Enabling Process Improvements through Systems Thinking

By

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B.S. Industrial and Systems Engineering, Ohio University, 2000

Submitted to the Sloan School of Management and the Engineering Systems Division in partial fulfillment of the requirements for the degrees of

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Abstract

Manufacturing organizations around the world strive to improve processes with varying degrees of realization. There is no right way or latest and greatest process that can guarantee success, therefore the approach, and not necessarily the process, is critical. Since every process improvement project is different, using the systems thinking approach decreases the risk of failure as the implementer(s) is/are more aware of critical items on the fringe which might otherwise be neglected.

Process metrics are vital for many reasons including motivating employees, determining the level of need for process improvement, and evaluating the outcome of a process improvement project. When evaluating whether a project should be pursued, the expected results on the subsystem and other subsystems should be estimated and tied to the highest level metric, which ultimately should equate to bottom line impact. This evaluation technique ensures a positive impact on the entire system, rather than producing only a subsystem optimum. A subsystem metric indicates a project's success through the use of a hypothesis test. This usage requires that the subsystem metric, which will be used to measure a process improvement, must be stable before initiating the project.

The individual, team, and organization all play a vital role in a company embracing systems thinking. Individuals and teams need to keep an open mind to issues outside the focus department and accept and encourage involvement of cross-functional representatives on process improvement teams. An organization where systems thinking is integral becomes a learning organization and has a higher percentage of successful projects through a systematic evaluation and approach to projects. To maintain the systems thinking culture, an organization as a whole must encourage the hiring of individuals with varied experiences and who believe in systems thinking.

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1 Introduction

1.1 Overview

Increased competition from globalization has forced many manufacturing companies to improve at a faster and faster rate. This is one motivation for the recent increase in continuous improvement programs like those based on the Six Sigma and Lean concepts. Many companies find these programs only marginally successful, specifically the following may be experienced:

- The cost, yield, or cycle time improvements claimed by such projects are never actually realized in the aggregate
- Employees spend an increasing amount of time on projects with a decreasing return
- Improvements in metrics created by projects are not sustained
- Projects linger for long periods of time and are never completed

These are all results of an organization implementing improvement projects without employing systems thinking. "Pushing harder and harder on familiar solutions, while fundamental problems persist or worsen, is a reliable indicator of nonsystematic thinking."[14]

Systems thinking is about widening the scope of consideration both vertically and horizontally, without necessarily widening the scope of responsibility. Project managers employ systems thinking by managing cross-functional stakeholders on different levels of the organization, making use of a cross-functional team, and managing the project such that it ultimately impacts the larger system rather than producing a local optimum. Additionally, system thinking entails consideration of both external and internal upstream and downstream operations as well as the end customer and the shareholders.

This thesis explains the concept of systems thinking, illustrates how it applies to process improvement projects, and teaches specific tools, or frameworks, that can be used to expose employees to systems thinking.

1.2 Organization of the Thesis

This thesis is organized in six chapters, each of which is described below:

1. Introduction: Introduces the benefits of systems thinking during process improvement.
2. Systems Thinking and Project Management: Presents the hypothesis, defines system thinking, and further discusses the advantages of systems thinking within project management.
3. Implementing Systems Thinking in Project Management: Introduces tools and concepts that utilize or promote systems thinking in project management such as a project selection tool, metric collection and monitoring, and project evaluation after implementation.
4. A Case Study: Describes a team project at Raytheon and discusses a recommended approach.
5. Recommendations: Describes some potential improvements for Raytheon from an outside observer.
6. Conclusion: Highlights some core advantages and critical elements of systems thinking.

2 Systems Thinking and Project Management

2.1 Hypothesis

Process improvement success, particularly in an environment of complex designs, is repeatable only if systems thinking is utilized during project selection, implementation, and post-implementation evaluation. It is critical that the individual managing the project and the individual "assigning" and prioritizing the projects each focus on the system. This means that some fundamental steps need to be performed during process improvement. However, because systems thinking is a perspective or view taken by individuals, following these steps alone does not provide the complete value.

Ultimately the issue with complex design is that a seemingly negligible change to the process or product can unpredictably impact the performance (in the field or during a test sequence). Some additional steps in the implementation of process improvements can increase the probability of predicting the outcome or indicating when unexpected results have occurred, resulting in a faster response to avoid or mitigate problems. These steps include understanding interactions, defining key metrics, and monitoring key metrics.

Looking at a system is a science, therefore many analyses and frameworks have been developed to analyze systems of different types. This thesis discusses general systems tools as well as explores using tools that are typically used in product design to manage process projects. Many manufacturing companies that can benefit from using systems thinking in managing process improvement projects are already familiar with some of the tools presented in this thesis because they use them for design activities.

2.2 Systems Thinking Definition

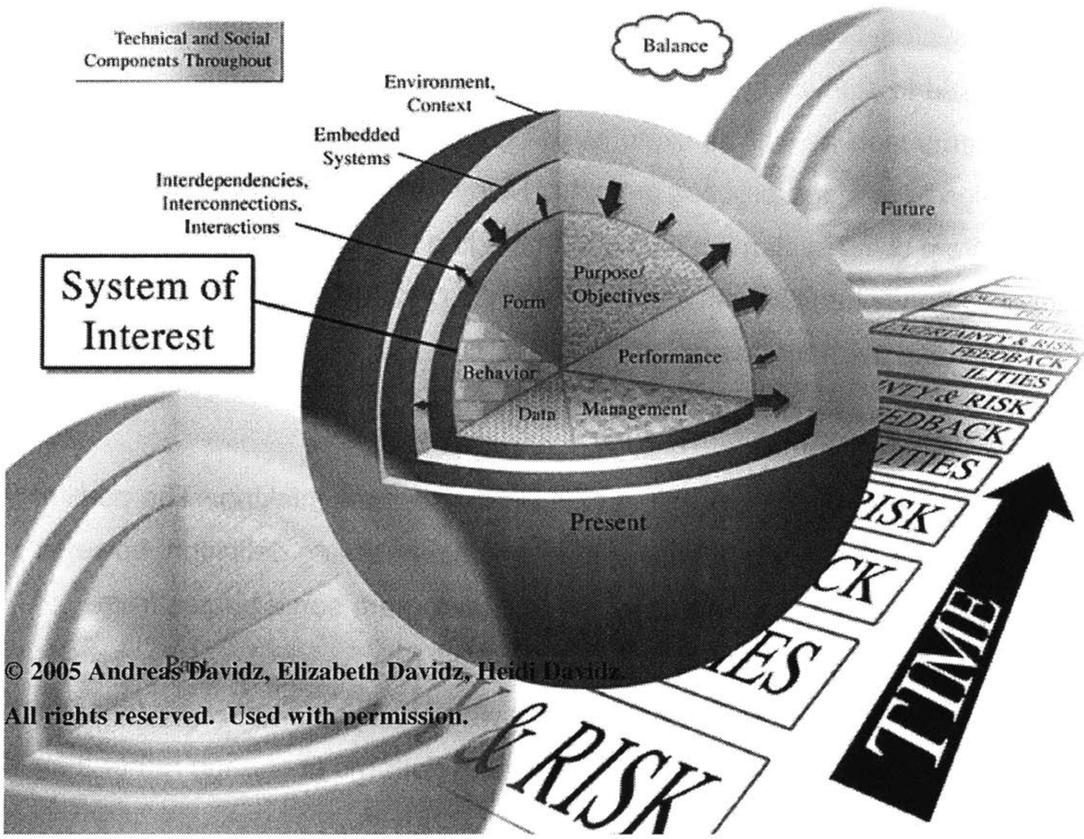
In the literature, there are numerous definitions for systems thinking. The point of this thesis is not to attempt to create a new, all-encompassing definition; however it is important to clarify the terminology. The following are some quotes from literature describing systems thinking:

- "Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots' [14]."
- "Systems thinking is utilizing modal elements to consider the componential, relational, contextual, and dynamic elements of the system of interest [7]."

- "The Engineering Systems Division understanding of a system includes interactions, interrelationships, and interdependencies that are technical, social, temporal, and multi-level [7]."
- "Objective thinking is a fundamental characteristic of the system approach [9]."
- "The systems approach is an approach to a problem which takes a broad view, which tries to take all aspects into account, which concentrates on interactions between the different parts of the problem [6]."

Important elements of systems thinking include the concern for both the internal and external environments and the awareness of interactions within and between these environments. Figure 1 shows an illustration of this concept.

Figure 1 – Systems Thinking Diagram [7]



Systems Engineering is not equivalent to systems thinking because Systems Engineering is based on reductionism [16]. The purpose for reductionism is that some engineering systems are so complex they cannot truly be understood in a systematic sense. In these cases, reducing the system into understandable parts leads to successful system development. Systems thinking in its truest sense does not involve reductionism. However, because it can be difficult for some people to obtain a system perspective, particularly without practice, it may be necessary to apply some of the tools used to achieve reductionism. The goal is ultimately to use systems thinking throughout the process without the need to apply specific reductionism tools.

2.3 Advantages of Systems Thinking during Project Management

Project managers who employ systems thinking experience such benefits as increased project impact and higher stakeholder satisfaction through the thorough consideration of the project's surroundings. The greatest benefit is achieved when whole organizations practice systems thinking. One of the biggest benefits is a better use of resources as improvement projects are selected and prioritized such that they optimize the entire system, not just one area, and projects are more likely to be successful because risk mitigation includes consideration of outside factors. This eliminates the common problem of "successful" improvement projects that have no impact to the bottom line. Additionally, systems thinking breaks down functional barriers allowing for freer flowing information and organizational integration because employees are consulting with other departments to understand the impact of the changes they are making. Stakeholders will have a higher level of satisfaction including project sponsors, internal and external customers, and suppliers because they are all considered throughout the duration of each project. Workers have a higher level of fulfillment because the impact of their effort is more visible and project success is more frequent. Additionally, systems thinking blames the system for problems, rather than the individual. This puts the employees in the mindset of fixing the system to solve the problem, rather than pointing fingers at others and protecting themselves. In The Fifth Discipline, Senge elaborates on how systems thinking is critical to becoming a learning and growing organization due these interactions [14].

3 Implementing Systems Thinking in Project Management

In an environment of systems thinking where everyone embraces and facilitates the systems approach, the concepts described in this section become obvious and occur naturally. Utilizing the tools suggested in this thesis alone does not mean that the organization is an environment of systems thinking. The point is for the employees to use systems thinking to evaluate the tools that are appropriate in each case and to utilize the ones that help themselves or others to understand the system better. The tools and concepts that will be elaborated on in this thesis include metrics, value stream mapping, System Life-Cycle Model, “Vee” Process Model, project selection, project implementation, and post-implementation evaluation.

3.1 Metrics

Metrics are extremely important for any process, regardless of whether or not a systems approach is being emphasized, because they measure process capability, identify areas for improvement [8], evaluate the success of a project, communicate to the workforce their performance, and allow for appropriate scheduling and ordering. The Leaders for Manufacturing Thesis of Neville McCaghren also explores the idea that metrics and real-time information can improve decision-making on the factory floor [11]. Process level and sub-process level metrics are as important as technical system and subsystem performance measures in design [2]. In both situations, they are responsible for making sure the customer gets what is ordered. Higher level process metrics are particularly important in an environment of systems thinking. For example, after evaluating the plant throughput and cycle time, one can determine, with little additional effort the location of the system bottleneck and thus has identified a very valuable project for the facility. If the higher level metrics are neglected and only local or subsystem metrics are monitored and improved upon, time and money may be wasted improving issues that impact only the local area and do not impact the system. The issue with high level metrics alone is that many things impact these metrics. Consequently, if a project's success is evaluated only its impact to the high level metric, the project assessment will likely be impacted by other changes in the larger system not caused by the project. Therefore, metrics at the lower levels also serve an important purpose by confirming project success and sustaining change by being a more constant measurement than the system level metric. Of course, lower level metrics can also be a motivational tool for workers in the plant.

There are numerous writings about selecting metrics and therefore, this thesis will not elaborate. However it is important to have metrics that drive the right behavior to impact the desired end results. The selection of metrics used in rationalizing projects is where systems thinking comes into play. For example, if a process improvement project is resource supported because it improves a station cycle time by 10%, this may impact the system; however it may have no impact on the system. If this station is not a bottleneck, improving its throughput by decreasing cycle time may provide little value to the system. The section on Project Rationalization elaborates more on how metrics impact a process improvement project.

