducing the visibility of the feedback, which sought to identify if the feedback produced behavior change that would be sustained without easily visible feedback.

Testing the third component of the hypothesis relied more on analysis and research, mainly because right-sizing experiments would have involved capital allocation and purchase of new process equipment which was beyond the constraints of the study. Therefore, the impact and opportunity around right-sizing equipment was assessed on an analytical level using data gathered in the facility over the course of the research period. This portion did not include a field experiment but instead relied on projections based on observations and data gathered in the field and from Subject Matter Experts (SME) input.

Finally, as stated before, all research conducted at the facility was focused on making more efficient use of electricity in manufacturing processes.

4.2 Data Collection and Analysis

All interviews, data collection, and analysis was performed at Raytheon, primarily at the IADC site.

4.2.1 Electricity Data

Electricity data was gathered through a variety of methods. A brief discussion of these data collection methods, and the existing methodology at the site at the start of research is warranted, as the hypothesized value of electricity measurement is a major component of this thesis, and a variety of data collection methods were utilized depending on the equipment under study.

Historical data collection and uses of energy data

The IADC has an extensive electricity metering system installed to support energy management and maintenance activities. The facility has over 200 Schneider Electric Circuit Monitors (often referred to as sub-meters) installed in the facility. These sub-meters continuously record power, energy and other electrical data at various locations in the facility. All this data is automatically uploaded to a SQL database operated by Schneider Electric. This data is then used by Schneider Electric's ION EEM web interface software in which authorized Raytheon employees, namely the facility Energy Champion and select electrical engineers and members of the EET, can remotely access the data to make historical charts of power and energy usage using any combination of sub meters. In general, sub meters are installed at the substation level and one level below in the distribution tree as depicted in Figure 4-1. While care had been taken to isolate electricity use of support systems such

as HVAC and lighting functions for each substation to use in historical energy management projects, the rest of the other sub-meters each monitor a hodge-podge of manufacturing and office process equipment that is not separated by department, equipment type, functionality or even necessarily geographical location. As a result, gathering data on individual process equipment was, by and large, not supported by the sub-metering data collection system. At the time of arrival at the facility, use

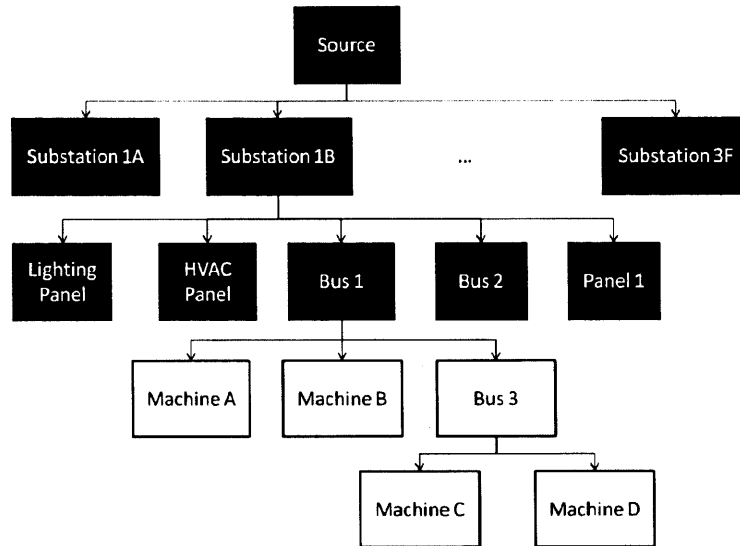


Figure 4-1: The simplified electricity distribution tree for the IADC as shown in Figure 2-6 with shaded boxes indicating sub-meter locations.

of the ION EEM system was limited. The facility Energy Champion would track electricity usage of the overall facility over time using the system, and email weekly reports to department-level Energy Champions that included key metrics such as cumulative percentage increase/decrease of electricity use versus the same date the previous year, and energy usage trends for each substation. While this approach provided some visibility into the overall trends of electricity use in the facility, the value of the information, especially to manufacturing employees, was limited due to the fact that there was no direct relationship between energy usage at the substation level and for individual departments and cells. In general, no followup analysis or investigation in terms of determining causal impact was performed that incorporated this data. This is a major example of why installing metering alone is not a panacea for improving energy efficiency, and why it is imperative that workable business processes and structure are developed to utilize the meter data effectively[43].

There was also evidence that Energy Champions and others used various other techniques (described below with the exception of use of the AEMC power meter) to periodically measure energy use of select equipment during previous improvement projects. However, data collection was done on an ad-hoc and unstructured basis, and not stored in any central location accessible by team-members or the Raytheon community.

The net result of the historical data collection approaches was a general lack of understanding (on behalf of both facilities and operations personnel) in terms of how much electricity individual process equipment actually used. Based on SME interviews, it was found that the lack of understanding largely stemmed from the fact that there was no existing process in which to use the data to improve energy efficiency. Nevertheless, the lack of general institutional knowledge and data in this area was found to be a critical barrier to overcome during process improvement activities.

Estimation from Equipment Documentation

The easiest, cheapest, and least accurate way to determine how much energy a piece of equipment uses is to use the power supply label on the machine itself. In most cases, this label will include the maximum power draw of the equipment. In some cases, however, it will only include maximum current for different voltages the device supports. In that case, it is possible to estimate real power using the equation,

$$P_{real} = VI\rho \quad (4.1)$$

for a single phase circuit, where P_{real} is real power, V is voltage, I is current, and ρ is the power factor. If I is measured in amps, then P_{real} is in units of watts. The power factor, ρ , is a dimensionless number between 0 and 1 and is defined as the ratio of the real power flowing to the load to the apparent power in the circuit. Usually, ρ , or the power factor, is not included on the label. Based on measurement of a variety of equipment in the facility, however, we assume for simplicity that when we need to estimate ρ , inductive loads (motors, pumps etc.) have $\rho = 0.75$, resistive loads (heating elements) have $\rho = 1$, and older computerized test equipment have $\rho = 0.6$.

For a three phase circuit, which most of the large industrial equipment in the IADC operates on, the equation becomes

$$P_{real} = \sqrt{3} \sum_{i=1}^3 V_i I_i \rho_i \quad (4.2)$$

where i indexes each phase.

While this method is fast and inexpensive, there are significant drawbacks stemming from the fact that the label only indicates maximum power draw rather than a profile of energy use over different operational modes. Occasionally, this information may be furnished by other equipment documentation or manufacturer support, though based on experience the likelihood of those resources existing tends to decline with the age of the equipment. In general, experience suggests that a good rule of thumb is that equipment uses about half the maximum power when it is on, though this can vary significantly with operating mode and type of equipment.

Hand-held Ammeter Readings

Handheld ammeters, readily available and familiar to electricians, provided more accurate but still limited measurements of actual current and did not require equipment shut down. For analyses using this method, we assume voltage to the equipment is constant at the required level indicated by the equipment power label. Using Equation 4.1 and Equation 4.2, we can then calculate instantaneous real power.

A drawback to this method, beyond the inability to measure the power factor ρ , is that it is impractical to continuously monitor current using a handheld meter. Whenever using this method, we attempted to sample power draw for each piece of equipment in several operational modes, though this was not always practical given production scheduling.

Watts Up Pro Wattmeter

The Watts Up Pro meter accurately measures the instantaneous real power usage for any equipment that can be plugged into single phase 120V circuits (i.e. the ubiquitous three-pronged wall outlet). This equipment includes the majority of typical office and workbench equipment, and did not require an electrician to operate.

AEMC 8335 Power Quality Analyzer

Four AEMC 8335 Power Quality Analyzers were purchased to support extended data logging on industrial floor equipment. The analyzers, each costing about \$5,000 including accessories, provided a relatively easy to use, portable, programmable power logging system which could be installed on three-phase high voltage industrial equipment, automatically log real power use every second for weeks at a time, recovered, and then quickly re-deployed.

Use of these meters required shutting down equipment for an average of about 30 minutes for each installation, and then again for about 10 minutes for retrieval. Occasionally, they were too bulky to use safely within certain small equipment and cluttered environments.

Schnieder Electric Enercept Meter

These meters, previously installed for the six ovens discussed in Section 5.2, provided real-time power use for oven heating elements, vacuum pumps and fans. The meters transmit energy usage data over an ethernet communication network and the data is then stored in a SQL Server database as 15 minute average readings[1]. Although relatively low cost, they are not intended for portable use, and have no user interface software.

Method	Networked	Portable	Data Logging	Electrician	Accuracy	Downtime	3-Phase	Retail Price
Documentation	N/A	N/A	N/A	No	Low	No	Yes	\$0
Ammeter	No	Yes	No	Yes	Medium	No	Yes	\$100
Watts Up Pro	No	Yes	No	No	High	Yes	No	\$100
Enercept	Yes	No	Yes	Yes	High	Yes	Yes	\$1,500
AEMC 8335	No	Yes	Yes	Yes	High	Yes	Yes	\$5,000
CM5000	Yes	No	Yes	Yes	High	Yes	Yes	\$15,000

Table 4.1: Features for each type of measurement method used during the study.

Schnieder Electric CM5000

These circuit monitors, already described in some detail, are permanently installed on switchgear in the ten substations in the IADC. Like the Enercept meters, the circuit monitors transmit real power data over the ethernet which is stored in a SQL Server database as 15 minute average readings. While some circuit monitors are dedicated exclusively to functional equipment categories such as lighting and the HVAC system, most others monitor high level distribution nodes within the substation, and thus tend to aggregate the data on dozens or even hundreds of equipment loads².

Discussion

The methods of electricity measurement listed are far from exhaustive, but were the primary methods used for this thesis. Table 4.1 displays the features of each approach. In general, the less expensive, less capable meters were used to measure low-power, low complexity equipment, while the more expensive meters were used to measure high power, high complexity equipment. In all, the electricity usage of 64 pieces of individual equipment was measured using portable meters or estimated using other techniques during the study period, including eight weeks of data logging during continuous operating time for eight high energy intensity pieces of equipment. In addition, the previously installed network of circuit monitors and Enercept meters provided an additional two years of raw energy consumption data for analysis.

4.2.2 Other Data

A variety of other data was compiled during the study period. Gathering of operational data was greatly facilitated through the use of Raytheon VBS. VBS aggregates and archives a wide variety of data, including Manufacturing Resource Planning (MRP) systems and material tracking systems in a structured relational database[1]. Through VBS, we were able to track any individual component

²with some notable lucky exceptions

in real time through the manufacturing process, as well as create dashboards to display real time data to operators. VBS will be discussed in further detail in Section 5.2.

In addition, much of the analysis in this study relied upon interviews with dozens of SMEs in facilities, manufacturing, engineering and support.

4.3 Chapter Summary

This chapter described the methodology of testing the hypothesis in terms of both the study design and data collection. The research consisted of two field experiments and one analytical study, both based on data collected at the IADC. One field experiment tested the approach of using team-based continuous improvement projects that incorporated targeted electricity data, and the other tested the approach of simply providing electricity usage data to workers and managers on a real-time basis. The analytical study tested if greater energy efficiency could be achieved through right-sizing equipment. Electricity data was collected using a variety of meters and estimation techniques, operational data was collected using the existing MRP system and SME interviews provided valuable input as well.

The next chapter, the bulk of the document, details the results of the study in three sections, corresponding to the three approaches to enhance energy efficiency that were tested at the IADC. Each section discusses the application of the particular approach to improving energy efficiency, describes the background and actual implementation details, analyzes results of the test, and concludes with management implications based on the results and implementation experience.

Chapter 5

Energy Efficiency Program Enhancements

5.1 Using the DMAIC Continuous Improvement Process

In order to test the first part of the hypothesis, that while requiring additional upfront effort, defining and measuring electricity waste for individual equipment will yield improvements in energy savings, we conducted research in a manufacturing area that already had significant engagement and success with the proof of concept study in the previous year. As Norelli noted, “After the initial launch...more effort should be placed on quantifying the impacts of specific improvements. Not only will this help employees prioritize their actions but through the process...additional insights may be discovered”[1]. We chose to utilize the well understood DMAIC continuous process improvement framework common in six sigma literature[1]. The approach, data, and results of this approach are discussed in this section.

5.1.1 DMAIC applied to energy use reduction

Limited examples, confined to short case studies, exist in the literature of specifically utilizing the DMAIC process to reduce electricity usage, despite the fact that it is consistent with the PDCA continuous improvement process endorsed by the EPA[5, 4].

Individual elements of the DMAIC approach however, especially in terms of how to measure and analyze electricity usage of equipment, has been around since the beginnings of energy management, and is typically described in the context of energy audits[2]. A traditional industrial energy audit consists of a trained energy auditor and/or energy management specialist inspecting a manufacturing facility over a number of days or weeks to determine the main sources and uses of electricity in the facility and recommend energy improvement opportunities. Traditionally, these audits have focused

on large central facility support systems, and acknowledge the difficulties of producing recommendations around more efficient use of specialized equipment used in manufacturing operations[2]. Data sources for these audits are typically utility bills, equipment documentation and site specific knowledge, with a notable lack of emphasis on metering of individual equipment[2].

While energy audits play an important role in a high-level energy management strategy, the traditional auditing approach probably would not work to improve efficiency of manufacturing equipment in particular cell. From a process management perspective, traditional audits rely on one or two experts to gather and analyze data in relative isolation and produce recommendations based on experience and best practices. Moreover, these recommendations are typically confined to technological improvements such as installing more efficient or appropriately sized motors. However, in a complex environment like the manufacturing floor, where operational details are as important if not more important to improving efficiency, a team based approach incorporating front line employees and managers is likely more effective. In addition, the lack of energy efficiency standards for specialized process equipment, as noted in Section 1.2, prevents the use of standards based recommendations on behalf of expert auditors.

5.1.2 CCA Background

The area under study, referred to as Circuit Card Assembly (CCA), is a self contained manufacturing unit within the larger IADC that can be considered a high mix, low volume manufacturing environment. For purposes of this study, details of the products themselves (mainly circuit cards) are unimportant beyond the general requirement that they have extremely high quality standards which generally require each card to pass a battery of reliability tests in specialized equipment over the course of the manufacturing process.

CCA is approximately 95,000 square feet, around 8% of the total IADC footprint. Included in the CCA footprint is about 67,000 square feet of manufacturing floor, with the remainder being offices for support staff. Overall energy use of CCA, including support (HVAC and lighting) and process electricity combined, account for approximately 12% of the total electricity use in the IADC, which makes it one of the top users of electricity in the facility. Two electrical substations, labeled 3A and 3B, feed CCA with three phase 480V and 220V and single phase 120V power, though both also feed other nearby functional areas.

The CCA management structure includes operations personnel and engineering support personnel. Within CCA operations, there are approximately 10 cells/functional units and operations occur in multiple shifts. CCA, like the rest of the IADC, has a strong lean culture, a history of energy management including an active energy team constituted in 2005, and participated in the pilot energy use reduction program launched in 2009[1].

The area was chosen to test the DMAIC approach in part because of its size, its impact on the

overall electricity usage of the facility, its diversity of specialized process equipment, its active participation in previous research, as well as the stage of development of its particular energy management program. In its five year history, the team had already completed numerous improvement projects that were believed to be high impact and also have a high ease of implementation. In addition, through a program of regular audits, the team had largely driven out waste due to the behavior of leaving process equipment on unnecessarily. For example, over the course of three monthly audits the author conducted with the energy team, there was not a single case of an audited piece of process equipment that was left on by the operators against procedures.

5.1.3 Approach and DMAIC framework

Due to the complexity of CCA, we used a two tiered DMAIC approach. The first tier was a DMAIC improvement process for the entire area, with the “Improvement” step of the first tier consisting of smaller, second tier DMAIC improvement processes. These Tier 2 processes occurred in parallel with each other. Figure 5-1 shows a graphical representation of the overall improvement process.

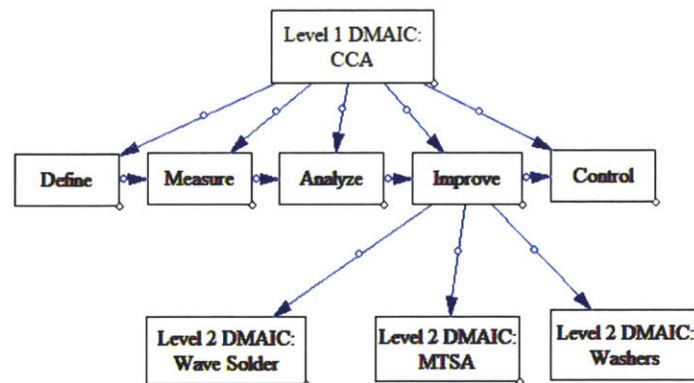


Figure 5-1: Schematic of the two-tiered DMAIC process used in CCA. Individual process steps (Define, Measure, Analyze etc.) proceed in chronological order and are dependent on the previous stage. These steps are not depicted for the Tier 2 processes.

5.1.4 First Tier DMAIC process

Define

The first step in the DMAIC process is to define the problem and project goals. With CCA senior leadership, the CCA energy team leadership, along with facilities electrical engineers, we defined the problem as wasted process electricity in the area, and set a primary goal of reducing process electricity use of CCA without disrupting the production schedule and keeping expenses low. Having only aggregate information of the existing electricity usage of the area on the substation level (which included electricity used by processes, support and other areas), we did not specify a reduction target,

though it was generally agreed that a 5% annual reduction would be satisfactory, while 10% would be excellent. In terms of absolute amounts, that translates into a reduction of about 7,395 kWh/week (\$1,035/week) or 14,790 kWh/week (\$2,070/week) for the area under study. During this stage, we also defined the production cycle of CCA to be a week, so most analysis is reported in terms of weekly totals.

The definition of “wasted process electricity”, especially in the context of lean manufacturing, deserves a brief discussion. Of the seven types of *muda*, or “deadly wastes”, in lean manufacturing, all generally can be expected to cause extra energy to be used that would not be used if the waste did not exist[4]. Wasted energy, and utilities in general, are not specifically considered *muda*. In CCA, we generally focused on the waste of “overprocessing”, in the sense of non-value added electricity used in process equipment.

Some further classify *muda* into two levels[44]. Type One *muda* is defined as activities that create no value but seem unavoidable with current technologies or production assets. Type Two *muda* are activities that create no value and are immediately avoidable. In terms of electricity used in overproduction, Type One *muda* includes the electricity required to pre-heat an oven and the extra electricity used beyond what is needed for the product by a piece of equipment that is not right-sized. While we documented several cases of Type One overprocessing *muda* during our improvement process in CCA, and ultimately even eliminated one (see Appendix C), our focus during the DMAIC process was mainly on Type Two overprocessing *muda*. The case studies in this section address some examples of this type of *muda* in detail.

The energy management program at Raytheon tracks overall electricity usage for the IADC and each substation in terms of cumulative kilowatt-hours. From these measurements alone, however, it is impossible to determine the amount of kilowatt-hours which were non-value added. The second step in the Tier 1 DMAIC process (Measure) was thus critical to uncovering the previously hidden *muda*, and where it was most prevalent.

Measure

The second step in the DMAIC process is to measure key aspects of the current process and collect relevant data. For the first tier process, this meant a full account of the electricity use in CCA, requiring the employment of all the measurement techniques described in Section 4 to equipment both within the confines of CCA and also in the surrounding areas.

Given the size of the area (there are literally thousands of pieces of equipment used in CCA), and the fact that some equipment was used for classified products, it was impossible to measure every piece of equipment directly. Instead, with the help of SMEs like electricians and cell leaders, we targeted equipment believed to be the highest users of electricity during a typical production cycle, and grouped some similar types of equipment together into general categories. For example, there

are 23 industrial-sized floor ovens used in CCA of varying models, sizes and usage patterns. Rather than measuring the electricity use of each one individually for this phase of the process, we divided the 23 ovens into two categories: conventional ovens and friction air ovens. Conventional ovens use a resistive heating element to generate heat, while friction air ovens use the friction created from a fan to generate heat. We then used an SME identified representative sample of each type of oven to measure electricity use during a production cycle for each category of equipment in CCA. Other examples of categorization and sampling were with office equipment (computers and monitors), workbench equipment (soldering irons, hot plates, ionizers, desk vacuums etc.), and process venting fans. For a complete list of equipment measured, see Appendix B.

Analyze

As stated previously, it was impossible to measure the electricity use from the thousands of pieces of equipment in CCA in the time frame of the project. Thus, for some categories, one or more SME designated pieces of equipment were used for measurement sampling. These measurements of electricity use were then combined with equipment operational records (where possible) and SME knowledge to get a reasonable projection of electricity use for the entire category. The process was repeated for each category of equipment.

While this analysis methodology certainly resulted in some degree of estimation error, it in fact produced a reasonable model for the electricity usage of CCA. The model can be described as:

$$E_{CCA} = \sum_{i=1}^M N_i P_i T_i K_i, \quad (5.1)$$

where i indexes the M categories of equipment in CCA, N_i is the number of pieces of equipment in the i th category, P_i is the average power draw of a piece of equipment in the i th category during a “run” (in kilowatts), T_i is the average length of a “run” (in hours), and K_i is the average number of “runs” on equipment in the i th category in a given week. A “run” is not defined in the traditional operational sense of a period of value added work, but instead as a period of continuous time when the equipment is drawing more than a nominal (.01 kW) amount of power. A simplified version of the model as applied to a typical residential living room is shown in Table 5.1. Inputs into the model included the measurements described in Section 5.1.4 for each category of equipment. The output of the model is the estimated energy used by CCA in a given week, \tilde{E}_{CCA} .

Verification of the model was accomplished using the archived substation level electricity data from the plant wide electricity metering system for the same week. The metering system installed in the two substations feeding CCA was already set up to provide total electricity use, HVAC electricity use, lighting electricity use, and electricity use for areas other than CCA. Total process electricity

Category	N	P (kW)	T (hr)	K	Energy (kWh)	Cost
Lights	2	0.06	6	7	5.00	\$0.75
Plasma Television	1	0.3	2.5	7	5.25	\$0.79
Laptop	2	0.02	6	7	1.68	\$0.25
Xbox360	1	0.14	2	1	0.28	\$0.04
Cable Box	1	0.03	24	7	5.04	\$0.76
Medium A/C window unit	1	.9	6	7	37.80	\$5.67
Total					55.05	\$8.26

Table 5.1: Example of model used in CCA analysis for a typical living room in a given week in the summer. Costs are calculated using a rate of \$0.15 kWh, the average residential price in Massachusetts in 2010[41].

use for CCA was then determined indirectly from the measurements using the following equation:

$$E_{CCA} = E_{Total} - E_{HVAC} - E_{lighting} - E_{Other} \quad (5.2)$$

where E_{CCA} refers to the process electricity used in CCA and E_{Other} refers to the process electricity used by equipment in areas other than CCA that were fed by the same substations. Comparing the model output, \tilde{E}_{CCA} with the actual electricity measured by the metering system resulted in a difference of 1.5%. The estimation error could be due to a number of reasons, including measurement error and unmeasured systems. Despite the error, the model was considered by SMEs to be good enough to use to identify areas to target for improvement.

While a variety of tools exist for the analysis stage of six sigma improvement processes, the focus of the Tier One DMAIC process in CCA was to guide the improvement phase through identification of the equipment with the most opportunity for reducing waste. Accordingly, the main analysis tool used was a pareto chart. For example, the pareto chart shown in Figure 5-2 shows the relative contribution of different categories of equipment towards the total process load of CCA during a typical week in CCA. The sum of the electricity used by the equipment categories in Figure 5-2 is the estimate of the total process electricity used during that week.

Figure 5-2 indicates that collectively the 84 test stations and the 23 floor ovens in CCA use the most process energy, collectively accounting for about 40% of the total process energy. However, the category of equipment with the third highest electricity use in CCA is from one machine - the MTSA environmental chamber - implying that some machines in CCA are much higher in electricity intensity than others. In fact, on an electricity intensity basis, shown in Figure 5-3, the MTSA machine is the single largest electricity user in CCA by a significant amount.

In light of the analysis presented in Figure 5-2 and Figure 5-3, we decided to focus on improving the efficiency of the high intensity equipment on the left side of Figure 5-3. Specifically, we would focus on improving the efficiency of the MTSA machine, the vacuum system, the two wave solder machines, the four SMT ovens, and the four washers (in that order). The decision was made with

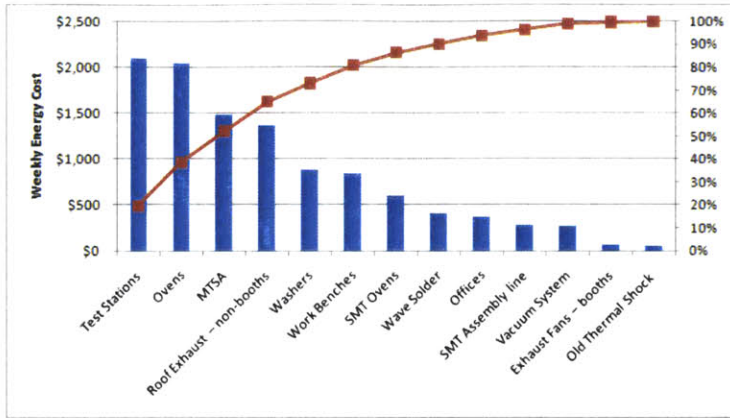


Figure 5-2: Pareto chart of the typical weekly electricity use for equipment in CCA by the category of equipment. For example, the category “workbenches” include the sum of the electricity used by the approximately 300 workbenches in CCA. The left axis refers to the bars, and the right axis refers to the line. Measurements were gathered using the approach of Section 5.1.4.

input from CCA operations senior leadership, as well as energy team leadership. Previous efforts, including those spurred by the pilot program in 2009, had focused on the more numerous, but less electricity intensive equipment on the right side of Figure 5-3[1]. Naturally, equipment that uses the most energy may not be the equipment with the biggest potential for reductions in use. However, at this point in the analysis, we decided to assume that the efficiency of all equipment can be improved by an approximately equal amount (in percentage terms). This assumption was reasonable because estimating the opportunity for improved efficiency for each category of equipment required a time-consuming detailed consideration of operational data that was reserved for Tier Two analysis.