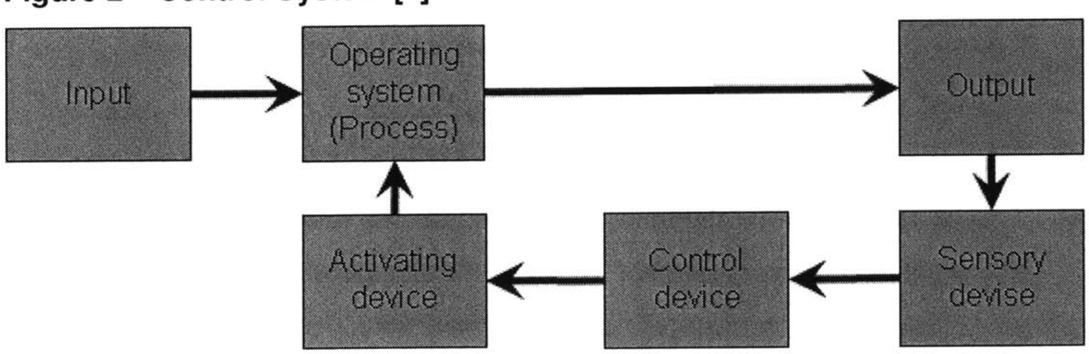
Anything that can be measured can be a metric; however it is advised to keep metrics simple and understandable as well as to limit the number. This allows for everyone's equivalent understanding. Process metrics generally include some variation of cycle time or throughput, yield, and inventory. Naturally, there will be several levels of these metrics as well (i.e., cycle time at one station and cycle time of the entire line). Metrics should be agreed upon by all employees, regardless of level or function. This aligns everyone to the same goals and provides an objective way of evaluating the system.

3.1.1 Metric Visibility and Control Systems

Once the metrics are defined and a system is in place to collect the data necessary to calculate them, the metric data should be made visible by all employees and regularly monitored. Both current state and trended measurements for each metric should be displayed close to real-time. This allows workers and engineers to be responsive when problems occur and potentially motivates those that directly impact the metrics. Metrics are only marginally useful if not monitored and reacted to when necessary.

When a drastic change occurs within one metric it can be obvious to the operator or supervisor. However, it is more likely a process will change to a smaller degree and thus is less obvious. According to Blanchard, "A changing environment can lead to system instability unless control action is applied [2]." A process that has experienced a statistically significant change in the readings is said to be out of control. A control process can be used on any metric, whether a continuous, discrete, or binary measurement. Figure 2 shows a graphical representation of a control system.

Figure 2 – Control System [2]



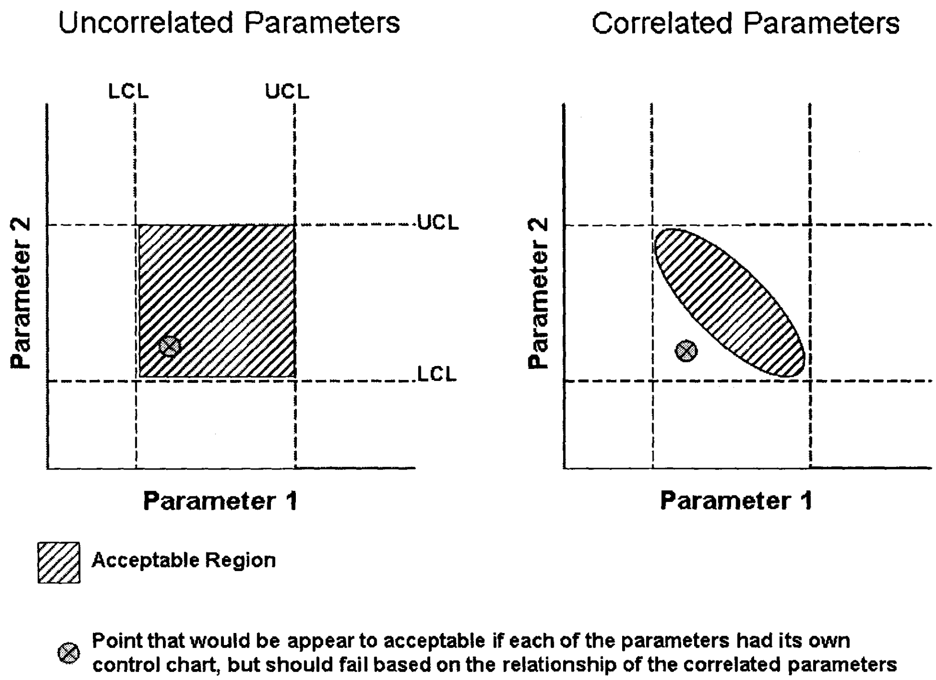
The typical control device is a control chart. Here are the basic steps for setting up a univariate control chart process [1]:

1. Determine the control parameters
    a. Using a reasonable amount of history (at least 20 points), calculate the average and standard deviation of the measurement readings
    b. Calculate the upper and lower control limits
        i. LCL = average - 3 x standard deviation
        ii. UCL = average + 3 x standard deviation
    c. Determine an appropriate sampling plan – each sample should be five or more test parts
2. Plot the average of the test readings for each sample on the control chart as testing occurs
3. Monitor for points out of control, the process is out of control if one of the following statements is true:
    a. One or more points outside the upper and lower control limit
    b. Seven or more consecutive points are all above or all below the mean
    c. Seven or more consecutive intervals are either all increasing or all decreasing
    d. Two of three consecutive points are between two and three standard deviations from the mean on one side
    e. Four out of five consecutive points are between one and two standard deviations from the mean on one side
    f. Fourteen consecutive points alternate one up and one down
    g. Fourteen consecutive points are within one standard deviation from the mean on either side
4. If the process becomes out of control, actively seek an explanation
    a. If the impact is negative, implement corrective action
    b. If the impact is positive, implement measures to ensure sustainability

5. Update the average and standard deviation as stabilization is reached following a process improvement

There are situations when using this univariate control chart process should be cautioned. First, it is possible that a control chart indicates an out of control state when the process is actually in control. The seven scenarios describing the out of control state are identified as such because the probability of any one of these occurring randomly is less than .01. This means that more than 1% of the time, a control chart will randomly indicate the process is out of control in error. Generally this is not a problem, however when many variables are being monitored, 1% of the measurements becomes more significant. Second, when the measurement parameters are correlated (or depend on similar factors) a multivariate control chart (generally a T2 Control Chart) should be utilized. This type of chart identifies an out of control state for any one of several related parameters while only monitoring one parameter. Like the univariate control chart, a historical sample of stable data is required to create the multivariate control chart. Using this data and the Principal Component t-Scores table, the correlations are broken into multiple linear Principle Components (PCs). These PCs are used to create the model that will be used to reveal when the process becomes out of control. In reality most parameters are correlated, however in some cases a few parameters can be monitored using univariate control charts to monitor the process because they are only loosely dependent. Figure 3 is a pictorial representation of correlated and uncorrelated parameters. In this figure, there is a point that should indicate the process is out of control if the parameters are correlated, however if univariate control charts are used instead, the control chart would not call the point out of control. Additionally, when using univariate control charts instead of a multivariate control chart, the risk of a control chart identifying an out of control state falsely increases because a larger number of charts are required [12].

Figure 3 – Difference between Uncorrelated and Correlated Test Parameters



Automating control systems can save time, ensure monitoring, and facilitate faster response times. Some systems can email or page individuals when a process is in the out of control state. Automated systems can range from homegrown visual basic code to sophisticated software systems.

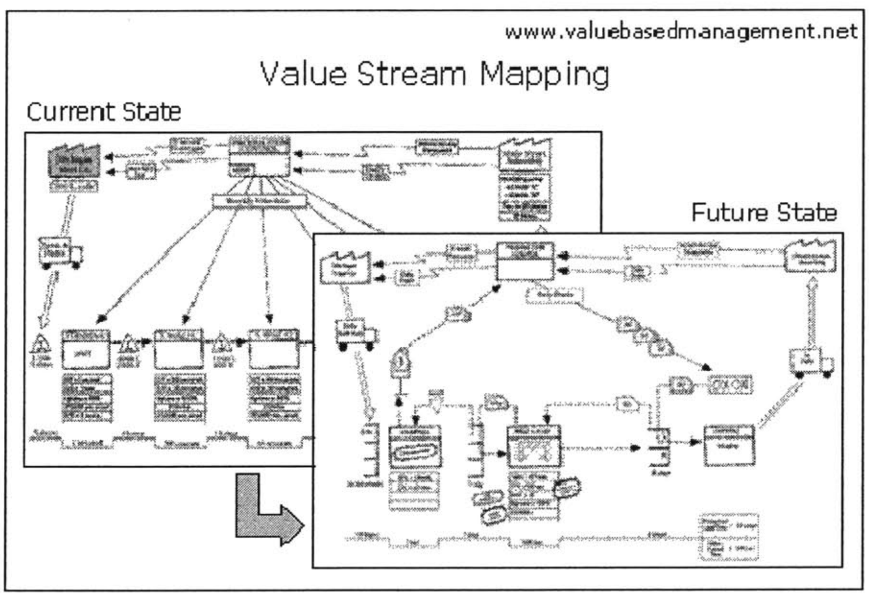
3.2 Systems Thinking Tools

Systems thinking can be applied to process improvement project management in two ways. One way is to apply systems thinking to the process. Value Steam Mapping and the System Life-Cycle framework are two of the tools that assist with this aspect. The other way to employ systems thinking is the approach to the project management process. The "Vee" Process Model tool assists with this application.

3.2.1 Value Stream Mapping

The Lean tool Value Stream Mapping is based on the Six Sigma tool Process Mapping but is different in that it generally identifies higher level information. The goal of the Value Stream Map is to identify waste, or valueless processes, in the system, which can then be eliminated to decrease cycle time. This tool can be extremely valuable "as 60% of operations in small and midsize manufacturing plants do not add overall value to the final product and can be eliminated [18]." The process for developing a Value Stream Map includes identifying all of the tasks that add value to the manufactured or assembled product and mapping these as the future or desired state. Additionally, mapping the current state, including the cycle times, down times, in-process inventory, material moves, and information flow paths, should be performed to allow for quick identification of the wasteful steps [20]. Figure 4 shows an example of a Value Stream Map.

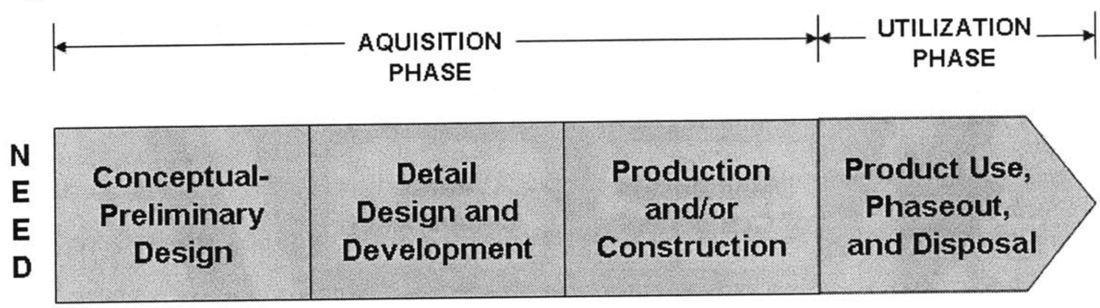
Figure 4 – Value Stream Map Example [20]



3.2.2 System Life-Cycle Model

The System Life-Cycle Model is typically used in product design to support Systems Engineering, but it can be directly applied to process development or improvement. The reason for system life-cycle engineering is to shift the focus from performance alone to development of the entire system [2]. Figure 5 is the product life cycle, which identifies what must be considered in system life cycle engineering. Just as with products, processes must go through each of these phases, therefore the ability to purchase, reliability, maintainability, supportability, serviceability, and disposability should be considered during initial development and improvement.