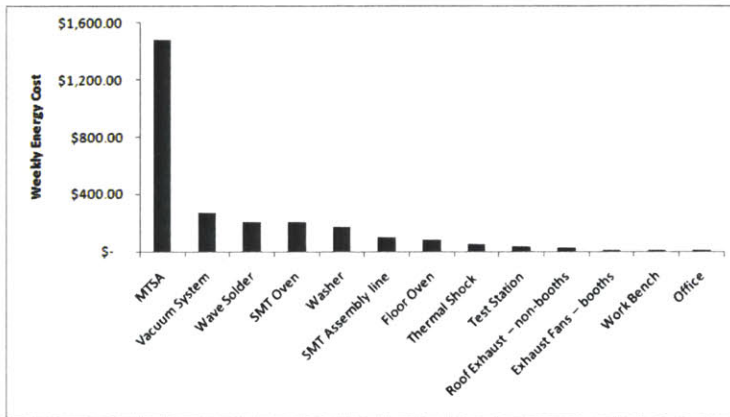


Figure 5-3: Electricity intensity chart for individual equipment in CCA. “Work Bench” includes all items on a typical workbench in the area and “Office” includes all items in a typical area office. A more detailed table of measurements is included in Appendix B

Improve

The electricity intensive equipment required a different approach to improvement than the less intensive equipment. By their nature, high intensity equipment tended to be larger, more expensive, more specialized, and more process critical when compared to the equipment on the lower end of the spectrum. Therefore, any change to the operation of such equipment required high levels of confidence that the change would not damage the equipment or disrupt the delivery schedule of the product.

To alleviate these concerns, each improvement project also utilized the DMAIC approach, where input from SMEs, measurements, and experiments were analyzed before operational changes were implemented. These projects are referred to as the Tier Two DMAIC processes from Figure 5-1. Section 5.1.5 provides two deep dives into two such projects, and Appendix C provides higher level details from additional DMAIC projects in CCA.

Control

Tier One control was accomplished by making the projects compatible with existing process management programs in the facility that required documentation. For example, most improvement projects that resulted from the DMAIC approach were documented on “kaizen plaques” and submitted by cells during the Lean Olympics. Other projects were submitted by cells as “R6 σ ” projects. “R6 σ ” is the Raytheon implementation of lean-six sigma, and submitted projects can be highly visible within the larger company. While documentation does not guarantee control, the fact that the overall approach was able to spawn a variety of highly visible projects for which front line employees and managers were able to “get credit” for improvements creates a feeling of ownership for the improvements. In addition, as stated before, the social culture of CCA, and the energy team in particular, provides a degree of control that should not be understated; while the staff in CCA had not taken this particular approach before, and did not necessarily know how much electricity every piece of equipment used, they had the motivation and proven structure in place to maintain control once an improvement was made.

Specific Tier Two control methods depended on the type of equipment and the implementation and are explained in Section 5.1.5 and Appendix C.

5.1.5 Second Tier DMAIC case studies

This section details two deep dives into Tier Two DMAIC projects that were conducted in CCA. While some data has been disguised for confidentiality, the analytical techniques and challenges are based on actual experience in the production environment. Additional information on other Tier Two DMAIC processes are included in Appendix C.

Wave Solder

Wave soldering is a large-scale soldering process by which electronic components are soldered to a Printed Circuit Board (PCB) to form an electronic assembly. The name is derived from the use of waves of molten solder to attach metal components to the PCB. The process uses a tank to hold a quantity of molten solder; the components are inserted into or placed on the PCB and the loaded PCB is passed across a pumped wave or waterfall of solder. The solder wets the exposed metallic areas of the board (those not protected with solder mask, a protective coating that prevents the solder from bridging between connections), creating a reliable mechanical and electrical connection. The process is much faster and can create a higher quality product than manual soldering of components[45, 46]. CCA has two different high volume wave solder machines, each of which contains approximately half a ton of molten tin/lead solder.

Define For this piece of equipment, operators and SMEs determined that there was potential Type Two overprocessing *muda* due to electricity being used to keep the solder molten during production down times. Specifically, the wave solder machines were typically utilized only by first shift operators, and during downtime on nights and weekends the solder pot heating elements were engaged such that the solder in the tank remained molten even while the machine was idle.

The DMAIC wave solder project goals were thus to determine whether there could be any electricity savings achieved by shutting down the wave solder machines during nights and weekends, while still maintaining product quality, production schedules, and equipment integrity. There was particular concern by operators around the effects of allowing the solder to solidify on a regular basis.

Measure We tested our electricity savings hypothesis by measuring equipment power use data over the course of a week using the AEMC 8335 power quality analyzer. The week included three normal operating days, a holiday weekend when the machine was already scheduled to be completely shut down and the day following the shutdown. This allowed us to get an exact measurement on the amount of electricity required to remelt the solder. For example, Figure 5-4 shows the recorded power use of the equipment for the period of time when the equipment was being restarted after the holiday.

Other measurements, provided by the equipment itself, included solder pot temperature during the remelting process which allowed us to measure how long it took to remelt the solder as well as normal self-diagnostic metrics on equipment functionality.

Analyze Electricity cost savings would be achieved for a given period of time if less electricity was used to reheat the solder from room temperature to operating temperature than would be used to

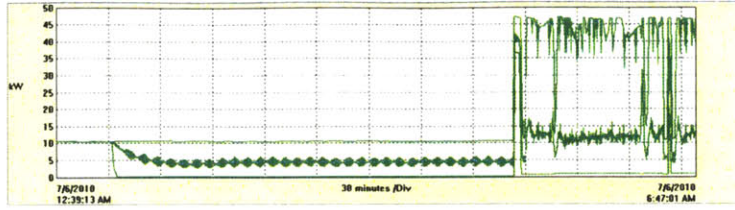


Figure 5-4: The average, minimum and maximum power usage in 1 second intervals of a wave solder machine between 12:30 AM and 6:50 AM on 7/6/2010, the period in which the solder remelted after shutdown and production use began.

keep the temperature of the molten solder constant at the operating temperature. The equation to approximate the break even point was thus

$$t = \frac{E_{heat}}{\bar{P}_{idle}}. \quad (5.3)$$

where the E_{heat} is the energy required to heat the solder from room temperature to operating temperature, and \bar{P}_{idle} is the average power used by the equipment in idle mode to keep the solder molten. This equation assumes that electricity costs are constant over the course of the day. For the wave solder machine we measured, $E_{heat} = 35 \text{ kWh}$, $\bar{P}_{idle} = 5 \text{ kW}$ and $T_{heat} = 200 \text{ min}$, which yields a break even time of $t = 7 \text{ hrs}$. Therefore, if the equipment is scheduled to be idle for more than 7 hours, there will be electricity savings, as long as the machine is turned on precisely 200 min before it is scheduled to be used. The cycle savings can then be determined by

$$S = C\bar{P}_{idle}(T_{idle} - t), \quad (5.4)$$

where C is the cost of electricity per kilowatt-hour and T_{idle} is the time the equipment is idle during a cycle. Using these methods, we determined the typical weekly savings for a single wave solder machine in CCA is approximately \$35. For both pieces of equipment, the annual savings are \$3,560.

In addition to the electricity costs, we evaluated the risks associated with restarting the equipment after a shut down. SMEs determined that, historically, there have not been any issues with restarting the equipment after the periodic shut downs that occur over the course of the year. Moreover, research revealed that allowing solder to solidify prevents “dross” from forming due to molten solder interacting chemically with oxygen in the air[47]. The prevention of dross is critical to maintaining solder quality and smooth equipment operation.

Improve As a result of the analysis, the improvement was that the wave solder equipment was shut off by the operator at the end of first shift (if no second shift operations were scheduled on the equipment), and that a third shift operator was responsible for restarting the equipment at 2:30

AM. (about 3 hours and twenty minutes before the start of first shift).

Control This improvement process, credited to operators on all three shifts as well as cell leadership, was documented and submitted to the corporate R6 σ program. In addition, the cell is currently exploring installing software or hardware timers on the equipment to make the process less subject to human error.

MTSA

The MTSA chamber is used as part of the environmental stress screening process for some CCA products. It is specifically designed to test the functionality of circuit cards over the course of changing temperature conditions according to pre-programmed profiles. A nominal temperature profile used by the Department of Defense for this type of test, though not the one actually used by the MTSA in CCA, is shown in Figure 5-5. Each circuit card in a batch is loaded into a slot

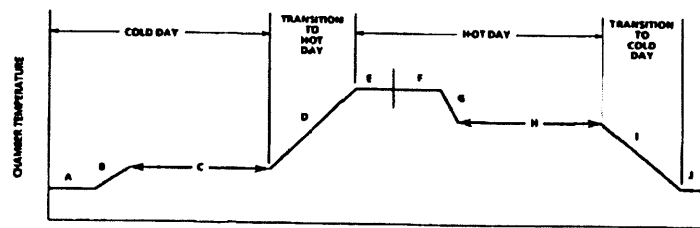


Figure 5-5: An example thermal cycle similar to the one used by the MTSA[48]. The letters correspond to segments of the profile that simulate specific product operating modes.

in the chamber, and is tested while the temperature in the chamber rises and falls according to the pre-programmed temperature profile over a number of cycles called a “run”. Each run takes exactly the same amount of time, unless there is an error in equipment operation. Based on historical data, there was an observed average of 5.5 runs per week.

Define Like the wave solder equipment, operators and SMEs determined there was potential Type Two overproduction *muda* for the MTSA. However, unlike the wave solder equipment, the equipment was automated and did not use any power when not in operation. Moreover, the runs were pre-programmed and could not be changed. However, it was hypothesized that the machine was being overused in the sense that it would be possible to achieve the required throughput to satisfy customer demand by using fewer runs and increasing batch sizes for each run.

Measure In order to test the hypothesis, we gathered data on the electricity use of the equipment, as well as operational data from a variety of sources.

Electricity use of the MTSA chamber was measured using the CM5000 circuit monitors installed in the CCA substation. While in general each CM5000 monitor collected power usage on dozens or

hundreds of pieces of equipment in CCA, analysis of the power distribution system and electrical data during the Tier One DMAIC process revealed that the MTSA shared its circuit only with the CCA vacuum system and its power usage was readily isolated. Figure 5-6 shows the electrical power usage on the MTSA circuit over a 24 hour period. Electrical data from the CM5000, such as what

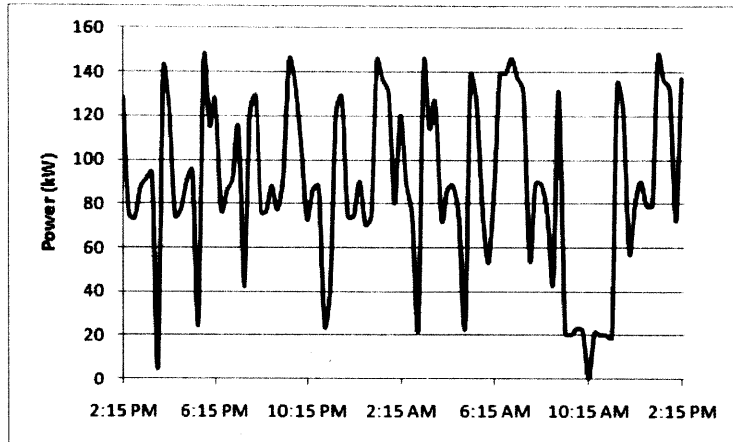


Figure 5-6: Power usage on the MTSA circuit over a typical 24 hour period.

is shown in Figure 5-6, from several time periods was compared with temperature control charts automatically generated by the MTSA and operating records of the vacuum system during the same period. In the time period shown in Figure 5-6, one run began at 2:15 PM and ended at about 9:15 AM the next day. Another run began at about 11:30 AM. These times correspond to elevated power use in the circuit. It was also seen that when the MTSA finished a run and the vacuum system was off, no power was used in the circuit. Likewise, when the vacuum system was on, and the MTSA was not running, power use averaged 20 kW (as seen in Figure 5-6 between 9:15 AM and 11:30 AM). Moreover, power usage peaks corresponded to times when the MTSA was using its air compressors to cool the chamber (as seen in the temperature control charts). Thus, while the system was not directly monitored using an AEMC8335 power logger like the wave solder equipment, we determined with a high degree of confidence that the MTSA chamber uses an average of 73 kW while in operation.

Historical throughput data was gathered electronically from the MRP system archive and manually from equipment operational logs. Future customer demand data was provided by SMEs in the form of contractual delivery dates.

Analyze Using the measurements, we determined the minimum number of runs per week required to satisfy customer demand given the system constraints.

Based on throughput data and SME input, it was determined that the manufacturing process could be modeled using the process map shown in Figure D-1. While this map does not detail the

assembly processes preceding the MTSA machine, or the final steps including functional test, the simplification was acceptable for purposes of the analysis.

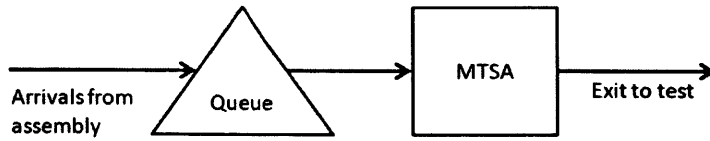


Figure 5-7: Conceptual process diagram for cards tested using MTSA machine. Upstream (assembly) and downstream (test) were assumed to have excess capacity for purposes of this analysis.

Future customer demand was determined using upcoming contractual delivery dates. Based on contracts due in the next 319 days, it was determined that customers demand, on average, 11.7 cards per week that are tested using the MTSA. This result was roughly comparable with the operating logs for the MTSA during a recent 85 day period which showed that average throughput was 14.3 cards per week with a standard deviation of 8.9. Though the discrepancy was small, and may have been due to sampling error or variation in demand, there was some anecdotal evidence based on SME interviews that operators were overproducing to get ahead of the customer demand. Given the data, however, and a desire to be conservative, it was assumed that weekly customer demand was a random variable, D , where

$$D \sim N(13, 9). \quad (5.5)$$

Capacity constraints in the system deserves a brief discussion. Based on SME input and operational records, it was clear that upstream assembly process capacity was greater than customer demand. Likewise, downstream functional testing processes were also assumed to have excess capacity. The MTSA machine had a capacity that varied depending on the mix of cards being tested: particular cards could only be tested in particular slots in the machine and there were only a fixed number of each type of slot. There were 49 different types of cards scheduled to be produced, and equipment documentation indicated that the average capacity for a particular type of card in the MTSA machine was 7.5 cards, with a standard deviation of 3.8. Because it is likely that multiple card types in the same run will not need the same slot, actual capacity of the equipment is generally somewhat higher than the average, but for conservative purposes, we say that the capacity of the equipment for a given run is a random variable, C , where

$$C \sim N(7.5, 3.8). \quad (5.6)$$

Each run was programmed to take 19 hours to complete, although in some cases the equipment failed to achieve the temperature profile within the control limits and had to be manually restarted.

Based on equipment records, the length of each run (in hours) was a random variable, T , where

$$T \sim N(21, 2). \quad (5.7)$$

With the amount of variation in the process, predicting the impact of different policies analytically is difficult. Instead, analysis was performed using a simple discrete event modeling and simulation in ProModel Silver. The framework and details are found in Appendix D. The results of the simulation indicated that with current levels of process variation the MTSA machine could be run in a stable manner at a minimum of four times a week. With this policy, however, average inventory increases by about 7 cards (or 38%) and average cycle time increases by about 80 hours (or 39%). While the increase in inventory was negligible in terms of required floor space (each card measures about one square foot), the increase in cycle time required the changes to be made during a lull in customer demand so as to avoid breaking short-term delivery commitments.

According to simulation and real-world experience, the policy change resulted in a negligible increase in inventory cost due to increased floor space usage and holding costs. On the other hand, reducing the number of runs from 5.5 a week to 4 a week resulted in an average weekly savings of \$310, or an estimated \$15,520 annually due to reduced electricity usage.

Improve While waiting for the modeling and simulation process to provide insight, management decided to experiment with running the MTSA on a restricted weekly schedule. Based only on average customer demand, average capacity of the MTSA equipment, and cycle time, a simplistic analysis indicated that it would be possible to reduce the number of weekly runs to twice a week; weekly demand was 13 cards/week and MTSA capacity with two runs was $7.5 \times 2 = 15$ cards/week. In light of this simple analysis, management decided to try to run the equipment three times a week on Mondays, Wednesdays and Fridays. However, this schedule, as subsequent modeling and simulation revealed, was found to be unsustainable due to the level of variation in the system. While this variation may have been reduced by changing the sequence in which cards are tested, the production scheduling was assumed to be fixed for this study.

Despite the failure of the initial policy, operators agreed to try to restrict operations to four times a week after calculations revealed it was possible. In addition, the modeling process also revealed sources of variation in the process that could be addressed to improve throughput. For example, the average capacity of the MTSA equipment could be significantly improved by repairing a select number of broken card slots in the equipment. An analysis conducted as part of a separate $R6\sigma$ project during the study time period indicated that 25 runs in the previous six months could have been avoided if broken slots were repaired.

Control The cell leader had ultimate control over the number of weekly runs made by the MTSA equipment. As in the case of the wave solder DMAIC improvement process, the cell leader and relevant operators were involved in every step of the MTSA DMAIC process, and documented the process with an energy improvement kaizen plaque that was submitted to the spring Lean Olympics (despite the fact that the initial restrictions documented were ultimately unsustainable). In addition, the operations policy itself was designed to make the improvement easier to control. Specifically, runs were scheduled to occur only on specific weekdays (Mondays, Wednesdays and Fridays initially) which created a repeatable, easy to remember, and predictable schedule for operators. Finally, management had visibility into historical machine operation through both equipment logs and ultimately an electronic interface similar to the one presented in Section 5.2 which used power data from the CM5000. The ability to easily check to see how often the equipment was actually run in any given week will aid in adherence to the new policy.

5.1.6 Overall Results

In order to assess the results of using the DMAIC process in CCA, we compared the anticipated annual savings resulting from projects documented with kaizen plaques during the Spring 2010 season of the Lean Olympics with the savings from projects during the Fall 2009 season for all cells in CCA. Both seasons lasted three months, and the teams in CCA were exactly the same. The only major difference between the two seasons (besides the time of year) was the fact that the DMAIC process for continuous improvement in electricity usage was utilized in 2010.

Figure 5-8 shows both the total annual savings and the average savings per project resulting from activities in the two seasons of the Lean Olympics since energy was included as a category. Figure 5-8 shows that total savings more than doubled, and average savings per project more than

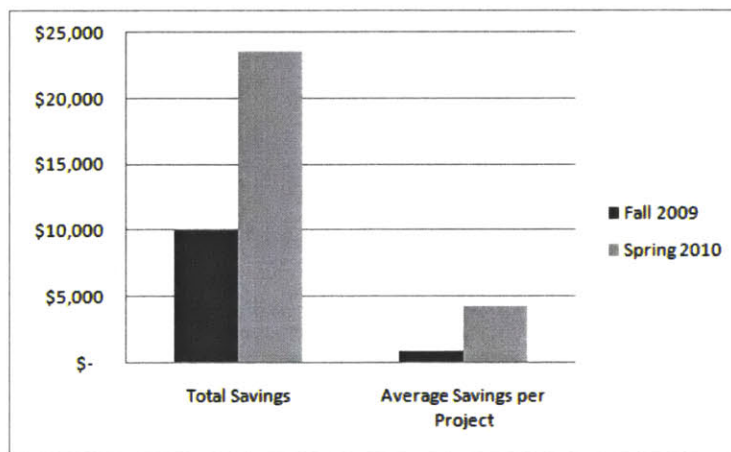


Figure 5-8: Energy cost savings in CCA due to projects submitted to the Lean Olympics. There were 11 projects completed in Fall, 2009 and 6 projects completed in Spring, 2010.

quadrupled as a result of the DMAIC process. In essence, fewer projects in 2010 were completed, but the total impact was ultimately more valuable than the projects completed in 2009 due to the higher marginal value of each project. That result is not surprising; following the DMAIC process took longer than the previous approach to continuous improvement, but it was clear from the results of the Tier One DMAIC process analysis step that we were targeting systems with higher electricity usage in 2010 so our savings would likely be higher, on average, than previous efforts.

Notably, the Spring, 2010 data shown Figure 5-8 does not include the results of some projects which were in process by the time the Spring Lean Olympics season concluded. For example, it does not include the results of the wave solder machine Tier Two DMAIC process described in Section 5.1.5 and other projects that resulted from the Tier One DMAIC process. A full, but abbreviated, listing of all energy projects completed, pending, and recommended in CCA between February 1st, 2010 and August 15th, 2010 can be found in Appendix C. If these projects are included in an analysis of the effect of the DMAIC process, the total annual savings that can be directly attributed to using the process is about \$56,830, or 10.3% of the expected total CCA process electricity use as of January, 2010.

5.1.7 Management Implications

Beyond the positive impact on results from using the DMAIC process to reduce electricity usage, there are three compelling management features for using DMAIC for this problem. There was also one unexpected implication that deserves some further discussion around the role lean manufacturing played during the improvement process.

Departmental Alignment and Senior Management Participation

As explained in Section 2, historically, there has been a separation between the approaches that facilities personnel and operations personnel use to manage electricity use. Facilities personnel have typically been focused on reducing electricity usage of support systems such as HVAC and lighting using the tenets of energy management. Operations personnel are more familiar with continuous improvement approaches like lean manufacturing and six sigma, and generally have been engaged in energy conservation efforts through awareness programs like leaflets and signage or participation in infrequent passive training modules. The use of a continuous improvement process such as DMAIC can align the two departments, and allow both to contribute unique expertise and abilities that has been developed over the course of time to achieve a common goal.

Specifically, the DMAIC process itself, for this problem, splits naturally into stages that can be led by facilities, operations or both. The following structure was found to be particularly effective:

- **Define:** A collaborative conversation between Operations and Facilities personnel, this stage helps set the tone for the rest of the project.

- **Measure:** Led by Facilities, in consultation with Operations. Facilities has the expertise with measurement equipment and knows the safety procedures for dealing with high voltage equipment.
- **Analyze:** A collaborative effort between Facilities and Operations. This stage also represents a critical transfer of knowledge between Facilities and Operations personnel as operators get educated about electricity usage in the environment. This stage could be greatly facilitated by an energy manager and/or others familiar with operations research techniques.
- **Improve:** Led by Operations, this stage depends upon operators' intimate knowledge with the equipment and various production constraints that will impact implementation.
- **Control:** Led by Operations, in consultation with Facilities, this stage must incorporate the culture of the work cell and documentation should include all participants in the process to create ownership and a sense of accomplishment.

Moreover, each stage of the process involved employees at different levels and job functions within the respective department. At Raytheon, each DMAIC process involved senior managers from both Facilities and Operations, process engineers, cell leaders, front line operators, electricians, and electrical engineers, occasionally from multiple shifts. The process thus engendered cross-functional communication, and occasionally resulted in discovering other improvement opportunities, as was the case with the MTSA machine and the broken card slots.

Finally, the fact that the DMAIC approach is a well known operations management process likely affords the ability to easily integrate process energy usage into existing continuous improvement programs at most manufacturing facilities, and ensures that operations personnel are familiar with the process, especially if the ultimate goal (energy management) is something that may be new to them.

Optimal cycle time for improvements

The structured and linear nature of the DMAIC process, while perhaps taking longer than more ad-hoc approaches, is likely to take less time to get to an effective and workable solution than a more iterative approach. While the DMAIC process may not be adaptable to more complex endeavors (although a version for design is also well understood in the literature), it was found that the process electricity usage problem is well suited to a linear approach like DMAIC. That may be due to the fact that electricity usage of manufacturing equipment tends to be both highly measurable and predictable, which enables solid measurement and analysis, which ultimately leads to concrete improvement interventions and verifiable control plans. It was found that the process provides a convenient mapping of actions to project status so that everybody involved is coordinated and

minimal time is wasted revisiting previous stages once they are completed. In addition, the linear and stable process allows the project team to plan ahead and gather necessary resources to enable the next stage, which results in less overall time for projects versus a more iterative approach. Finally, in a resource constrained environment such as in a manufacturing plant, it is preferable to only use available resources once, especially if the results of the improvement are likely to be savings of thousands, rather than hundreds of thousands or millions of dollars.

General and repeatable

The DMAIC process is also general and repeatable in the respect that the approach can be applied to any shop in the facility employing any variety of equipment. In fact, as a result of the CCA experience, a “roadmap” for electricity waste reduction in Raytheon manufacturing operations was published which will guide future endeavors to spread the approach across the facility.