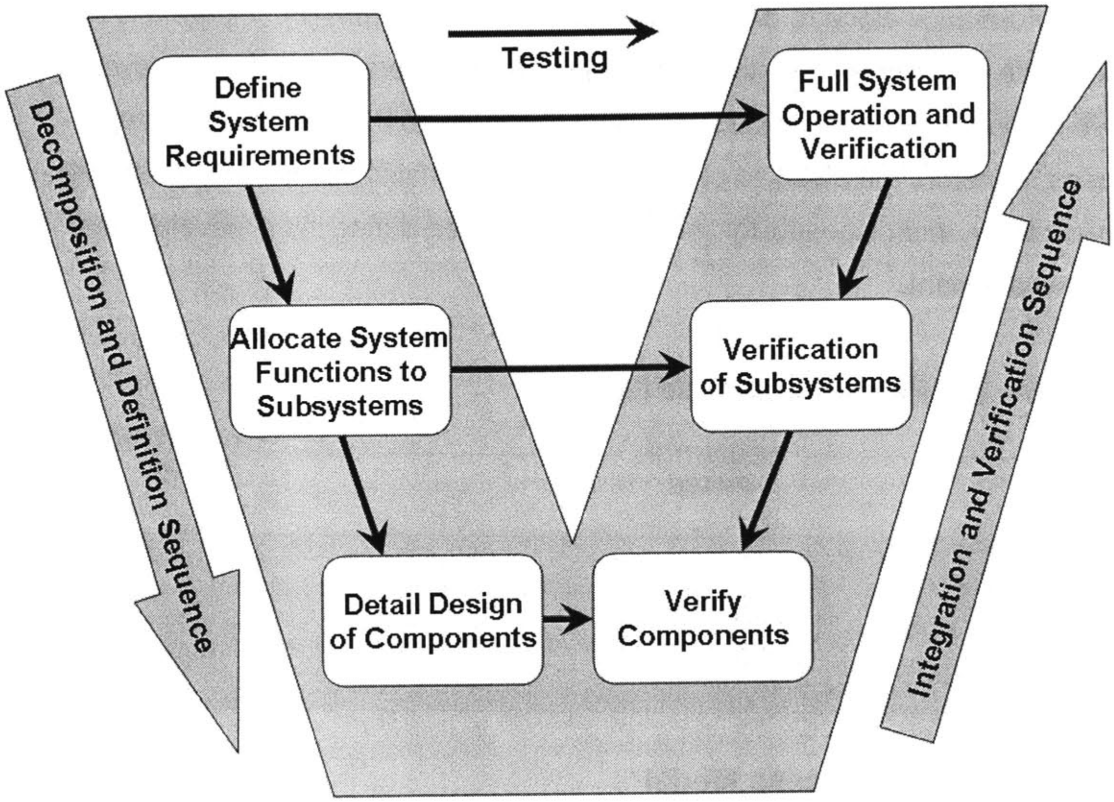
Figure 5 – The Product Life Cycle [2]



3.2.3 The "Vee" Process Model

The "Vee" Process Model is generally used in Systems Engineering when developing a complex system. Using systems thinking to improve a process is also an appropriate application for this model. Figure 6 is the traditional "Vee" Process Model. The "Vee" Process Model is a systematic way of decomposing a system into parts. True system thinking avoids decomposition; however this tool can be useful in managing process improvement projects because it forces one to look at the larger system first and then break it down to the subsystem level. This ensures impact on the system level metrics.

Figure 6 – The "Vee" Process Model [2]



3.3 Using the System to Find and Rationalize Projects

This process of identifying projects begins with drawing a process diagram and finding the process times and probability of flow for each arrow. An example of the output of this step is found in Figure 7. Second, the additional time required for troubleshooting and rework per assembly is calculated. This is done by computing the sum of the products of hours spent in rework and percentage of parts that require rework for each node. Next, the additional cost required for these activities is calculated by multiplying the additional time required by the burdened wage rate. The calculations for the base case in the example are:

1) .45 x 4 + .32 x 4+ .14 x 4 + .21 x 4 + .35 x 3.5 = 5.705
2) $104 x 5.705 = $593.32 (assumed burdened wage rate = $104/hr)

This means that on average 5.7 hours per assembly unit are spent on troubleshooting and rework, which costs the company roughly $593 per unit. Next, a simulation is run in MatLab to find the capacity burden of the troubleshooting and rework activities. The excess load on the system from these non-value added activities is 17% in this example (the load of a system with no rework is 1, the total load in this situation is 1.17). The formulas and MatLab code are in Appendix 1. A sensitivity analysis was completed on both the financial and the capacity burden analyses and is shown in Table 1. The sensitivity analysis shows that a total of $390 per assembled unit minus the cost of the project would be saved if all the card yields were increased to 90%. If the company plans to makes 500 more units, the company could rationalize spending up to $195,000 on a project if they were guaranteed to increase all the card yields to 90%. If this improvement is not possible for the price, the project should not be initiated. Additionally, modifications to the time of rework and troubleshoot can reduce the costs. For example, if a few units take a significantly longer period of time to troubleshoot and rework, it may be cheaper to scrap these units rather than to spend the time troubleshooting. (This assumes that this situation can be identified early in the troubleshooting process.) A reduction of 1 hour to each rework process as a result of scrapping the units that take the longest saves the company $267 times the number of cards to be built in the future minus the cost of the scrapped items and the project costs. The sensitivity analysis can be done for an infinite number of iterations to identify numerous potential projects.

Figure 7 – Process Model

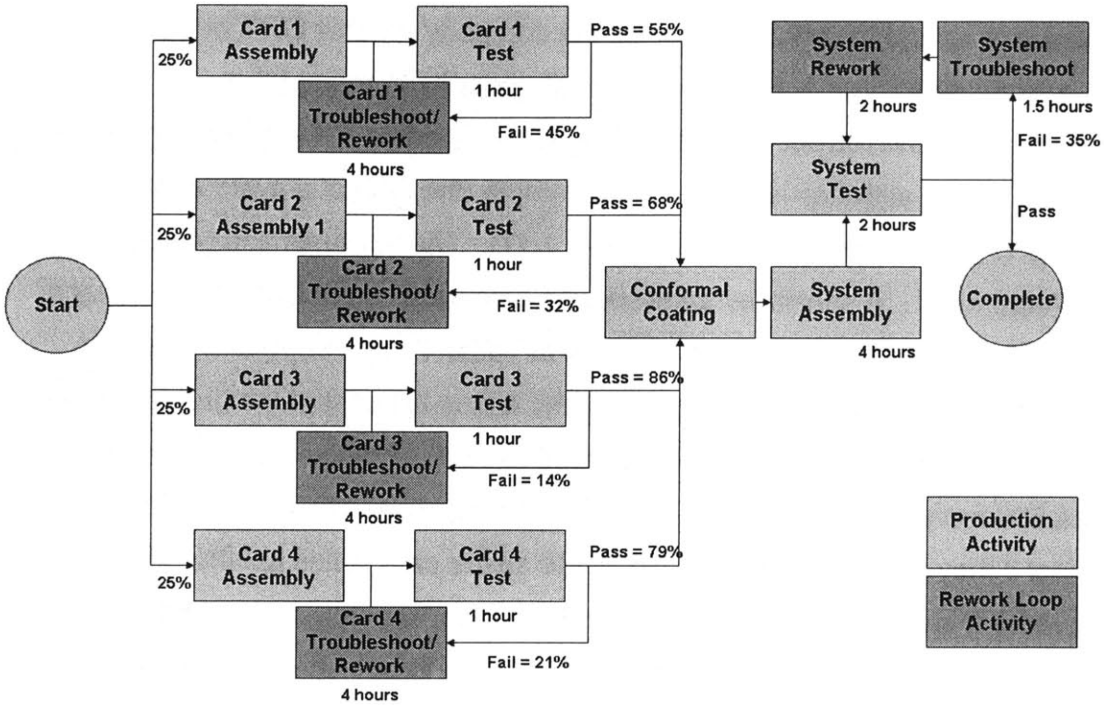


Table 1 – Sensitivity Analysis of Process Model

	Total Addl Hours/ Assembly	Total Addl $/Assembly	Improvement over base case	Excess Load	System Yield	Card 1 Yield	Card 2 Yield	Card 3 Yield	Card 4 Yield
base case	5.705	$593		20%	65%	55%	68%	86%	79%
all yields increase by a 10 percent points	3.755	$391	$203	10%	75%	65%	78%	96%	89%
all yields increase by 10%	4.26	$443	$150	10%	72%	61%	75%	95%	87%
System yield increases to 90%	4.83	$502	$91	20%	90%	55%	68%	86%	79%
all card yields increase to 90%	2.825	$294	$300	0%	65%	90%	90%	90%	90%
all yields increase to 90%	1.95	$203	$391	0%	90%	90%	90%	90%	90%
System yield increases by 10 percentage points	5.355	$557	$36	17%	75%	55%	68%	86%	79%
Card 1 yield increases by 10 percentage points	5.305	$552	$42	14%	65%	65%	68%	86%	79%
Card 4 yield increases by 10 percentage points	5.305	$552	$42	13%	65%	55%	68%	86%	89%
Reduce rework stations ave time by 1 hour	3.135	$326	$267	20%	65%	55%	68%	86%	79%

The highlighted cells are the model inputs that are equivalent to the base case.

3.4 Project Selection and Rationalization

There are many ways to evaluate whether or not a project is a good one to pursue. The most popular financial evaluations include [4]:

1. Net Present Value Method (also called the Discounted Cash Flow Method) – This method is merely the sum of the present value of all future cash flows, where the discount rate is equal to the cost of capital. A project

should be approved if the new present value is greater than zero as this means the project adds value to the company. This theory assumes that there is infinite access to cash, either on hand or through lending (interest is captured in the cash flows).

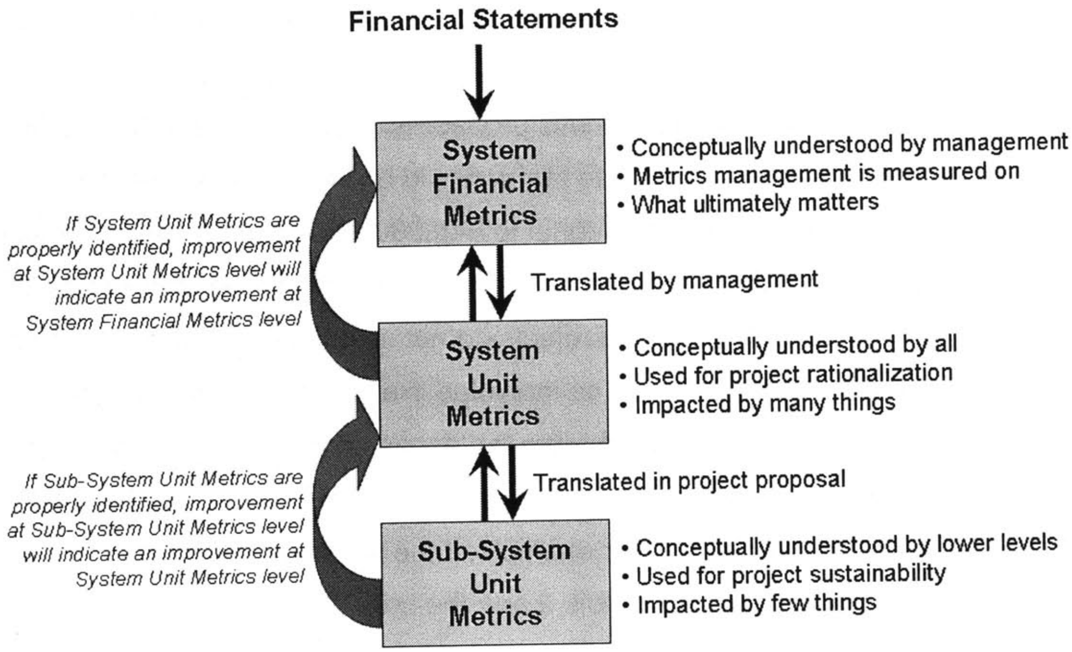
2. Payback Period Method – This method involves calculating how many years it will require to recover the money spent on the project. The money that is made in addition to what was originally spent is ignored and it gives equal weight to all cash flows regardless of year (i.e., no discounting).
3. Internal Rate of Return Method – This method identifies the rate of return, or discount rate, required to make the net present value of the project zero. The project is accepted if this rate of return is greater than the cost of capital. The formulation does not adequately value projects if some years have a positive cash flow and other years have a negative cash flow. Additionally, this method generally favors short term projects.
4. Profitability Index Method – This is a variation of the Net Present Value Method, but includes prioritization. Because infinite access to cash is not always practical for corporations, this method rates projects by the profitability index to indicate which project should be done first. The profitability index is the net present value divided by the total investment amount required. Companies should pursue the projects with the highest profitability index.