Lean manufacturing as an unexpected impediment to improvement

One unexpected obstacle encountered during the MTSA improvement process was a perceived conflict between the principles of lean manufacturing and improvements required to achieve electricity usage reduction. Specifically, there was resistance on the part of operations personnel to increase batch sizes, with the cited reason because a principle of lean manufacturing is single piece flow. While it is easy to see how this belief may have arisen, it is not easy to dispel. In general, there was a lack of understanding that there are tradeoffs involved in batching: in some environments (namely large volume consumer manufacturers with uncertain demand) it tends to increase inventory, hide defects, and can lead to overproduction. However, in the case of the MTSA machine and the products in question, the increased inventory costs (both in terms of storage and capital) were minimal, hidden defects are irrelevant because every card must be rigorously tested for quality regardless of whether they were batched or not, and production is “pulled” from customer demand on existing contracts. Therefore, these concerns were far outweighed by the extra electricity cost due to overprocessing *muda* with the existing equipment and flow. While smaller batch sizes can ultimately be a goal, it should be achieved in conjunction with right-sizing the equipment to customer demand.

5.2 Real-time feedback

The second component of the hypothesis field tested at Raytheon was that real-time feedback on electricity usage to operators would reduce electricity waste. As noted in Chapter 3, real-time feedback is consistent with generally accepted continuous improvement principles, and may be a way to accelerate the DMAIC process (and more generally the PDCA cycle) that was tested in the first part of the hypothesis.

This section will discuss the motivation for testing the effect of real-time feedback through a short literature review, describe a case study that included a field study that utilized real-time feedback conducted at Raytheon, and conclude with some remarks on the management implications of a real-time feedback approach.

5.2.1 Real-time feedback applied to an energy use reduction program

Section 5.1 described the DMAIC business process, popular in six sigma literature, that accomplishes the PDCA cycle which is the hallmark of continuous improvement and *kaizen*. As previously noted, the PDCA cycle is often described as applying the scientific method as a business process [49]. Organizations that accelerate the process of learning from these cycles tend to perform better than organizations that do not[19]. As a result, much research has gone into figuring out ways to decrease the time required to apply the scientific method repeatedly in real-world organizations.

There are three broad approaches described in literature, which can be applied concurrently, to accelerate the process of learning from the PDCA cycle by decreasing time and reducing cost. One approach is focused on the structure and management of an organization. These approaches tend to focus on the use of quality circles and other organizational features to train and develop personnel to more rapidly design and conduct experiments[19]. A second approach is to use statistical methods, such as sampling and experimental design, to minimize the number of samples required or experiments performed before reaching a conclusion[50]. A third approach is to utilize technology and automated data processing to make the measurement and/or the analytical process faster, easier and less expensive to perform[6, 7]. The real-time feedback discussed in this section is an example of the third approach.

Real-time feedback to operators in a manufacturing setting can come in many forms, for numerous types of processes, and has been described using a variety of terminologies (visual factory, visual indicators, shop floor visualization etc.)[6, 7]. The working definition of real-time feedback used in this setting is the visual display of process-relevant data which continuously updates and can be viewed by operators who interact and control the system being monitored at any time. Under that definition, real-time feedback systems need not be technologically complex or involve advanced IT or analytics; temperature control charts for industrial ovens can be considered a good real-time feedback system, as can a car odometer.

An advantage of real-time feedback on electricity usage is that electricity waste is largely a “hidden” waste. As a previous study in this facility noted, “unlike traditional forms of manufacturing wastes, like inventory and defective parts, an employee cannot see kilowatt-hours pile up next to a manufacturing cell”[1]. The implication of a waste that cannot be easily visualized, such as electricity waste, in a fast-paced environment like a manufacturing plant is that it is easily overlooked. The lack of a good user interface to view and analyze electricity usage may partially account for the lack

of attention paid to it in typical manufacturing operations environments. Another explanation is that a certain amount of energy is fundamentally required by a manufacturing process. Taken to the extreme, a metric that measures only electricity usage (rather than waste) may drive behavior that ultimately harms the manufacturing process in the absence of other metrics. The best metric to use in a manufacturing environment to drive energy efficiency is likely dependent on the industry and organizational structure, and there currently is no standard in the literature.

To date, there has not been an academic study on the effect of real-time electricity usage feedback to operators in an industrial setting. However, there have been multiple experiments performed in the home, where residents are given real-time feedback on their household usage of electricity. The results of these experiments indicated that residents will reduce their energy usage by 5-15%, generally through voluntary behavior modification[8, 9].

5.2.2 Case Study - Magnetics/Oil Room Experiment

The hypothesis that real-time feedback of electricity usage will lead to reduced electricity waste was tested in a series of field studies involving operators in a cell referred to as the “oil room”. This section is presented as a case study, and presents the setting, the methodology, the design and the results of the field studies. Some data and names have been modified to protect confidentiality.

The Oil Room Cell Background

The Oil Room cell was selected for the field experiment because it was relatively easy to meter (only three additional meters would need to be purchased and installed), the cell is a fairly large energy user (average load was estimated to be 45 kW, the equivalent of the energy usage of approximately 25 homes), and the employees were interested in participating.



Figure 5-9: Picture of the type of walk-in oven in the Oil Room. Note: this is not an actual photo taken at the IADC.

The cell consists of an array of six ovens. Each oven, as shown in Figure 5-9, was approximately six feet tall, four feet wide and eight feet deep. Each of the six ovens was slightly different in terms of features and capabilities, but for purposes of this study those differences are unimportant. Each oven had three distinct electrical power draws; heating elements, vacuum pumps, and fans. The heating elements and fans were under manual operator control but the vacuum pumps were generally left running continuously.¹ Thus, the existing policy in the cell was to turn the fans and heating elements off when there was no product in the oven, but ultimately the decision was left to operator discretion.

Each oven consumes an average of 30-40 kW when the heating element is engaged (depending on the temperature and oven). Of that total, 1-2 kW is from the fans, 3-7 kW is from the vacuum pumps, and the balance (26-31 kW) is from the heaters. On average, two or three ovens are used during any one shift, though there are certainly times when all six or none of the ovens are being used to heat product. The processing instructions for the parts that are processed in these ovens vary substantially. Some parts just need to be placed in the oven for a set amount of time (this process is called a bake), while other parts needed to be placed in a tank of oil within the oven and cannot come out until a certain minimum vacuum pressure is achieved and a specific time threshold is surpassed (this is called a vacuum bake). Therefore, helping to reduce the amount of energy wasted due to over processing (i.e. leaving the part in the oven longer than its minimum requirement) is not always as straightforward as just setting a timer for each product[1]. Currently there are two employees that regularly use the ovens and a third employee that occasionally uses the ovens when the regular employees are absent from work.

Data Sources

In order to allow for the quick integration with the existing metering and energy management system used at the IADC, Enercept power meters from Schneider Electric were selected to be used in our case study. Essentially all the power meters currently installed at the IADC, as well as the energy management software package used, are Schneider Electric products. Thus, just about any Schneider Electric power meter would have integrated into the existing IADC system, however, the Enercept meter provided the data we needed (real energy and power) at the lowest hardware cost. The meters automatically transmitted average power readings from each oven on 15 minute intervals over an internal ethernet network which were timestamped and stored in a SQL Server database. The 15 minute interval time for averages was chosen to balance fidelity, storage, bandwidth, and smoothness of the data.

Along with electricity data, we also incorporated operational data into the feedback. The source

¹The mechanics assigned to this cell claimed that the pumps should not be turned off because the pumps have problems starting after shutdowns.

of the operational data was an electronic MRP system which tracked material, components, and worker operations throughout the plant. This system (which the operators used prior to the introduction of the realtime feedback) provided a real-time record of when specific operators put specific items into and took specific items out of the seven ovens in the Oil Room. Because the MRP system depended upon a manual operator user interface, there were occasional lapses and mistakes leading to inaccuracies in the operational record that were observed. Whenever possible, these data entry mistakes were manually corrected in the system as soon as possible, and in general the measurement error from these inaccuracies are considered random and insignificant for purposes of this study.

The two types of data were combined in a user interface dashboard developed and deployed within VBS.

The Raytheon Virtual Business System

The principal advantage of VBS, a homegrown information system at Raytheon IADC, is to allow any employee at the IADC to rapidly develop and deploy easily learnable user interfaces, called dashboards, which allow users to create, read, update and delete data (depending on user permissions) from the myriad of data systems and sensors found within the IADC and increasingly at other Raytheon locations. These VBS dashboards, developed in the LabView graphical development environment from National Instruments, provide real-time, objective production information in a format and context that enables real-time decision making by all employees in the facility including managers and frontline employees[40].

VBS dashboards are displayed on about 80 flat screen monitors throughout the IADC in hallways, offices, the dining center, and on the factory floor. Each monitor, which are usually placed in highly visible locations, will continually cycle through critical dashboards chosen by local manufacturing cells. In addition, there are 3,832 installations of VBS on the workstations of manufacturing employees (represented employees, cell leaders and senior managers) which allow any employee to use dashboards at their convenience.

Approach - Feedback Dashboard

Optimizing the user interface design of an industrial electricity use feedback system was not the main topic of this research. Instead, a good faith effort was made to adhere to the recommended design principles for such feedback in the literature, but given the time constraints, we were not able to follow the iterative approach necessary to optimize design given user interface design criteria and usage studies. Nevertheless, this section will present the deployed interface, which took the form of a VBS dashboard called "MAGS PWR STDS", and give some insight behind various design decisions.

The general interface layout, style, and controls follow the standard dashboard user interface

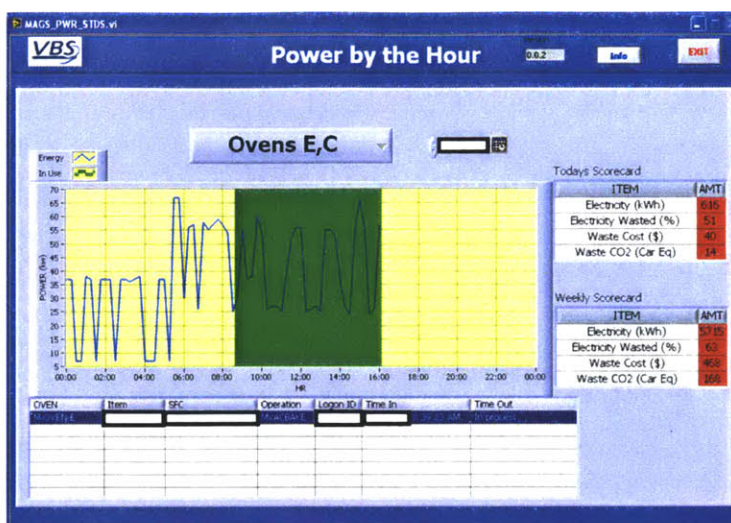


Figure 5-10: A typical example of feedback as might have been seen during the field experiment using the MAGS PWR STDS dashboard. Please note that dates, operator and item identifiers have been redacted for confidentiality.

template for VBS, which helps learnability on behalf of operators. That being said, it was necessary to train the operators to use and understand the information on the dashboard, shown in Figure 5-10.

The central features of the dashboard are the large plot in the middle and the table just below it. The plot displays real-time power usage of the ovens as a blue trend line, with green shading indicating that an item was in one of the ovens during that time. The table displays operational data from the MRP system relevant to those ovens. For example, in Figure 5-10, the user selected to view the power used by Ovens E and C on a Tuesday.² The blue line indicates that the power use was fluctuating between 7 and 37 kW between midnight and 5:30 AM, indicating that the heating element was engaged in either oven E or C. At about 5:30 AM, the load on the circuit increases to fluctuate between 25 and 65 kW, which means that the heating element in the other oven was turned on. According to the table, at 8:39 AM, the operator put an item into oven E where it continued to remain until about 4:00 PM, the current time.

Based on the information in the dashboard, it is possible to deduce that that oven C was accidentally left running overnight and throughout the day without any product inside it. Oven E, on the other hand, was properly shut off overnight but turned on first thing in the morning, three hours before it was used in an operation. While the dashboard does not explicitly present those conclusions, feedback from operators and managers familiar with the cell indicated that once they were trained, it was easy to arrive at such conclusions.

By correlating the electricity data from the meters and operational data from the MRP system,

²Due to installation costs, we were unable to individually meter each individual oven. Instead, the data from ovens E and C were combined and data from ovens D and F were combined because those two ovens were on the same circuit. Ovens A and G were individually monitored

we were able to gauge the amount of wasted electricity from oven operations in the Oil Room. Wasted electricity was defined simply as electricity used by empty ovens; in that sense, we were combining Type One and Type Two overproduction *muda*³

Other features of the dashboard included two “scorecards” to the right of the main plot. The daily and weekly scorecards presented data on how much total electricity has been used, and the amount of wasted energy in terms of percent of total usage, dollars and car equivalents for the day and week respectively⁴. Scorecards that focus on waste, rather than use, are recommended by previous researchers as more effective for behavior change, and putting energy waste in dollar terms is a general tenet of energy management[52, 1, 36]. If energy waste comprised higher than 25% of the total energy use (an arbitrary number), the scorecards were highlighted red, otherwise, they were green. The intent was to provide operators with a quick way to evaluate and track their performance over time.

Field experiment Design

The field experiment proceeded in four phases:

Control Period The control period lasted for eight weeks. Statistics on electricity waste was gathered using the definition and method described in the previous section. During this time, no feedback was given to operators.

Feedback to Operators The second phase was characterized by training the three operators who regularly used the ovens to understand and use the real-time feedback dashboard. The dashboard was made available on the operator workstations and displayed on a continuous loop on large overhead monitor in the Oil Room visible to all personnel in the area. The hypothesis was that electricity waste would significantly decline versus the control period. Phase II lasted four weeks.

Feedback to Managers The third phase was characterized by explicitly training managers on how to use and understand the real-time feedback dashboard. Until the third phase, operations managers were not personally engaged and trained on how to use the feedback, though nothing was preventing them from viewing the dashboard on their workstations and via the overhead monitor if they were curious during Phase II. The hypothesis was that electricity waste would decline further than in Phase II. Phase III lasted two weeks.

³The reported amount of waste electricity in this study is likely conservative because in the case of ovens E and C and ovens D and F, we could not separate the electricity use of the two ovens. Therefore, if an item was put into oven E, like in Figure 5-10 for example, the wasted power (approximately 30 kW) from continuing to heat an empty oven C was not captured

⁴The “car equivalent” is the equivalent number of cars in a given day it takes to produce the amount of CO₂ that is required to produce a given amount of electricity. In this application, we used 1.1×10^{-4} cars kWh[51]

Feedback Removal The final phase was characterized by removing the dashboard from continuous loop on the overhead monitor in the Oil Room. The dashboard was still available via operator and manager workstations. The hypothesis was that electricity waste would rise, but remain below the control period levels. Data collection on Phase IV lasted two weeks⁵.

Each phase began after the previous phase ended. No attempt was made to control for personnel, production volume, or product type. However, as previously stated, these factors are not considered too significant as the personnel was constant, production volumes were relatively stable during the time period under study and the product mix was fairly constant as well. Because time constraints prevented a more robust study design in terms of both sample size and control, the results drawn from this study should be viewed as indicative, rather than conclusive for the given hypotheses.

Results

The results of the feedback field experiment are mixed in terms of support of the hypotheses. The average dollars of electricity wasted per week during each phase of the field experiment are shown in Figure 5-11. Based on our experience during the field experiment and the data, we make the

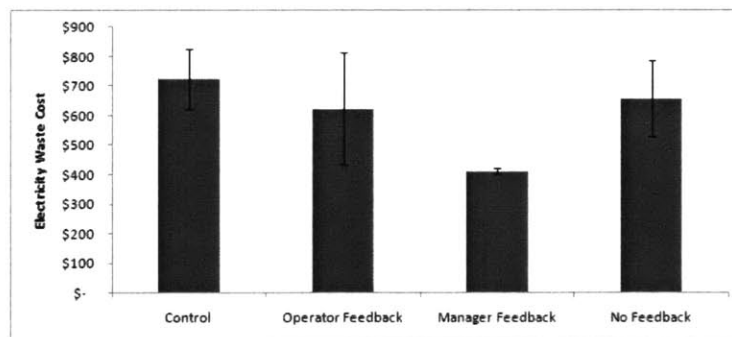


Figure 5-11: Results from real-time feedback experiment in the oil room. The solid bars depict the observed average weekly dollar value of electricity waste. The whiskers on the bars indicate 95% confidence intervals around the mean.

following observations:

We cannot conclude that operator feedback alone significantly decreased electricity waste Using the data from the control period and the first four weeks after training the operators to use the dashboard, we tested the null hypothesis that there was no difference in means using a two-sample Student's T-Test with unequal sample sizes and equal variances. Given the small sample size, and because we are looking for a definite decrease in waste, we use a one-tailed test to increase the power of the test statistic (perhaps at the expense of stronger assumptions around the impact

⁵Data collection on this phase also occurred after the researcher had left the plant at the end of the study period

of the feedback). Even so, the p-value of the test (0.84) indicates that we fail to reject the null hypothesis with any generally acceptable level of confidence.

Despite the relatively low statistical confidence using this approach, however, it is also observed that average waste during the operator feedback period dropped about 14%, corresponding to an overall energy reduction of 11%, which is fairly consistent with previous results from published studies in other environments. If prior beliefs about the positive causal effect of giving feedback are incorporated, then results from this field experiment at least argue at least for further testing with more samples.

When managers pay attention to the feedback, waste is significantly reduced Using the same approach to compare the two week period after managers were trained on how to use the feedback, but before the display was taken away, we can conclude that electricity waste feedback to both operators and managers makes a significant difference. The observed average reduction in waste from control during the third phase of the field experiment was 43%, corresponding to an absolute reduction in energy usage of 26% on measured equipment.

The argument can be made from both a statistical and analytical sense. On a statistical level, the p-value of the test (0.01) indicates that we can reject the null hypothesis with confidence. Moreover, it was observed that soon after being trained on using the dashboard, senior management introduced a simple paper audit checklist (Figure 5-12) that was taped prominently to one of the ovens in the middle of the room. The checklist included the elements of each oven that should be shut down at the end of the shift (if empty) and columns for each work day with a place for operator initials for who conducted the audit. During the two week period of the third phase of the field experiment, it was observed that this audit was completed fully every day by cell members.

The effect of management intervention can be short lived The fourth phase of the study removed the automatic continual display via the monitor in the Oil Room. It was observed during this time frame that waste levels increased to about second phase levels. Average waste was still about 9% lower than what was observed during the control period, but, as with the second phase of the study, the difference was statistically insignificant from control. Although it was hypothesized that waste levels would rise, the abruptness of the rise was nevertheless surprising given the impact of management intervention in the previous phase of the experiment. It is unclear what happened during this time period to the audits because field observations were unable to be made due to time constraints. However, based on their impact during the third phase, it is likely that the audits were discontinued. Whether that is a result of removal of the visual feedback or for some other reason is unknown.

PLEASE INITIAL YOUR NAME WHEN YOU SHUT THESE ELEMENTS OFF

	2 Aug	3 Aug	4 Aug	5 Aug	6 Aug	9 Aug	10 Aug	11 Aug	12 Aug	13 Aug
Oven E										
Heaters										
Exhaust Fan										
Circulator Blower										
Booster Pump										
Oven D										
Heaters										
Exhaust Fan										
Circulator Blower										
Booster Pump										
Oven C										
Heaters										
Exhaust Fan										
Circulator Blower										
Oven A										
Heaters										
Exhaust Fan										
Circulator Blower										
Booster Pump										
Oven G										
Heaters										
Exhaust Fan										
Circulator Blower										
Booster Pump										

Figure 5-12: The Oil Room oven audit checklist developed by cell management.

It is likely that this field experiment suffered from the Hawthorne effect The Hawthorne effect is defined as when the presence of a researcher temporarily improves or modifies subject behavior simply because they are being studied[53]. This effect could explain the significant increase in waste observed in the fourth phase of the study, when the researcher was gathering data remotely rather than at IADC.

5.2.3 Management Implications

The implications of the real-time feedback case study are more nuanced than the those resulting from introducing the DMAIC process to an already engaged workforce.

Electricity waste reduction can be achieved through display and tracking of metrics

The real-time feedback dashboard saw its greatest impact when managers assessed the performance of their cell using the dashboard metrics on waste and then took counter measures (such as audits) to reduce that waste. While the intention of the real-time feedback was to accelerate the PDCA experimental cycle on the part of operators and managers, in reality it was most successfully used as a way to enforce top-down style compliance in adhering to existing procedures, such as shutting down ovens at the end of the shift. Regardless, the fact that managers were able to quickly and accurately assess the current state using the dashboard no doubt aided in developing and deploying those counter measures effectively.

That being said, there are more cost effective ways to display and track metrics that are tightly correlated with energy waste that would produce the same effect. For example, compliance with

energy audits can be tracked as a metric, as audits for other purposes already are at Raytheon. It is likely that tracking metrics on these audits would have produced the same end result as the direct measurement of energy waste using networked meters on equipment, without the cost of hundreds or thousands of dollars per installation.

Passive feedback is no substitute for active managers when it comes to behavior change

Based on the results, it is unclear whether feedback alone had any significant impact on operator behavior. However, there was a significant change once cell leadership got actively involved and participating in the improvement process. While these results may not be generalizable to all manufacturing environments given the unionized structure at Raytheon, it is interesting to consider the general difference between a residential environment, where previous feedback studies were conducted, and a typical manufacturing environment.

In a residential environment, the homeowner is owner, manager and operator; they have both incentives and authority to immediately adjust their behavior in response to data. In a manufacturing environment, however, especially in a highly hierarchical environment such as Raytheon, the ownership, incentives and authority to adjust behavior unilaterally is not as tightly aligned. Thus, the role of management is critical to support operator behavior change, and passive feedback such as dashboards to operators without management engagement, no matter how good the user interface, is probably not the most effective solution to reducing energy waste.

Real-time feedback systems might be more suited for those already concerned about electricity usage

The final implication, which incorporates the previous two implications, is that real-time feedback is probably more suitable for those manufacturing environments that have already harvested the “low hanging fruit” in terms of enforcing procedural compliance. A good example at Raytheon would be CCA. CCA produced compliance with energy audits, without the benefit of real-time feedback systems, by leveraging their organizational structure and aligning incentives for operators to actively participate. As a result, as described in Section 5.1, they were able to incorporate additional data on electricity usage, provided via the AEMC handheld meters, to perform PDCA cycles in the form of DMAIC processes to tackle more difficult issues. Indeed, one can easily imagine the next step to be installing real-time feedback meters in CCA on certain equipment to both help automate and accelerate the experimentation process on large electricity users, as well as supporting the “control” phase of DMAIC. In fact, this process had already begun, as previously noted, on the MTSA and vacuum system at the time of writing.

An estimated impact to using the feedback to similarly fine tune operations in the Oil Room may be projected using data gathered in the field. It was observed that diligently shutting the ovens off

overnight reduced overall energy usage of the ovens by 23%. However, if operators or managers then took the next logical step and examined their usage of the ovens during working hours, they would find ample opportunity to further reduce energy consumption. For example, Figure 5-10 depicts a common operator practice of turning ovens on well before product was likely to be placed inside the oven. SME input and equipment documentation, however, indicate that it usually takes no more than 30 min to warm the oven up to temperatures used in the process. For the day depicted in Figure 5-10, turning the oven on only when necessary would have shaved about 2.5 hours of idle energy usage off. If we assume the oven was in operation for the remainder of the day (18.5 hours), then that would have resulted in a 13.5% reduction in electricity usage that day. If we combine that result with similarly observed behavior in terms of operators leaving ovens on unnecessarily until the end of shift, a conservative estimate is that an additional 15-20% of electricity usage could be saved based on diligent manual oversight of oven usage. Furthermore, installing timers and automating vacuum pressure monitoring could save even more electricity for instances when ovens are left on unnecessarily overnight and during weekends after minimum bake times and vacuum pressure are achieved. It is easy to imagine real-time feedback enabling such process improvements, assuming an engaged workforce.

5.3 Right-sizing equipment

This section analyzes the potential impact of applying the concept of right-sizing process equipment as part of an energy efficiency program and is based on research and a variety of field observations over the course of the study period.

5.3.1 Right-sizing applied to an energy efficiency program

A fundamental principle of lean manufacturing is “right-sizing” process equipment to demand and flow through the manufacturing plant. Right-sizing means sizing equipment to meet the needs of individual manufacturing cells or process steps, rather than the needs for multiple cells at once or the entire facility[4]. This concept is highly correlated with eliminating Type One overproduction *muda*, as large “monument” equipment designed to accommodate maximum possible demand is typically run well below capacity.

Previous research indicates a large opportunity to be achieved using this method based on experience in right sizing support system equipment. In particular, 60% of building fan systems are over-sized, most chillers are oversized by 50-200%, and energy savings from right-sizing motors and using variable speed drives is estimated at 50-85%[4]. It has been estimated that 11% of the overall electricity usage of motors in industrial support systems can be reduced through right-sizing and updating[3]. While similar data is not available for process equipment, anecdotal evidence from the

IADC indicate at least as much opportunity in this category.