Stewart Myers, a leading financial researcher, teaches that the Net Present Value is the best method for evaluating projects. On the other hand, he does admit companies can not always pursue all projects with a net present value greater than zero due to cash availability. In these cases the profitability index is the method to use [4]. This is not where the discussion ends as calculating the net present value accurately for an operations project, particularly one of a smaller scale, is not easy to do and it is often hard to conceptually understand the financial impact.

It is often said that a good middle manager can translate from dollars to production units and vice versa. This skill is valuable because upper management tends to speak in terms of dollars while line workers, supervisors, and engineers speak in terms of production units. Financial drivers are rarely understood at lower levels of the organization. Taking a systems approach means that projects must impact the total system, which is ultimately measured in terms of financials. The project evaluation method must translate the system financials to units so the system can be used by not only upper management. One way to perform this conversion is to assign a financial value to the system level metrics, which are normally displayed in terms of units (except in the case of inventory dollars). For example, an increase in throughput of one per day can be equated to one additional unit of sales and profit per day. Of course this translation assumes the unit will be sold. If the unit will not necessarily sell, but a throughput increase of eight per day will eliminate a shift, one eighth of the shift costs can be attributed to a project that can increase output of one unit per day. (An additional increase of seven units per day must be realizable in the future in order for the above value to be claimed.) Once the system metrics are equated to financial figures by management, one can propose projects based on the system metric and not necessarily just financial benefit. This translation is shown pictorially in Figure 8.

When the system metrics are not related to financials and strictly financial evaluations are required for project evaluation, a number of challenges arise. First, employees that are not familiar with the financials of the company (i.e., how much an employee plus overhead costs, how much a reduced cycle time saves the company) will not submit accurate project proposals or may not submit any project proposals. Second, different employees may have different ways of claiming financial savings. Most companies would find that after adding all the savings claimed on projects and comparing this total figure to the amount that has actually been saved, there would be a large discrepancy.

Figure 8 – Metric Hierarchy



System metrics still may not be sufficient information for a project, particularly one of smaller scale. For example, if the system metric is cycle time of a manufacturing line, there are many things that impact this metric, most of which cannot be attributed to the project being proposed. At this point, it is wise to define or identify subsystem metrics that will indicate the success of the project solution and implementation. Ideally this subsystem metric is already being monitored in a control system, or at least measured, and will not be impacted by another project until the project at hand has stabilized the metric at its new level. Since the success of the project is being measured on the subsystem metric(s), it is important that these are well defined and have been sufficiently equated to its impact on the system metric. The subsystem metric should be identified and its impact on the system metric defined, if possible, during the project rationalization phase. "If project selection is done improperly, a project may be selected that doesn't have the full business buy-in, project roadblocks may not be removed due to other business priorities, the team may feel ineffective and the end result may be less than ideal [8]."

3.4.1 Probability of Success

Since projects have different probabilities of success, it is wise to include a factor to account for this difference when evaluating and prioritizing projects. For example, with no consideration of success probability, a project that costs $10,000 and saves $50,000 in net present value terms would be implemented without question because the total savings is equal to $40,000. However, if the probability of complete success is only 10% and the probability of complete failure is 90%, the project should not be pursued. Most projects do not completely fail or completely succeed so a range of outcomes can be identified like in Table 2. In order to account for probability of success, calculate the expected value of the project (the sum of the products of the savings, the percent of predicted outcome actualized, and the probability for each row). For example, if the success probability distribution is like that displayed in Table 2 and the project costs $10,000 and saves a net present value of $50,000, if successful, the calculation would be:

$$40{,}000 \times \frac{1.00 + .75}{2} \times .25 + 40{,}000 \times \frac{.75 + .50}{2} \times .25 +$$
$$40{,}000 \times \frac{.50 + .25}{2} \times .25 + 40{,}000 \times \frac{.25 + 0}{2} \times .25 = \$20{,}000$$

The present value of this project should be presented as $20,000 and not $40,000 during evaluation and prioritization. This same calculation can be done with expected metric improvements rather than dollar values if that is the way the projects are being evaluated.

Table 2 – Probability of Metric Realization Example

Percent of predicted outcome actualized	Probability (must sum to 100%)
75%-100%	25%
50%-75%	25%
25%-50%	25%
0%-25%	25%

Determining the probability values requires knowledge of the process, culture, and previous projects in the area. Some information can be obtained by looking up the results of similar projects in a database of historical projects. Additionally, consulting with someone that has experience in project management in the area would provide more information on how to estimate these percentages.

3.4.2 Metric Tradeoffs

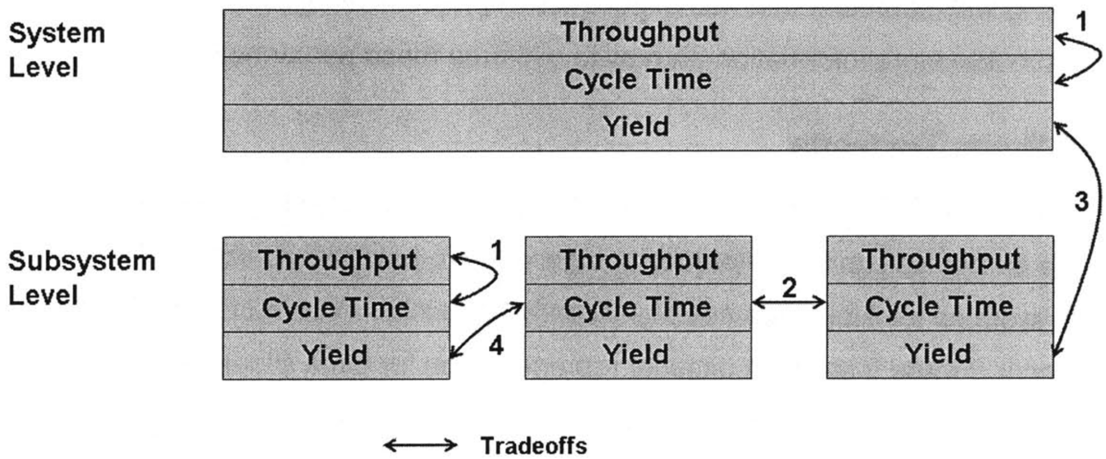
The benefit, implementation, and usage of metrics seems rather simple, however the use of metrics can become quite complex due to potential conflicts. Once again, systems thinking becomes significantly beneficial. A conflict in the metrics may occur (Figure 9 shows a pictorial representation for each situation)

1. between different metrics on the same level (e.g., improving the yield on a station may decrease the throughput of that station because it could take longer to perform the quality check before passing the part along)
2. between the same metric in different areas on the same level (e.g., decreasing the cycle time at one station increases the cycle time at another station because a process step is removed from one station and added to a different station)
3. between the same metrics at different levels (e.g., increasing the yield at a station decreases the yield of the line because by performing a preventative step to decease the yield, a quality problem at another station occurs)
4. between different metrics in different areas on the same level (e.g., in order to increase the yield at a station, another station must have an increased cycle time because they must perform a preventative quality step)

Figure 9 is rather simplistic as there may be more than two levels of metrics, the metrics on each level are likely not exactly the same, and there are likely more than three metrics on each level to consider. In a single improvement, there may be any number of tradeoff combinations including many others in addition to the four mentioned above.

Figure 9 – Metric Tradeoffs Examples

The numbers in the picture correlate to the number preceding the examples described above.



Maintaining a system perspective throughout the evaluation and implementation of process improvement helps to alleviate some of the challenges associated with metric tradeoffs. The following tasks associated with metrics should be considered:

1. Anticipate as many metric tradeoffs as possible so they can be weighed adequately when the project is under initial consideration. The Failure Mode, Effects, and Analysis tool may assist, which is described in the Risk Management section of this thesis.
2. Weigh tradeoffs considering the highest level metrics. Find the impact on the highest level measurable throughput and cycle time metrics by calculation or simulation and using the financial equivalents to these metrics evaluate the cost and benefit of the tradeoff.
3. Be aware of all metrics while implementing something new. Not all tradeoffs can be anticipated. This is where control charts are beneficial as it is impossible to be aware of everything, so if a control system sets an alarm that a metric is out of control, consider how the project at hand may have impacted the metric. Furthermore, take actions to mitigate the

negative impacts on the other metrics or reverse the implementation if the tradeoff is no longer in favor of the project.

None of these tasks are easy as there is no one right answer. An important aspect is that this analysis should be objective and consistent for all projects. Using system thinking allows individuals to step away from the thought that improving one metric in particular is good regardless of its impact on another.

3.4.3 Managing Project Management

In order to promote systems thinking throughout the organization, the evaluation method for process improvement projects should motivate the project teams/managers to apply systems thinking. If the incentives for system thinking are in place through the project selection and the evaluation method is consistent, systems thinking will become more prevalent in the organization. Project sponsors should also be aware of the number of projects being evaluated and implemented at anyone time, particularly in a certain area or on a certain process. This becomes easier if there is a database for open and closed process improvement projects and the results. Projects should be implemented only at a rate that is sustainable within the company. "When growth becomes excessive – as it does in cancer – the system itself will seek to compensate by slowing down; perhaps putting the organization's survival at risk [14]." The impact of a project cannot be identified if multiple projects are occurring that will impact the same metric, not to mention the duplication of work and effort that can ensue. Another improvement project should not be considered until the subsystem metric has stabilized after the previous project.

3.4.4 Project Proposal Process

Once it is determined how a project is going to be evaluated, there must be a process for submitting project proposals. The most important thing about a process for submittal is that it is consistent. Maximum success will occur if the projects are selected based on a consistent analysis and selection method. Figure 10 is an example project proposal form, which encompasses the metrics translation technique combined with the Net Present Value Method. This form also serves as a check for sustainability. Since the subsystem metric is theoretically dependent on limited factors, the control system should indicate if the project implementation is being sustained, however it is wise for a project sponsor or management to review the sustainability of each project at a later point in time. This time obviously depends on the clockspeed of the company's industry, the throughput, and the speed at which new projects are being implemented. The goal is to measure long enough after the implementation that stability has been reached, but before a new project has been initiated which will impact the metric. Three to six months should be appropriate for most industries. The form in Figure 10 does prompt the project team/manager to perform this check.

Figure 10 – Example Project Submittal Form

Project Rationalization and Metric Form

This form is intended to facilitate you and/or your project team in proposing a process improvement project to a sponsor and in presenting a successful completion.

General Project Information - *Complete this section before starting the project.*

1. **Project Name**
2. **Project Scope**
   Describe the objective and scope of the project including specific details, but excluding the external system details.
3. **Team Members**
4. **System Considerations**
   Decribe all considerations outside the scope including the interaction with processes upstream and downstream and design.

System Metrics

Throughput/Labor hour

Area 1 A savings of 1 unit per labor hour is equal to a net present value of $3,000
Area 2 A savings of 1 unit per labor hour is equal to a net present value of $2,500
Area 3 A savings of 1 unit per labor hour is equal to a net present value of $4,000

Average Inventory Dollars

All Areas A savings of $1 average inventory is equal to a net present value of $.50

Project Metrics - *Complete 9 after the implementation and all others before the project*

3. **Project Impact on System Metric**

	Expected reduction		**Probablity of Actualization** Amount of expected actualized	Probability (add to 100%)
Throughput/Labor hour				
a. Area 1		units/labor hour	75%-100%	
b. Area 2		units/labor hour	50%-75%	
c. Area 3		units/labor hour	25%-50%	
Average Inventory Dollars		dollars	0%-25%	

4. **Define Sub-system Improvement Metric**
   Define the metric that will be improved by this project and susequent solution. This should be the highest level metric that can be collected and withstands impact from other current projects. For example, select line cycle time over station cycle time. Explain how improvement of this metric improves the whole system (avoid selecting just yield or number of nonconformances without explaining the ultimate impact, which may be dollars on rework or throughput at bottleneck).
5. **Linkage from Sub-system metric to System metric**
   Describe why the exptected improvement of the sub-system metric will result in the impact on a system metric above.
6. **Performance of sub-system metric before solution implementation** — ***units***
   - Average
   - Standard Deviation
7. **Target for sub-system metric after solution implementation** — ***units***
8. **Define Sustainability Metric and Monitoring Method**
   Define the metric that will be insure that the improvement remains effective. How will this metric be measure and how often. What happens if the metric regresses? Who will monitor and at what point will something be done to address the degrading metric?
9. **Performance after solution implementation** — ***units***
   - Average
   - Standard Deviation

Resources Required - *Complete prior to the project implementation*

10. **Human Resources** — ***Number of Hours Required***
    - Level 1
    - Level 2
    - Level 3
11. **Other Financial Resources Required**

Project Success - *Calculates based on inputs on "Before Readings" and "After Readings" sheet*

Alpha 95% *Assumes more than 30 samples, if less use T-test*

Probability sub-system metric is equal to or greater than target

P = #DIV/0!