5.3.2 Field observations and examples from the IADC

During the study period, several examples of process heating and cooling equipment that could be right-sized were studied. It is relatively easy to predict the impact of reducing the size of process heating and cooling equipment, especially if the process itself does not change. Specifically, we see from the heat equation

$$Q = mc_p\Delta T \quad (5.8)$$

that there is a linear relationship between mass (m) and the energy (Q) required to heat (or cool) the mass. If we assume a constant density of the mass being heated (or cooled), then there is an approximately linear relationship between energy and volume. While the specifics of equipment designs, materials used, and location of items in the equipment result in different levels of efficiency, the linear relationship is what really matters when trying to get a sense of potential savings. This model has been verified using a sample of oven vendor data (see Appendix E).

A good example of a “monument” that is significantly over capacity for the observed production flow at Raytheon is the MTSA machine in CCA. This piece of equipment, decades old at the time of study, was designed to be able to test 270 circuit cards at the same time. In current conditions, however, looking at over six months of data, we observed batches of no more than 23 cards at a time, with average batch sizes around seven circuit cards (largely due to constraints explained in Section 5.1). Moreover, current customer demand only averaged about 13 cards a week, with a standard deviation of 9.

A simple analysis based on the linear model of energy savings indicates that the energy of the MTSA process can be significantly reduced by right-sizing. For example, if it were possible to reduce the size of the equipment from a volume big enough to handle 270 cards to a volume right-sized for customer demand and operational flow (say 3 cards per day, five days a week), there would be a staggering 99% reduction in energy required to satisfy customer demand for this process. While this approach would probably require acquiring multiple smaller MTSA machines, or at least a more flexible design to handle the variety of circuit cards tested in the equipment, the payoff in terms of energy, estimated at around \$51,200 annually, would be significant.

Other examples of equipment that were consistently well over-sized in terms of volume for current demand at the facility (by 50% or more) were many of industrial ovens, including the vacuum ovens in the Oil Room. While anecdotal evidence from the facility indicates that management and operators are aware of and currently addressing this problem, for example by purchasing several smaller ovens to replace one large shared oven, the full extent for energy savings from applying this principle to equipment throughout the facility is well worthy of further focused research.

5.3.3 Management Implications

Barriers to right-sizing

The MTSA machine also provides a good case study for the barriers to right sizing equipment. At the time of the researcher's arrival at IADC, the current MTSA machine was due to be replaced with a brand new, custom designed version that was only half as large. However, this re-design and installation project, still not completed at the time of writing, had already taken over a year from the date of kickoff. Long cycle times for capital allocation projects and the long lifetimes of specialized process equipment such as the MTSA machine (measured in decades) naturally result in large buffers continuing to be built into equipment, in order to accommodate variability in future demand. At the same time, however, the long lifetimes of the equipment also argue for maximum flexibility at a minimal operating cost.

Another barrier to right-sizing is the current procurement process at the plant. In a short analysis of capital equipment purchasing forms at the IADC, there is no clear indication that anticipated customer demand has been analyzed from the perspective of sizing the equipment appropriately. Moreover, the only analysis of energy usage of the equipment required is in the context of notifying facilities personnel as to the voltage and current required from an electricity delivery perspective, rather than ongoing operating cost.

Addressing and removing these barriers is projected to result in a greater impact on energy savings than all other activities described in this research combined, but as noted in previous research (Appendix A), integrating energy efficiency concerns into the capital allocation process, especially for process equipment, is a difficult challenge from both an organizational and a financial perspective.

5.4 Chapter Summary

This chapter covered the details and results of three energy efficiency improvement approaches at the IADC, each corresponding to a different best practice in the hypothesis.

The best practice of measuring energy usage of individual equipment as part of team-based continuous improvement projects resulted in a clear improvement in energy efficiency. The general approach taken to continuous improvement was to use the DMAIC process, which helped align different functional organizations (facilities and operations) and was compatible with existing the existing continuous improvement program of the organization. A key tool developed during this process was a model of energy usage, which incorporated field measurements and SME input. The reduction in total process energy using the approach was 9.3% compared to 2010 levels, and was double the savings attributed to a previous, more ad hoc approach to continuous improvement.

The best practice of providing continuous, real-time data on energy use to operators produced mixed results. The approach was to use software to analyze data from energy meters and an MRP

system and publicly display continuous feedback to staff on the amount of electricity wasted by particular equipment. This approach produced inconclusive results when displayed just to operators, but produced significant reductions in waste when area managers were trained on how to use the feedback. It was noted during field observation that the reduction occurred primarily due to the introduction of an audit system, but that the reduction was unable to be maintained beyond two weeks. During times of peak observed efficiency, the reduction in total process energy using the approach was 26% compared to control, and the reduction in electricity waste was 43%. However, it is hypothesized that a more likely sustainable level of improvement from feedback is probably around 10-15%, as noted in residential studies in the literature, though more data is needed to prove that result beyond what was collected in this study. Additional analysis showed that potential continuous improvement approaches including optimization or automation could further reduce energy usage of the ovens by 15%.

Finally, the best practice of right-sizing equipment was analyzed in the context of select systems at the IADC as well as through existing literature. While specific estimates on savings do not generally exist for process equipment, a literature review indicates that installing newer, smaller motors can reduce overall electricity use of motors in industrial support systems by 11% nationwide. Furthermore, anecdotal evidence from limited observation at the IADC indicates that many pieces of process equipment are significantly oversized relative to current levels of customer demand, product mix and operational flow. Additional study is needed to estimate the potential reductions in process energy using this approach, and given the lack of focus in this area, the 11% figure from support systems is likely a lower bound at least for the IADC.

Chapter 6

Discussion

6.1 Hypothesis review

A review of the hypotheses of Chapter 3 indicates that all three lean approaches can be used to increase energy efficiency of manufacturing processes without major impact on production schedules. Moreover, two of the three (measuring energy usage of individual equipment as part of team-based continuous improvement projects and using real-time data feedback to operators) do not require major capital allocations but instead are achieved by behavior and operational changes with existing equipment.

More specifically, a field study proved that applying process management approaches such as the DMAIC improvement process can increase energy efficiency in a manufacturing area by approximately 10%. Increased energy efficiency resulted from a structured approach to cross-functional collaboration, analyzing energy data to identify significant opportunities, and sustaining improvements through employee ownership and existing continuous improvement structures.

A separate field experiment with real-time feedback showed statistically significant improvements, but only when senior operations managers in the area participated in the improvement process. This important result, although likely influenced somewhat by the Hawthorne effect, supports prior research that showed that low awareness and attention on the part of senior managers is a major barrier to improving energy efficiency in manufacturing processes. Although real-time feedback is probably not necessary to prompt the observed implementation behavior-changing programs such as end of shift audits, it definitely increased visibility of the problem and additional improvements with such a system in place is likely assuming engagement on behalf of area employees and managers.

Finally, right-sizing equipment likely represents the largest opportunity from a cost-reduction perspective, but also requires capital investment, reorientation of production towards true manufacturing cells, and potentially changes in the way new equipment is procured and justified within

an organization. Based on observations in the field and prior research, it is likely that right-sizing opportunities, which are especially prevalent for the largest, most energy intensive equipment, could be on the order of 50% or above for some equipment.

6.2 Recommended execution approach

One of the motivations of this research was to design a practical, repeatable approach to executing an energy efficiency program in a real manufacturing facility as a guideline for energy management organizations like the Raytheon EET. Through a combination of independent research conducted at the IADC and literature review, a management approach to executing such a program is proposed in this section. This approach is general enough to be applied in any manufacturing facility, and is designed to be compatible with popular manufacturing process management methodologies such as lean manufacturing and six sigma. The approach, outlined in Table 6.1, is described as a maturity model with five levels, and incorporates results and analysis discussed previously in Chapter 5 and can be considered an overview of research findings.

The magnitude benefit associated with each level corresponds with research findings described in Chapter 5 at the IADC. Level 0 comes from previous experience developing an employee engagement program[1]. Level 1 corresponds to the results from the experiment in the Oil Room, and reflects conservative estimates based on the impact of ongoing employee audits. However, it is important to note that other areas of the same facility, namely CCA, were able to achieve nearly 100% compliance with equipment shut-down, in which case the potential savings could be closer to 25%. Level 2 corresponds to the results from the DMAIC approach in CCA (which can be considered a Level 1 area in this framework). Level 3 corresponds to the analysis based on Oil Room data in which oven energy use could be optimized within the day via improved scheduling or automation. This category also may include process design changes like altering baking temperatures or times or adding insulation to process equipment which was beyond the scope of this research. Finally, Level 4 corresponds to the analysis around right-sizing process equipment.

The magnitude benefit from the maturity model in Table 6.1 should be construed as an approximation. The numbers are based on independent research conducted within a limited portion of one plant in one company and one industry over six months, and are likely highly dependent on factors local to the research environment. However, an attempt was made to corroborate collected data with existing literature and to be conservative in terms of the potential benefits based on observed results.

The order of the levels reflects both logical order and a qualitative assessment of difficulty in terms of implementation barriers based on field experience. For example, employee engagement is critical if project-based improvement is to take place. Meanwhile, while right-sizing probably represents

	Description	Enablers	Magnitude of Benefit	Major barriers
Level 0	Employee engagement	Metrics on employee engagement	100% increase in employee engagement	Changing social norm
Level 1	Employee accountability	Behavior audits	5-15% cost reduction	Participation of operations managers
Level 2	Project-based improvement	Pareto charts, energy audits	5-15% cost reduction	Lack of business processes and/or measurement capability
Level 3	Continuous improvement (<i>kaizen</i>)	Real-time feedback	5-15% cost reduction	Meter cost, software development, indifference
Level 4	Major improvement (<i>kaikaku</i>)	Right-sizing	10% or more cost reduction	Internal capital allocation processes

Table 6.1: Maturity model for manufacturing process energy efficiency programs. Cost reductions refer to process electricity costs, and each level builds on previously achieved reductions. For example, the project-based improvement phase may reduce costs by an additional 10% after the employee accountability phase reduces cost by 10%, leading to an overall reduction of 19%.

the greatest opportunity, it likely requires a fundamental change in the way capital is allocated and budgeting takes place within the organization. It may be possible that other organizations may not have the same types of barriers as those observed at Raytheon, in which case the order of implementation may be slightly different. However, regardless of the organization, it is recommended that employees are engaged as a first step[1]. Other phases, however, could likely be performed in parallel or serially. For example, a Level 0 organization could likely start right sizing equipment at the same time as improving employee accountability, in which case the magnitude benefits from right-sizing would likely be more substantial than what is estimated in Table 6.1.

Successful execution of the energy management program outlined in Table 6.1 is likely to achieve significant savings in process energy. Based on results from field experience and analysis, a facility starting at Level 0 can be reasonably expected to reduce process energy costs by 35% if all departments in the entire facility achieves a Level 4 designation.

6.3 High-level management challenges for program improvement

Raytheon, and industry in general, faces some high-level management challenges in improving the energy efficiency of manufacturing processes based on field experience and research conducted over the course of this study. A brief discussion of these challenges are outlined here, though they were not specifically the main topic of this research:

- **Cross-functional coordination:** It was observed that before the new initiative was begun in 2009, the Raytheon energy management program was fairly typical in that focus was placed on improving support systems largely under the facilities department's direct control. Improving the energy efficiency of process equipment absolutely requires participation by both operations and facilities staff, and can also be greatly aided by dedicated energy managers to facilitate activities like DMAIC improvement processes. Still, this type of coordination can be a challenge in the fast paced environment of a busy manufacturing facility such as the IADC.
- **Fluctuating energy prices:** We showed that general interest in energy efficiency over the years is highly correlated with oil prices, and prices of energy in general. An energy management program needs to be robust enough to withstand periods where energy prices decline, which directly reduces the financial impact of efficiency improvements and priorities within the organization.
- **Aligning incentives, power and accountability:** In a hierarchical and multi-functional environment like a typical manufacturing facility, incentives, power and accountability are not easily aligned when it comes to a goal such as improving energy efficiency. On a departmental

level, as stated previously, savings from improved energy efficiency typically accrue to facilities budgets, while operations budgets actually pay for the more efficient equipment. On a stakeholder level, front-line employees may lack the authority to act on information received from systems like real-time feedback by changing processes, and yet are asked to shoulder responsibility for implementing process improvements. Finally, there is typically a lack of true accountability for realizing energy efficiency goals, leading to programs relying on contributions from volunteers with competing priorities.