Sample Statistics
μ = #DIV/0!
σ = #DIV/0!
n = 0

Z = #DIV/0!

Probability sub-system metric is greater than before the project

P = #DIV/0!

Old Sample Stats	***New Sample Stats***	
μ = #DIV/0!	μ = #DIV/0!	Z = #DIV/0!
σ = #DIV/0!	σ = #DIV/0!	s = #DIV/0!
n = 0	n = 0	

Lessons Learned - *Complete this section throughout the project and after project completion*

12. Project Management
13. Team Dynamics
14. Managing Stakeholders
15. Process/Product Interactions
16. Process Learnings
17. Potential Sustainability Issues and Mitigations

3.5 Project Implementation

The exact process to follow when implementing a project in a systems thinking environment does not necessarily need to be different than the process that was used in the previous environment. However, ensuring consideration of systems interactions can be best done when a consistent process, like a Six Sigma process, is followed. In this section, several systems thinking concepts that should be considered during project implementation are elaborated upon. These are not just tools or frameworks to be applied. Understanding the concepts is only the first step in systems thinking. Ultimately, the goal is to utilize systems thinking to determine the appropriate tools for the project.

3.5.1 Scoping

The scope definition of the project goal should be very specific; however the actual scope of consideration should be quite a bit larger with systems thinking. The "principle of the system boundary" says that "interactions that must be examined are those most important to the issue at hand, regardless of parochial organizational boundaries [14]." Therefore, the team should additionally consider the scope of interactions that needs to be included in the analysis because obviously everything under the sun can not be included. It may help to refer to or draft a Value Stream Map or a Process Map.

3.5.2 Team Selection

The team member selection process can impact the level of systems thinking. As the organization becomes more systems oriented, team selection becomes more intuitive. A team should select individuals with diverse backgrounds and experiences as well as represent each of the different functional areas. Even if a project is not necessarily related to a functional area, a representative should be on the team and attend at a minimum the "all hands" meetings, any brainstorming sessions, and solution evaluation meetings. For example, if a team is working with cycle time reduction on the manufacturing line, although not directly related to supply chain, a supply chain representative should participate, even if only for a very limited amount of time. This person may be able to share the impact of the different solutions on the front end of the process. Additionally, during solution brainstorming, this individual may be able to share solutions that the supply chain organization has implemented to improve their turnaround on transactions or a cycle time reduction success story at a supplier.

3.5.3 Challenge the Basics

While using systems thinking, it is not tolerable to accept things as they are. The project team/manager should always question the basics. For example, he/she/they should ask "Is the equipment that I am using to measure the metric accurate and consistent?" Traditionally, a Measurement System Analysis (Gage Repeatability and Reproducibility) can answer the question. Always confirm the data used to calculate the metric's current state to check that the metric is "as advertised". For example, does the station cycle time include the time it waits prior to or after being processed? It may be the case that the worker signs on many parts into the system at once and performs the operation in a batch manner, but this may not be realized without asking these questions up front.

3.5.4 Root Cause

Before determining a solution to the problem, the team must determine the root causes of the problem. "System Thinking shows us that there is no outside; that you and the cause of your problems are part of a single system...The system perspective tells us that we must look beyond individual mistakes or bad luck to understand important problems...We must look into the underlying structures which shape individual actions [14]." The implication of this is that a root cause cannot be identified as human error and the solution should never be strictly training. There is something innately wrong with the system if an individual was able to make the mistake and such a root cause should be identified and fixed. Also during root cause analysis, data should be used whenever possible.

3.5.5 Interactions

Systems thinking causes a project team/manager to consider surrounding issues. This can include technical, cultural, and political issues. For example, design and process should be closely linked. A solution to a process problem may be something that can be solved by changing the product design and the design community should then in response incorporate design for manufacturability into their future design specifications including the specific lesson learned. Another technical consideration is the interaction between the project and upstream and downstream processors. The project team/manager should keep these traditionally external groups under consideration (or have a representative from these groups on the team) during root cause analysis, solution generation, and implementation plans.

3.5.6 Risk Management

One benefit of applying systems thinking is that risk mitigation includes a larger scope of issues. It is true that "solutions that merely shift problems from one part of a system to another often go undetected because...those who 'solved' the first problem are different from those who inherit the new problem [14]"; however systems thinking theoretically prevents this pitfall. The Failure Mode, Effects, and Analysis (FMEA) is a tool that is used in Systems Engineering to identify design weaknesses. This tool can be transformed to be applied to process weaknesses identification. During a FMEA, the project team/manager should ask the following questions [2]:

1. Have reliability quantitative and qualitative requirements for the system been adequately defined and specified?
2. Are the reliability requirements compatible with other system requirements? Are they realistic?
3. Has system or process design complexity been minimized?
4. Has system failure modes and effects been identified?
5. Has the system or process "wearout" period been defined?

6. Are system and process failure rates known?
7. Have processes with excessive failure rates been identified?
8. Have adequate de-rating factors been established and adhered to where appropriate?
9. Is protection against secondary failures (resulting from primary failures) incorporated where possible?
10. Have all critical-useful-like items been eliminated from system design?
11. Has the use of adjustable components been minimized?
12. Have cooling provisions been incorporated in process “hot-spot” areas?
13. Have all hazardous conditions been eliminated?
14. Have all system reliability requirements been met?

3.6 Project Evaluation

The final step in any project is to collect the results and present them to the project sponsor and other key stakeholders. Although the results are not always as predicted, it is important to be honest about the results and to reflect on what was and was not effective. The goal is to become better at predicting the outcome of projects. As all employees become better at this process, the risk of implementing projects that are unsuccessful becomes lower. A method used to calculate project success is Hypothesis Testing. If a control system has been implemented on the metrics of interest, the system should become out of control (in a good way), but this is not a consistent way of evaluating project success. Once the hypothesis test has been complete, the control limits should be reset based on the data after the implementation and stabilization. Hypothesis testing works in the following way:

1. Gather values required:
    a. Recall the old mean ($\bar{y}_o$) and standard deviation (s_o)
    b. Recall the targeted mean (m)
    c. Calculate the current mean ($\bar{y}_n$) and standard deviation (s_n) using a reasonable sample size (n), typically greater than 30

d. Decide the confidence percent (i.e., how sure do the results need to be – usually either 95% or 99%)

2. Follow hypothesis test steps to compare the target to the actual [1]
   a. State the hypothesis
      i. H_0: m $\leq \bar{y}_n$
      ii. H_1: m > $\bar{y}_n$
   b. Determine a planning value for α (= 1-confidence percent)
   c. Calculate $Z_0 = \dfrac{\bar{y}_n - m}{\dfrac{s_n}{\sqrt{n}}}$
   d. Using the value for Z_0 and the Standard Normal Distribution Table, determine the area under the curve "a" from $-\infty$ to Z_0(a)
   e. Conclude that there is an "a" percent change that the mean is equal to or greater than the target. If the value for "a" is greater than or equal to the value for α, then the H_0 statement is not rejected. It is generally considered to mean that the metric readings are greater than the target.
3. Follow the hypothesis test steps to compare the old to the actual. (This would generally only be done if the hypothesis test described in step 2 above fails [1].)
   a. Determine variables
      i. If the goal is for the new readings to be greater than the old readings (which is what the hypothesis test above assumes), $\bar{y}_o$ is equal to the old average, s_o is equal to the old standard deviation, $\bar{y}_n$ is equal to the new average, and s_n is equal to the new standard deviation.
      ii. If the goal is for the new readings to be less than the old readings, the values for $\bar{y}_o$ and $\bar{y}_n$ should be flipped as well as the values for s_o and s_n (i.e., $\bar{y}_o$ is equal to the new

average, s_o is equal to the new standard deviation, $\bar{y}_n$ is equal to the old average, and s_n is equal to the old standard deviation.)

iii. This hypothesis test assumes the variances of the samples are equal. If the following formula is true then this is a good approximation.

$$\frac{s_{max}^2}{s_{min}^2}\sqrt{\frac{n_o + n_n}{2}} > 10$$

where S_{max}=maximum(s_o,s_n) and S_{min}=minimum(s_o,s_n)

b. State the hypothesis
   i. H_0: $\bar{y}_o \leq \bar{y}_n$
   ii. H_1: $\bar{y}_o > \bar{y}_n$

c. Determine a planning value for α (= 1-confidence percent)

d. Calculate $s_p = \sqrt{\frac{(n_o - 1)s_o^{\ 2} + (n_n - 1)s_n^{\ 2}}{(n_o - 1) + (n_n - 1)}}$

e. Calculate $t_0 = \frac{\bar{y}_o - \bar{y}_n}{s_p\sqrt{\frac{1}{n_o} + \frac{1}{n_n}}}$

f. Calculate the degrees of freedom: $v = n_o+n_n-2$

g. Using the value for Z_0 and the Standard Normal Distribution Table, determine the area under the curve "a" from -∞ to Z_0(a)

h. Conclude that there is an "a" percent change that the new mean is equal to or greater than the old mean. If the value for "a" is greater than or equal to the value for α, then the H_0 statement is not rejected. It is generally considered to mean $\bar{y}_n$ is greater $\bar{y}_o$.

3.7 Systems Thinking and the Organization

To capture the most value, the entire organization must adopt systems thinking. Encouragement to view things using a systems approach must be from the top down, from the bottom up, and everywhere in between. The following sections discuss specific things that individuals and teams can do to help facilitate and succeed in this type of environment.

3.7.1 Systems Thinking on the Individual Level

According to Davidz, systems thinking is most attributed to personality, aptitude, task assignment, happiness, and expertise [7]. Obviously, an individual does not have control over their personality, however he/she may have control over task assignment and the level of expertise they are able to develop. Rotational programs make individuals more aware of his/her surroundings, however it does not necessarily facilitate high level thinking [9]. Participating on and selecting cross-functional teams, interviewing people in other departments, and studying systems dynamics are other ways to develop a systems thinking perspective [9].

According to a study done at The Aerospace Corporation, Boeing, Booz Allen Hamilton, BMW, general Dynamnics, MITRE, Northruo-Gumman, Pratt & Whitney, and Sikorsky with 188 participants, the following three mechanisms enable systems thinking development [7]:

- Importance of Experiential Learning – an opportunity to see systems view through work experiences and life experiences outside of work
- Individual Characteristics – include thinking broadly, curiosity, questioning, open-mindedness, strong communication skills, tolerance for uncertainty, thinking out-of-the-box
- Supportive Environment – barriers include schedule and cost constraints, organizational boundaries/structure, and narrow job

3.7.2 Systems Thinking on the Group Level

Diversity within a team facilitates systems thinking, particularly when all group members are responsible for the outcome [9]. Davidz suggests that "communication and group dynamics dictate the level of systems thinking produced by a group [7]." In general, it is important to maintain the systems perspective to think of the best approach rather than to apply tools that are provided or implement practices without understanding their purpose and benefit.

3.7.3 Systems Thinking and the Project Manager

A project manager is "responsible for the planning, organizing, directing, and controlling of company resources for a relatively short-term objective that has been established to complete specific goals and objectives [9]." In this thesis, the term project manager refers to anyone who manages a project, whether or not he/she carries the title of Project Manager or Project Engineer. The project manager may or may not have a team of individuals working with him/her to accomplish the project goal (however some of the responsibilities listed later in this section would not apply if the project manager is not working with a team). Further, it does not matter what level of the organization or what functional area the employee works in. Being a project manager is a difficult role due to the traditional tasks, including [9]:

- Set objectives
- Establish plans
- Organize Resources
- Provide staffing
- Set up controls
- Issues directives
- Motivate personnel
- Apply innovation for alternative actions
- Remain Flexible

Maintaining a systems perspective makes a project manager much more effective, however it can also add some additional challenges, particularly if others in the organization are not systems thinkers. In a way, the project manager now has to think about how everything in the world is affected by the project and how everything in the world affects the project. Obviously, this is not practical in its entirety, which emphasizes the importance of scope definition. A large part of the system is people and their relationships, thus with a systems approach there are additional responsibilities for the project manager including [9]:

- Manage human interrelationships with the project team

- Manage human interrelationships between the project team and senior management
- Manage human interrelationships between the project team and the customer's organization, whether an internal or external organization

3.7.4 Systems Thinking and the Functional Manager

A functional manager's project responsibilities do not change specifically in a systems thinking environment, they still include basically the following [9]:

- define how the task will be done and where the task with be done
- provide sufficient resources to accomplish the objective within the project's constraints
- maintains responsibility for the deliverable

In general a great manager gives authority and takes responsibility; this should not be different in this environment. However, in this environment, the manager should provide rewards and incentives for his/her employees to use systems thinking in their daily roles and responsibilities.

3.7.5 Systems Thinking and the Project Sponsor

The project sponsor should encourage systems thinking by requiring that the team select the project based on maximum improvement of the system rather than localized improvement which may have little or no impact on the system. Additionally, the project impact should be reviewed by the sponsor after the project implementation and then again 6 months or so later to confirm that the metrics have been improved with statistical significance as claimed by the project team.

3.7.6 Organizational Challenges with Systems Thinking

Systems thinking is not a buzz word or new miracle process that can be implemented. It must be captured in the organization's strategies, people, and culture. This is a very challenging thing to do and there is no right answer or approach. The important thing is to understand the organization and the desired state and concentrate on bridging the gap in creative ways. In the following three sections, the three lens analysis [5] will be used to identify some of the considerations with a systems thinking culture.

3.7.6.1 Strategic

The strategic lens views the impact of the organization's initiatives and structure on the organization. To facilitate systems thinking, company initiatives and goals within the organization should include an emphasis on open mindedness, wholeness thinking, cross functional training, and collaboration. The structure should highly encourage cross-functional participation on teams. The matrix structure does not alone solve this challenge. Also playing a role in the amount employees communicate with other departments are the encouragement by management and the proximity of desks.

3.7.6.2 Political

The political lens views the impact of human relationships and behaviors on the organization. Politics play an enormous role in the way things are done in organizations. Naturally, an individual's work quality and prioritization depends on his/her relationships with the requestor and superiors, whether this relationship is based on respect, fear, or some other emotion. In order for an organization to become systems thinking, everyone must support the idea. This is a difficult thing; it requires unwavering support from the top as well as energy surrounding the idea throughout the company. This can be done by hiring or training "undercover cheerleaders" that truly appreciate the concept and are able to integrate systems thinking in all that they do. Individuals that have education and/or training in systems concepts and have a wide variety of experiences tend to think about the system over the details (as explained in the Systems Thinking on the Individual Level section of this thesis); therefore this type of person should be targeted in employee searches.

3.7.6.3 Cultural

The cultural lens views the impact of symbols, cultural norms, and attitudes on the organization. "The systems engineering process [like the system thinking culture] involves the use of appropriate technologies and management principles in a synergetic manner. Its application requires synthesis and a focus on process, along with a new 'thought process' that should lead to a change in culture [2]."

4 A Case Study

4.1 Project Setting

The objective of this study is to look at an improvement project at the Raytheon Company and to consider how systems thinking would improve or change the project. The following sections describe a real project, which was managed by an intern from the Leaders for Manufacturing program at the Massachusetts Institute of Technology, and provides recommendations of how systems thinking could have been or was applied in this situation. The goal of the project was to improve the cycle time of the AC/DC assembly and test process.

4.1.1 Raytheon Company

Raytheon offers over 250 services and products, typically in low volumes, in the following strategic business areas: Precision Engagement weapons, Missile Defense, Homeland Security and Intelligence, and Surveillance and Reconnaissance. The company is incorporated in Delaware and the global headquarters is located in Waltham, Massachusetts. In 2004, Raytheon had $20.2 billion in sales. The decentralized company is comprised of seven businesses: Integrated Defense Systems, Intelligence and Information Systems, Missile Systems, Network Centric Systems, Raytheon Aircraft Company, Raytheon Technical Services Inc., and Space and Airborne Systems.

4.1.2 Integrate Defense Systems (IDS)

IDS is comprised of 17 centers in the United States, Germany, and Australia. Jointly, these businesses represent $3.5 billion of Raytheon's net sales (2004) and employ 12,700 people. According to the company's website (www.Raytheon.com), IDS is the global mission systems integrator of choice.

4.1.3 Integrated Air Defense Center (IADC)

The IADC is one of the 17 IDS facilities. The facility produces, among other things, Terminal High Altitude Area Defense (THAAD) and Ballistic Missile Defense System (BMDS) Antenna Elements, the Phased Array Tracking to Intercept of Target (PATRIOT) missile, and the Advanced Electronic Guidance Intercept System (AEGIS) system. The facility's manufacturing and assembly capabilities include metal fabrication, microprocessor fabrication, circuit card assembly, cable assembly, microwave assembly, electronics assembly, missile assembly, and radar assembly. The IADC was recently awarded the Northeast Shingo Prize for Excellence in Manufacturing at the gold level. (The Shingo award levels are bronze, silver, gold, and platinum.) This award symbolizes the facility's strive to become a Lean manufacturing facility, however different areas within the facility are at different places in their Lean journey.

4.1.4 Power Value Stream of Radar Subsystems Solutions

The Power Value Stream of the Radar Subsystems Solutions (RSSS) at the IADC is primarily responsible for assembling, testing, troubleshooting, and reworking, when necessary, the AC/DC Converter, which is used in three of the programs mentioned above. Additionally, this value stream tests four of the five cards that are later put into the AC/DC Converter. These cards are manufactured by Circuit Card Assembly (CCA). One of these cards requires some assembly in the RSSS prior to testing. If any card or AC/DC Converter fails during test, the RSSS group is also responsible for troubleshooting the item. The standard process flow (or router) for the AC/DC in the area is mapped in Appendix 2. A deviation from this process does occur if the unit fails in which case it enters into one of several different routers.

This area has a total of 27 union workers and seven engineers, including two process engineers and three test engineers. Additional support is provided by a Lean/Six Sigma Expert and a Production Supervisor. Thirty percent of union employees and all engineers in the area are certified R6σ Specialist (see the section titled "Raytheon Six Sigma Tools and Experts" for explanation of Specialist and Expert statuses).

4.1.5 AC/DC Converter Assembly and Cards

Many AC/DC converter assemblies are required for one system. Each assembly is comprised of a housing and five different parts: input card, multi-volt card, capacitor bank assembly, EMI, and boost card.

4.1.5.1 Testing and Complexity

The ultimate goal of testing the AC/DC converter and its cards is to ensure that the unit will work when it arrives in the field. The testing strategy is to test 100% of the cards before they are coated, as the coating makes rework much more difficult, and then to test 100% of the AC/DC converter assemblies.

The design of the AC/DC converter is very complex and lacks modularity. As a result there are many interactions between the parts in the assembly. Testing the cards does not completely predict the success of the testing at the assembly level. One piece of evidence of this complexity is that test measurements taken on the card level are rarely identical to test measurements taken on the assembly level. Thus, most measurements for the AC/DC converter test depend on things occurring when the different cards are combined; otherwise an identical test could be performed at the card level which would truly predict the outcome. Another piece of evidence is the fact that the yield at the AC/DC level is not close to 100%. Every single card is tested and passes before being assembled into an AC/DC converter, therefore either damage occurs during assembly or successful card testing does not necessarily indicate the assemblies will pass. An engineering test was not performed on this to see if assembly quality or card testing that did not sufficiently predict was the cause of the lower than 100% yield at the assembly level; however assembly is not likely the major cause based on an experienced intuition.

4.2 Project Resources

4.2.1 Team

The first team member selected was the project manager, who was a Leaders for Manufacturing student at the Massachusetts Institute of Technology interning at Raytheon for six months as part of the program requirements. The remainder of the team members were suggested by the RSSS Manager and then recruited by the project manager. Appendix 3 is a organizational chart of the Power Rex area. The next team member added was the test engineer, followed by the buyer and a test technician. The test engineer had less than two years experience with the company, while the buyer and test technician have each been with the company well over ten years. Also initially two CCA area representatives, both engineers, were involved with the team.

4.2.2 Raytheon Six Sigma Tools and Experts

Raytheon began implementing a six-sigma program in 1999. Raytheon's goal is to have 100% of their employees certified as Raytheon Six Sigma Specialists (roughly equivalent to the traditional green belt six sigma level). To become and remain a Six Sigma Specialist, an employee must complete one project per year. In addition to the Specialist certification, Raytheon also has an Expert level certification. Individuals at this level spend time both leading larger projects that tend to cross departmental borders and mentoring Specialists during their projects.

Raytheon Six Sigma includes many tools to use throughout process and product improvement projects. One of which is a standard process for all projects to follow. Figure 11 shows a visual representation of the steps in this process.

Figure 11 – Raytheon Six Sigma Wheel

Raytheon used the traditional six sigma steps, DMAIC (define, measure, analyze, improve, and control) or DMADV (define, measure, analyze design, and verify), as a basis, but added the Commit step and renamed some steps. One significant difference is that in the Raytheon process the current state is assessed in the define step, however the traditional process, this is not done until the measure step. Table 3 shows some differences between the traditional six sigma project steps and the R6σ project steps.

Table 3 – Comparison of Traditional Six Sigma and R6σ

Six Sigma Step [15]	Six Sigma Step Description	R6σ Step	R6σ Step Description
Define	Define project goals and customer deliverables	Visualize	Assess the current state Visualize future state
		Commit	Sponsor and team members are committed
Measure	Measure the process to determine current performance	Prioritize	Determine improvement priorities
Analyze	Analyze and determine the root causes	Characterize	Define existing process and plan improvements
Improve	Improve the process	Improve	Design and implement improvements
Control	Control future process performance	Achieve	Celebrate achievements Build for tomorrow

In addition to the Raytheon Six Sigma wheel, other tools taught include Value Stream Analysis, Affinity Diagrams, Cause and Effect Diagram, Logical Process Map, Pareto Chart, 5 Whys, Control Charts, Histograms, Process Observation, Failure Mode and Effects Analysis, Action Plan, and Control Plan. The objective of Raytheon Six Sigma is to maximize customer value and grow the business by creating lasting improvements by using data to generate knowledge and sharing.

4.2.3 Schaffner Auto Test Station

The Schaffner test stations are used to perform the pretest and final test on the AC/DC Converter as well as the final test on the multivolt and capacitor banks. These stations are used by test technicians, who are union represented employees, and were used to collect data for this thesis. These stations were maintained by SVTAD (Systems Validation Test Analysis Directorate).

4.2.4 Data Management Systems

The main information systems used to collect data include the Shop Floor Data Management System (SFDM) and the Schaffner test station database, which is populated by National Instruments Test Stand (software used to drive the testing on the Schaffner test stations). SFDM collects the following data: activity log, non-conformances, and configurations (i.e., captures the serial number of the component and the serial number of the assembly where it was installed in the same record). The Schaffner test station database is intended to collect the Order Number (test step number), Step Name, Minimum Passing Value, Maximum Passing Value, Measurement Units, and Data Reading, among other things, for each parameter measured on each unit tested in the Schaffner test station. This database currently collects all data when a multivolt is tested and is being modified to collect all data on the other products tested.

4.3 The Project

4.3.1 Project Goal and Motivation

The initial goal given to the project manager was to decrease the cycle time of the AC/DC assembly and test system. The process flow for a typical AC/DC in assembly test is listed in appendix 2. In addition to this process flow, the cards that go into the AC/DC are tested in the AC/DC test station. These cards come from the CCA area and are then returned to the CCA area for coating. The scope of the project also included the card testing.

This goal was recommended by the project sponsor because the project manager had experience with cycle time analysis in a different area of the company. The resources for this project were available for up to four months.

4.4 Project Approach

The team was to use the R6σ process to complete this project. The next sections describe what the team did during each of the R6σ steps.