6.4 Suggestions for further research

There are significant further research opportunities on this general topic. Recommended subjects include:

- **Optimization of user interface for real-time feedback dashboard:** It is possible that poor usability of the feedback interface in terms of visibility, learnability, efficiency and/or error prevention prevented greater savings from being achieved. A variety of similar products now exist for residential use, and it would be interesting to research how an optimized interface for a manufacturing facility would be implemented based on design principles and further experimentation with users.
- **Overcoming barriers to right-sizing equipment:** Some hypothesized barriers, mostly supported by existing literature, to right-sizing equipment were advanced in this paper, but a treatment of how to overcome those barriers (if they indeed exist) in manufacturing organizations was not proposed. For example, one could ask, for a given new oven's cost and efficiency, how low could energy prices be and still have the ROI be attractive? Or, during the equipment procurement process, the purchaser might be required to right size and specify the energy efficiency of process equipment.
- **Quantifying the impact of manufacturing process design changes:** This thesis focused mainly on optimizing the use of equipment within the constraints of existing manufacturing processes and procedures. Additional effort could be made into the potential energy savings from modifying the process parameters themselves. For example, in the context of the Oil Room processes, this would involve modifying the length and temperature required for vacuum bakes of specific products. However, process design changes would also need to involve design engineers, likely increasing the complexity of the project.
- **Local social factors regarding energy management:** It was observed that some areas at the IADC (namely CCA) has been able to develop strong social and organizational norms regarding energy management that other areas in the same facility lacked. These norms were

critical in supporting movement beyond Level 0 in the energy management maturity model. Research into common features of areas and cells that strongly support energy efficiency goals could prove very fruitful when attempting to execute on Level 0 goals of employee engagement. This type of research also naturally dovetails with the problem of aligning incentives, power and accountability which is a major general management challenge for achieving greater energy efficiency.

6.5 Summary

The principles of energy management can be successfully applied to programs designed to improve energy efficiency of manufacturing processes, and can produce significant value to companies in the form of cost reductions. Many of the current barriers that exist to execution can be addressed through the application of proven process management techniques, with additional savings achievable through refining the capital allocation process in terms of right-sizing equipment. Companies seeking to implement such programs should proceed in stages, with the first phase, creating engagement on behalf of employees, enabling all subsequent phases. Manufacturing managers seeking to reduce operational costs should seriously consider implementing energy efficiency programs such as the one currently under development at Raytheon.

Appendix A

General Barriers to Industrial Energy Efficiency Programs

A recent McKinsey study cited barriers common to energy efficiency programs in general including[3]:

- **Low awareness and attention:** Due to the relatively low operational cost of energy in non-energy intensive industries, senior managers are not as focused on discovering available opportunities. Because savings in process energy are highly site and equipment specific, developing the necessary technical expertise to identify savings is often overlooked.
- **Elevated hurdle rate:** Manufacturing plants generally receive very tight operational budgets, and plant managers are encouraged to maximize production while keeping short-term quarterly costs low. Forty-three percent of energy managers indicate that they use a payback period of under 3 years, while in difficult economic conditions that period is lowered to 18 months or less.
- **Internal capital allocation competition:** Companies often allocate capital according to “core” and “non-core” projects, with “non-core” projects (typically including energy efficiency) having a higher hurdle rate than “core” projects. In addition, capital improvement funding typically comes out of plant operations, while energy efficiency savings typically accrue to facilities, which can create organizational challenges.
- **High transaction costs:** Transaction “costs” associated with implementing efficiency-related process improvements include space constraints, invested resource time, process disruptions, potential effects on product quality and safety concerns.

Appendix B

Equipment Electricity Usage

Table B.1 includes average power readings from various equipment found in workbenches and offices at Raytheon IADC. Based on these results, we assume that a typical workbench averages about 300 W of power draw and a typical office averages about 100 W of power draw at any given moment over the course of a shift.

Equipment Type	Power Draw (Watts)
Solder bath	640
Heat gun	550
Desk vacuum	138
Wirestripper	112
Computer Monitor	38
Hot tweezers	38
Soldering iron	35
Fluorescent light	25
Laptop	23
Ionizer	10
Microscope	5

Table B.1: Energy used by typical workbench items found in CCA. The energy reported is the average power for when the equipment is actually being used by operators.

Appendix C

Additional CCA Case Studies

Table C.1 briefly documents additional Tier Two DMAIC processes either completed or ongoing in CCA.

Description	Estimated Savings (\$/yr)	Implementation Period
Replace 1 big oven with 3 small ovens	\$168	Spring 2010
Five test station monitors shut down	\$365	Spring 2010
Oven removal	\$2,280	Spring 2010
Five ovens shut off nightly	\$7,560	Spring 2010
MTSA batching*	\$15,520	Spring 2010
Tighter vacuum system monitoring	\$1,130	Summer 2010
Wave solder shut down*	\$3,560	Summer 2010
Surface mount line upgrade	\$4,350	Pending
Oven exhaust fan nightly shutoff	\$7,400	Pending
Washer system re-programming	\$14,472	Pending
Total	\$56,833	

Table C.1: Additional CCA Tier Two DMAIC projects. Estimated yearly savings are calculated based on 50 work weeks a year, average equipment use, energy usage measurements taken during the study, and a \$0.135/kWh blended electricity rate. An (*) indicates projects described in further detail in Chapter 5.

Appendix D

MTSA Process Simulation

Figure D-1 shows the conceptual map for the MTSA process recreated in ProModel Silver, a discrete event simulator. The level of variation in the system (especially the variability of capacity) made it difficult to produce estimates analytically, so a simulation approach was used instead. This model is highly conceptual, and simulation is meant not to exactly replicate the actual process, but instead to give some guidance into the effect of various policy changes around the operation of the MTSA equipment. The fixed parameters of the simulation model are described in Table D.1. While it is

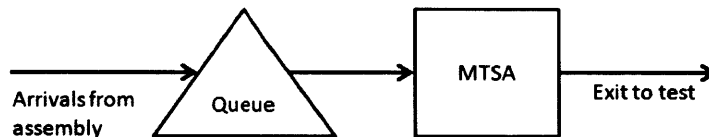


Figure D-1: Conceptual process diagram for cards tested using MTSA machine. Upstream (assembly) and downstream (test) were assumed to have excess capacity for purposes of this analysis.

Parameter	Description	Distribution	Assumptions
Arrival rate		$N(13, 9)$ cards/day	Assumed to arrive all at once at the beginning of each day
Capacity of MTSA		$N(7.5, 3.8)$ cards	
Processing time		$N(21, 2)$ hours	
Simulation length		50 weeks	Does not include holidays
Number of replications		10 replications	

Table D.1: Fixed modeling parameters for MTSA discrete event simulation.

assumed that arrivals occur all at once at the beginning of each day, in reality they are distributed throughout the day as they arrive from the upstream process.

With the fixed parameters from Table D.1, we ran three experimental blocks of simulations, with 10 replications each, varying the number of times the MTSA machine could be run in a given week between each block. Table D.2 summarizes the experimental structure. Block 1 corresponds to the

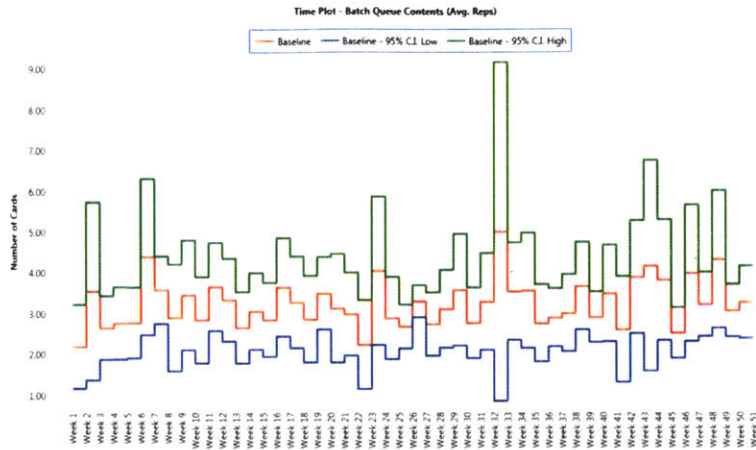
current state, where the machine is run at any point during the week Monday through Saturday. Block 2 corresponds to a state where the machine is run on Mondays, Tuesdays, Thursdays and Fridays. Block 3 corresponds to a state where the machine is run Mondays, Wednesdays and Fridays.

	Number of possible MTSA runs/week
Block 1	6 runs
Block 2	4 runs
Block 3	3 runs

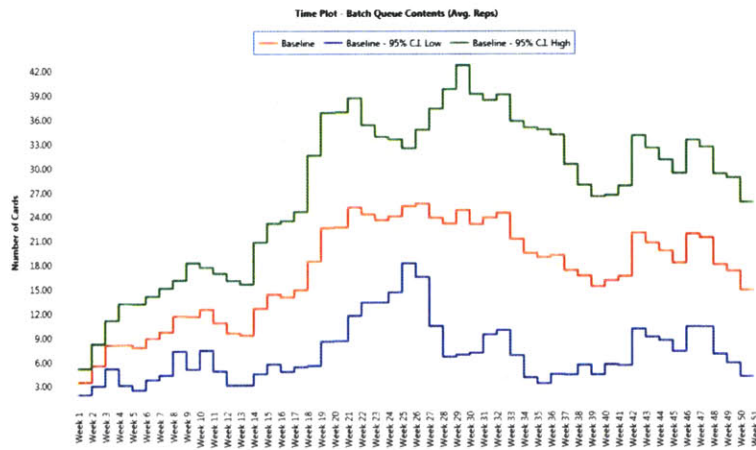
Table D.2: The three experimental blocks with the number of possible MTSA runs in each block. Block 1 corresponds to the current state in CCA (Monday through Saturday operations).

Some experimental results are shown in Figure D-2, specifically the predicted size of the queue in front of the MTSA machine over the course of the year. It is clear from these results, specifically Figure D-2(c), that running the machine only three days a week leads to a steadily increasing queue size, which translates into increasing cycle times. However, running the machine four days a week (Figure D-2(b)) appears to produce a slightly elevated but stable queue size compared to the current state (Figure D-2(a)). The queue sizes in Figure D-2 lead to average cycle times over the 50 week period of 1 day, 3.2 days, and 40.4 days for Block 1, Block 2 and Block 3 respectively.

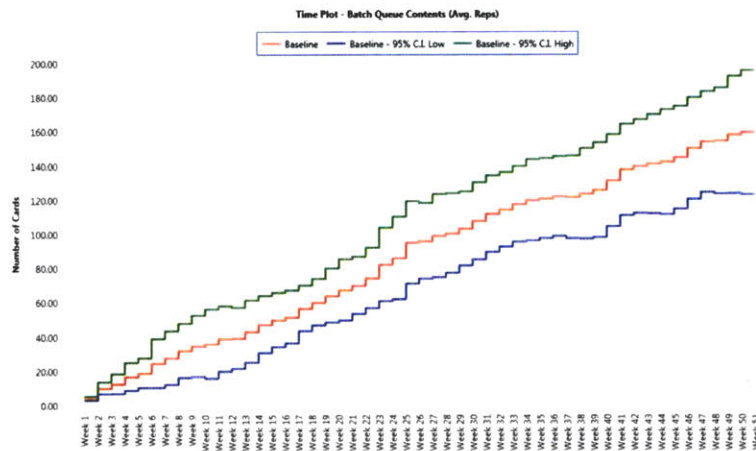
As stated before, while this simulation process relied on many simplifying assumptions, it produced reasonable results which were later verified during actual implementation.



(a) Block 1 queue size



(b) Block 2 queue size



(c) Block 3 queue size

Figure D-2: Estimated queue size for MTSA machine over time based on simulation. The red line is the average over 10 replications, the green line is the high 95% confidence limit and the blue line is the low 95% confidence limit. Data points are for each week in the simulation.

Appendix E

Verification of Linear Model for Energy Savings

Sample data for 13 oven models of varying sizes similar to those seen in Raytheon were taken from the specification sheet of the Grieve website[54], and the data is summarized in Table E.1. Using the data, a linear model was estimated using linear regression of the form

$$\text{Energy} = \beta_0 + \beta_1 \text{Volume} + \epsilon.$$

This equation is derived from the linear relationship between energy and volume from the heat equation, assuming a constant density. The results of the linear regression provided estimates of $\beta_0 = 8.83$ and $\beta_1 = 0.0945$, and indicated an R^2 fit of 98.8%. The predicted energy required to heat each oven achieved from the model is shown in Table E.1. Based on these results, we are confident that there is a linear relationship between volume and energy required in process heating and cooling.

Oven Model Model	Maximum Power (kW)	Rise Time (min)	Actual Energy (kWh)	Volume (ft ³)	Predicted Energy (kWh)
1	30	40	20	96	17.9
2	40	40	26.7	180	25.9
3	45	40	30	240	31.5
4	45	40	30	234	30.7
5	60	40	40	312	38.3
6	80	35	46.7	390	45.7
7	80	40	53.3	468	53.1
8	80	30	40	384	45.2
9	80	35	46.7	392	45.9
10	80	40	53.3	490	55.2
11	100	40	66.7	588	64.5
12	120	35	70	640	69.4
13	140	35	81.7	768	81.4

Table E.1: Data on energy requirements for various industrial oven models. “Rise Time” refers to the time required to reach 450 °F at maximum power. “Actual Energy” is Rise Time × Maximum Power. “Predicted Energy” refers to the amount of energy predicted from the linear regression model.

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