4.4.1 Visualize

The most time was spent in this phase as the project scope needed to be narrowed significantly in order to achieve the goal within four months. First, the project manager attempted to identify the bottleneck station by looking at the cycle time for each station. Cycle time data was pulled directly from the SFDM database by extracting the time a part entered a station and the time it was completed at the station and calculating the difference. Prior to this data extraction, the project manager was not able to get an idea of the cycle times as they were not displayed and not known by people in the department. Others told the project manager that the group was on the waiting list to get visual metrics from the appropriate group.

After the cycle time data was pulled, many employees in this area claimed that the data was not accurate because a pull system was just implemented. The only parts of the process that had not significantly changed were the test stations. The data for these test stations were not clear. After further research, it was found that one of the test stations batched units, which explained the extremely long average cycle time and the very short variation. The pretest and final test stations each had a large average cycle times and large standard deviations. It was then discovered that the yield is sometimes as low as 50%, therefore these cycle time calculations included a significant amount of debug and rework time. The yield values were also contested by the employees as there had been a recent redesign.

Based on this process, the team was able to modify the project scope. The new goal was to improve yield of the AC/DC during pretest. The thinking was that if the team were able to improve the yield, less time would be required at the debug station and test stations, thus increasing throughput and reducing cycle time.

4.4.2 Commit

All members of the team agreed to work toward this goal. The sponsor also agreed to support this project; however no charge number was assigned to this project at this time, except for the project manager.

4.4.3 Prioritize

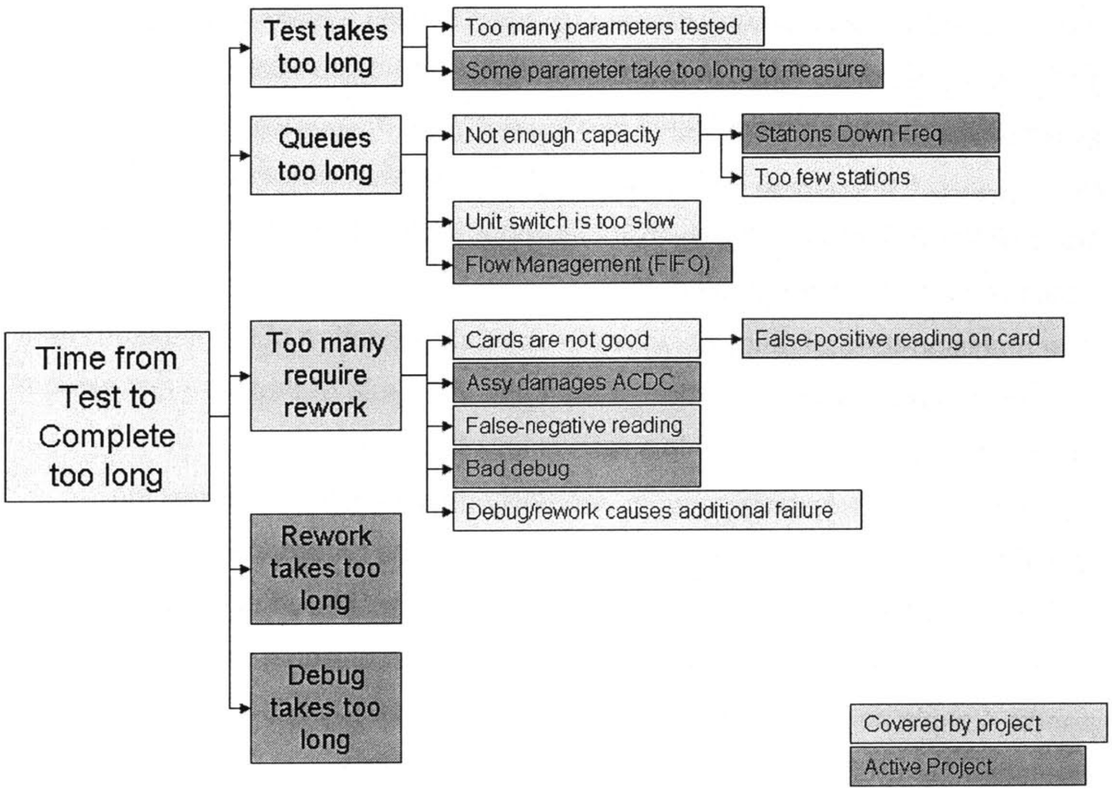
The team's objective for the prioritize stage was to identify a root cause for the low yield of the AC/DC in pretest. The project manager observed the test technician perform the tests to become more familiar with the process.

It was then learned by the project manager that all the test station data was being collected in formatted text documents. The AC/DC had over 200 test parameters; therefore each text document, one for each test occurrence, contained 200 different readings, some displayed as lists and some in tables. Many of these documents also had no serial number included, so the data could not be assigned to anything. The project manager immediately put in a request for the data to be captured into a database from that point forward and for the operator to be required to put in a serial number. When SVTAD added the database as an output form, less than half the parameters were saved in the database, therefore additional programming had to be performed.

At this point, the project manager asked how the parameters and pass/fail limits were determined. These questions never were sufficiently answered, potentially because the individual that wrote the test program was unavailable.

The team then used the 5 Whys Analysis to brainstorm root causes. The result is shown in Figure 12. Since there were many other open projects in the area, the team highlighted those factors that will likely be impacted by one of those projects in blue. The team decided it would address the items in green including false-positive reading on the card and false-negative reading on the AC/DC.

Figure 12 – 5 Whys Analysis



4.4.4 Characterize

The objective for the team in the characterize phase was to validate the root cause identified. They chose to perform a Measurement System Analysis (also called a Gage R&R where the R&R stands for repeatability and reproducibility).

The Measurement System Analysis requires testing at least two parts an equal number of times, and at least twice, on each test station. Some statistical formulas are then applied and the following outputs are calculated:

- Repeatability = the variation obtained by the same person using the same test station on the same unit for repeated measurements
- Reproducibility = the variation obtained due to differences in people or stations that are taking the measurements
- Part variation = the variation obtained by a perfect test station testing several parts (this can not be found in practice, only through calculations)

The relationship between these items is $\sigma^2_{total} = \sigma^2_{part} + \sigma^2_{repeatability} + \sigma^2_{reproducability}$ and $\sigma^2_{measurement} = \sigma^2_{repeatability} + \sigma^2_{reproducability}$ where the total variation is the total variation of the entire test sample. The following ratios are taught at Raytheon to indicate the R&R of the test system [1]:

- The precision-to-total ratio, which is the standard deviation of the measurement divided by the standard deviation of the total. As a rule of thumb, a test system is considered to be capable if this ratio is less than 10%.
- The precision-to-tolerance ratio, or capability ratio, which is six times the standard deviation from measurement divided by the difference in the specification limits. The measurement system is considered unacceptable if greater than or equal to .3 and adequate if less than or equal to .10.

Appendix 4 explains more about these ratios as it contains parts from the presentation the project manager gave to the stakeholders.

In order to identify if false-negative readings were occurring on the AC/DC, a Measurement System Analysis would have to be performed repeatedly on the AC/DC. This was hindered as complete test data was still not being saved properly to the database. Therefore the team performed the Measurement System Analysis on one of the cards that is used in the AC/DC to analyze the other potential root cause a false-positive read on the cards. There are four cards that are previously tested on the same test stations; however the data is fully being captured for only one, the multivolt. Therefore, due to lack of choice, the team performed the Measurement System Analysis on the multivolt card.

The setup of the Measurement System Analysis was to test two different units on two different test stations with two different operators. This made for a total of eight different combinations and each combination would be tested twice for a total of 16 tests. The AC/DC test area worked in the tests as available. The second unit selected came off the line immediately following the first unit selected. The data was collected in the database for all but one test due to a hardware issue. For this particular situation, the project manager typed all the values into the database from the text document, however the text document contains fewer significant digits than the database normally captures.

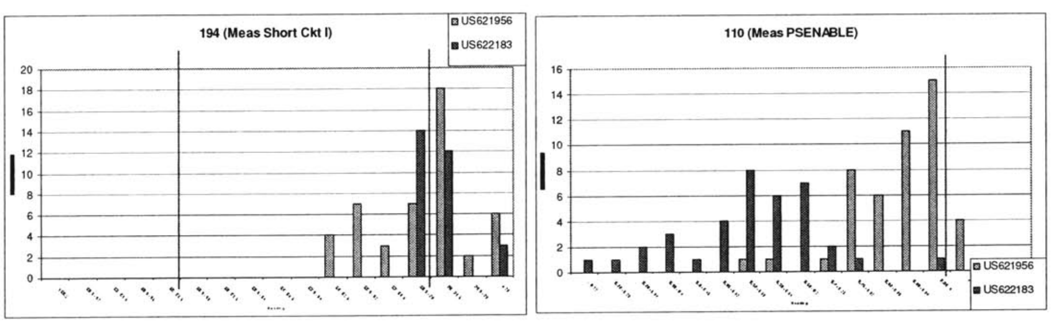
The data was then analyzed using the formulas described in Appendix 5. There were exactly 167 parameters tested. The calculations are performed on each parameter independently. Approximately 122 of the 167 (26.9%) had unacceptable precision-to-total ratios as they were greater than 10%. Only 132 parameters had both an upper and lower specification limit and thus were the only parameters for which the precision-to-tolerance ratio could be calculated: 119 of these parameters (90.2%) were acceptable at less than 30% and 110 of them (83.3%) were within the goal of less than 10%.

The team had a hard time rationalizing that all 122 of the parameters that were found to have unacceptable precision-to-total ratios were not capable. They believed that this was caused by a non-representative part variation due to testing two consecutive parts off the line. Additionally, the precision-to-tolerance ratio was not entirely credible as a measurement system evaluation as it was not clear that the specification limits were not ambiguously set. The team decided to look deeper into any parameters that were considered unacceptable for both ratios. Additionally, the team added another method of evaluating a parameter. Based on the concept that avoidance of a false-positive or false-negative reading is goal, the team looked at the probability that the parameter had ever tested falsely based on the measurement system variation and all historical data. Appendix 6 shows more detail on this evaluation.

After identifying the parameters that needed a closer look, the team looked at a data histogram of all historical data for these parameters. In the case where the same parameter is measured at the card level and at the AC/DC level, a correlation chart was created to see if the card reading truly predicted the assembly level reading.

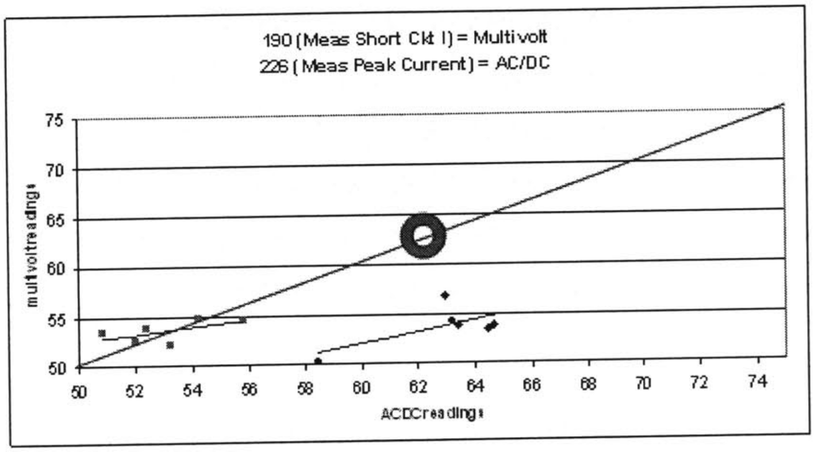
The histograms typically looked like the chart in Figure 13. Each test station was represented in a different color so a difference between the two could be easily spotted. Additionally, the upper and lower specification limits are added to the graphs. In the example on the left in Figure 13, the test data is not centered between the specifications. In the example on the right, one station tends to have lower output readings than the other station. Assuming that the stations test boards randomly, the output readings for both test stations should be completely overlapping.

Figure 13 – Historical Data Histogram



The correlation charts typically looked like that in Figure 14. This chart contains a point for each multivolt unit. This particular parameter is tested both at the multivolt level and at the AC/DC level (after the multivolt is assembled into a AC/DC). The location of the point along the x-axis represents the AC/DC reading and the location on the y-axis represents the multivolt level reading. The points should theoretically fall on the diagonal line through the center of the graph as this is where the reading is the same at both levels. The red bull's-eye in the middle is the middle of the specification, so ideally all dots would be on the target. The pink and blue represent the two test stations. The particular case shown below indicates that the pink (squares) station reads significantly below the target on both the multivolt and AC/DC level. The blue (diamonds) station reads below target for the multivolt, but relatively close to the target at the AC/DC level.

Figure 14 – Example Correlation Chart



Based on these graphing techniques, some changes to the test equipment and specifications were recommended. One change to the test equipment was to replace an intermittent relay as the histogram showed a few extreme points. As additional evidence, the test unit failed once due to this relay after it had passed four times. Another recommendation, which actually arose from another project, but was confirmed during this analysis, is that a load must be added when testing one parameter as the readings were misaligned. In the example shown in Figure 14 above, an upgrade had been done to only one of the AC/DC test fixtures, which had not been done to the other AC/DC test fixture nor either of the multivolt test fixtures. This information had been lost as new engineers came on board and the ones that were aware of this upgrade moved on to other roles.

4.4.5 Improve and Achieve

Within the four month project window no implementation took place, although several learnings for the team came about. Not only were the specific fixes for the test equipment identified, but they learned how to do a Measurement System Analysis and to look at the data in different ways in order to identify potential problem areas.

The project manager, in anticipation of leaving the team, created some tools so the team and new teams in the area could continue to do the same types of analyses. One of these tools runs the Measurement System Analysis at the click of a button assuming that the duplicate tests are run. The other tool creates the histogram and correlation charts with a click of a button when the parameter numbers are inputted. These tools were created in Microsoft Access and thus are not intended to be used wide-scale. However, if used significantly, a programmer could create a more robust tool to perform the analyses in a similar way.

4.4.6 Transition Plan

The project manager left the project, but prior to this, she taught the test engineer how to use all the new tools. The test engineer was focusing some of his time on the serial number inputs. He was trying to implement a bar-coding system of some kind because if the true serial number was not inputted correctly by the operator, the test data cannot be linked to any of the SFDM data. Alexey Salamini's Leaders for Manufacturing thesis "Capturing Value From Item Unique Identification (IUID)" discusses in detail unique identification strategies at Raytheon [13]. The SVTAD group was in the process of rewriting the software so that test data for all cards would be saved in the database.

4.5 Recommended Approach

Although the team did many good things in this case study, based on the suggestions in the earlier part of this thesis, there are areas of improvement.

Systems thinking was not always utilized. One very promising thing the team did was to check the measurement equipment. Furthermore, they thought about the Measurement System Analysis ratios and created a new evaluation method that fit their needs.

One overriding issue with this team and their work is that there was no stabilization in the system prior to them getting involved. For example, the test station was incurring upgrades throughout the Measurement System Analysis, which may have skewed the data. Furthermore, there were no metrics that indicated whether or not the system was stable. Although the group was on the "waiting list" for visual metric implementation, they probably should have focused on getting this done first. If the metric implementation is driven by an insider team rather than strictly by an outsider, individuals inside the group are more likely to understand the calculations and drive the metrics properly.

In retrospect, assigning a charge number to the project upfront for all participants may have helped to get the time required to complete the project within the four month window. Additionally, the scoping or resource allocation should have been managed such that the full implementation could be completed within the timeframe allocated.

Simulation is often a tool used to understand systems at a higher level. The project manager should have created a simulation of the process when looking at cycle times of different stations. The key is to create the current state and ensure that the metrics shown in the simulation are representative of the actual ones. Then modifications can be made to the simulation to see how it impacts the metrics. This is a great way to evaluate projects, or to see how changes in subsystem metrics influence changes in system metrics. The simulation, once created, will offer value to the department for many months to come. Additionally when looking at the cycle times, the project manager should have spent more time with the process engineer to understand how the cycle times should be calculated for each of the processes to learn, for example, if the process is done in batches.

The team should have identified the yield at the beginning of the project as well as identified the target yield. They should have calculated the impact on the system cycle time with a 1% improvement on yield in order to communicate the importance of the project on the system level metric. Once the target and current values were found, the team could have them performed a cost and benefit analysis to adequately evaluate the project.

While the Measurement System Analysis did provide interesting results, sacrifices were made to be more accommodating. This may have been the only way to get the entire test completed; however in a perfect world the two parts used would not be two sequential parts. Additionally, the stations should have focused solely on testing the parts for this analysis until they were done as changes on the test equipment were occurring. This would have also avoided the data loss due to hardware issues.

One significant challenge, which the team did not recognize sufficiently, was the design complexity. Although, this may not have been the right team for analyzing such a challenge, systems thinking should include the consideration of design. It is possible that the design of the AC/DC converter and the design of the test equipment were so complex that testing cards cannot predict the outcome of an AC/DC converter test. According to a seasoned employee, the design of the AC/DC converter was previously produced by an outside supplier, who was not able to manufacture the unit to Raytheon specification. Therefore, Raytheon decided to produce the same design in house. He said it was a bad design when the supplier produced it and it is the same bad design that Raytheon produces. Redesigning the AC/DC converter from scratch may not be a viable solution, and especially was not for this team; however the design/development team should be more involved in the testing of this unit to understand the challenges between the complexity and the testing.

4.6 Organizational Challenges and Observations

In this section, the author discusses some of her organizational observations while working on the project described in the case study above. The three lens analysis, which is an approach to examine an organization, is used. The goal is to gain a richer insight into an organization by viewing it through each of the three lenses, the strategic lens, political lens, and cultural lens [5].

4.6.1 Strategic Perspective

The strategic lens focuses on the structure of the organization including goals, strategies, and groupings. The organizational structure of Raytheon is extremely matrixed, not only are there functional groups and product family groups, there are also groupings associated with projects or customers. This leads to employees having many bosses and many dotted lines and therefore many stakeholders. Which group an individual is truly faithful to depends on the political and cultural aspects as well. I believe this structure did produce at least one negative side-effect for the AC/DC converter test team. The design/development and SVTAD individuals were not as involved in the test of the AC/DC Converter as needed. These groups sit in buildings offsite to the manufacturing facility. Since Raytheon inherited the AC/DC converter design and it caused many unpredictable issues, I think it is frustrating for people to work with it thus they tend to give it lower priority. This means that this design is a real challenge and it is getting limited attention from the groups it needs the most attention from.

Raytheon's goals for 2005 are outlined in RAMP speed. The concept is to do things faster and eliminate bureaucracy, so words like "agility," "energy," "momentum," and "decisiveness" are displayed throughout the facility and on name badges. These goals are relatively clear; however these goals do not include any reference to security (which is the "number one priority") and safety, which presumably is also important.

Raytheon had two major initiatives supporting the goals during the time of the case: The Singo Award and the Raytheon Six Sigma program. The Singo Award has motivated significant change within the organization. As an outsider, it seemed to me that the incentives were not always completely aligned with Lean concepts, which may bring sustainability into question. For example, the metrics used in the Metal Fabrication area did not align with the pull system that was being implemented at the time. The Six Sigma program also has done great things, particularly to the culture of the organization. Resistance to change is nearly non-existent; however so much change is occurring at once that the system does not have time to stabilize. This is likely why the full benefit of each project does not always come to fruition. Additionally it can be very frustrating or discouraging as an employee in this environment because it is very difficult to know which projects are higher priority and thus there is no real focus on any project. I believe the quantity of projects has reached the point of diminishing returns due to this prioritization problem.

4.6.2 Political Perspective

Looking at the organization through the political lens, the informal networks are highlighted. Specifically, this lens focuses on the individuals that hold the formal authority and those that control the informal authority as well as any alliances between individuals. There were two key points of interest in the area of relationships. One is the horizontal relationship between AC/DC test/assembly and CCA. Generally, I observed the AC/DC test/assembly being viewed as the department that just seemed to do nothing right, while CCA is identified as the Center of Excellence and as a more advanced department. Some specific feelings I observed between the two organizations include:

- The AC/DC test/assembly was held responsible to a large degree for the yield of the boards even though the boards were assembled in CCA.
- AC/DC test/assembly feels CCA causes many of their problems due to the low yield.
- CCA feels AC/DC test/assembly doesn't have a fast enough process as far as transporting, testing, and debugging the boards.

To an outside, it seems as though blame is back and forth without any significant collaboration. This is evidenced by the fact that the weekly meeting intended to discuss the cards and AC/DC yields was cancelled more times than it was held during the six weeks that I was involved. The second relationship observation is the vertical relationship between those that work on the floor and those in management. Some individuals in management tend to be very demanding, which I think is very frustrating for those working on the floor (not union represented employees). They feel overwhelmed with projects, firefighting, and demands without any real direction with regards to priorities.

4.6.3 Cultural Perspective

The cultural lens focuses on meanings to the situations, symbols, cultural norms, and attitudes and beliefs. I was pleasantly surprised with the culture at Raytheon because the pace was faster than expected. Raytheon has several cultural norms, which stood out in my mind. First, since I have never worked in the defense industry, the "Need to Know" policy was interesting for me to experience. My personal style of trying to see the system then drilling down was dampened by this policy and culture; however the need for such a policy is obvious.

This could not be a section about culture without the mention of the union, so my second comment is in this regard. The relationship is generally non-threatening. I believe that the non-union employees have low expectations for the union employees. In one instance, I expressed my general irritation that a union employee charged 15 minutes to my project charge number while he was "waiting" for someone to move out of his way. Some of the other employees thought it was funny that I was irritated. I gather from this reaction that there is an expectation that the employee would "waste" time. Just as an interesting note, I asked a union represented employee how to motivate employees and he said, "You can't, either they are motivated or they aren't."

Third, I observed what I believed to be meeting inefficiencies. I believe different departments vary widely on this issue. The first area I was placed in was very advanced in my mind. They make very impressive process improvements and can prove it with improvement in the key metrics. They meet regularly to discuss quality issues and to discuss the preventative actions and implementations of the solutions. This was great, they saw one unit fail and they were immediately preventing it from happening again. It was basically real time. However, there were three meetings per day to discuss this topic alone. Each meeting had somewhat different participants; however the same projects were being discussed with the same level of detail. This seemed amazingly inefficient. Probably at first, management would attend one of the meetings and receive general information about the projects, while the more tactical workers probably met separately to discuss the details, then an evolution occurred creating this inefficiency. A different area I was assigned to was not as proactive. In fact, they had the opposite problem. This group met weekly to discuss quality issues that occurred the week before and the meeting is frequently cancelled for "more important things." These meetings seemed to be rather inefficient. We rarely got through the failures on one product (there are five) before the end of the two hour meeting. My last week there, we used the meeting time to resolve the structure of the meetings. Hopefully, this will lead to improvements going forward.

My fourth cultural observation is that a significant root cause was not always sought out. Again, I believe this varies widely between departments. For example, one failure occurred because an individual loaded the wrong reel of parts into the PC board building machine. The root cause identified in the meeting was "human error" and the solution was to tell the person not to do that again. This solution may or may not prevent this situation from occurring again.

5 Recommendations

5.1 Future Projects Recommendations

This section lists some projects that Raytheon may chose to evaluation and potentially pursue. All ideas are based on the experience of working in AC/DC test and assembly, however some can be carried into other areas.

5.1.1 Hire Data Specialists

Raytheon collects an abundance of data. This data can be utilized to make virtually any decision easier. However in order to be useful, someone must ensure a clean collection of the data and be capable of pulling the data. Even if just one person in each department had a basic understanding of these concepts, all the data in the entire facility would be accurate and accessible to every department. This person should perform typical duties in the department in order to completely understand the processes and the meaning of the data as well as have the skills to use the databases. This is not an uncommon combination of skills.

5.1.2 Schaffner Test Data

If the Schaffner test data is going to be used beyond the traditional manual way (i.e., statistical analyses, control charts, predictability, etc), some changes should occur. If it is planned to be used in such ways, the data should be analyzed by a database specialist. This specialist, with the input of a test expert, should evaluate and modify, if necessary, the database structure. The current structure records are enormous amount of data, all of which is not likely needed. Additionally, one test step collects several different readings which are difficult to differentiate.

The test data should be linked in some way to the rest of the facility data. This would allow one to compare the cycle time or non-conformance data with test measurements.

The serial number is not always captured in a way that is useful. If the operator does not put in the number exactly as it is on the box, then the data is virtually lost without manual searching. A project to implement bar-coding is under way.

This test data is difficult to view unless the user knows SQL or Microsoft Access (and even Access may not work because the dataset is so large). Some kind of database interface should be implemented so users know what data is available and what it can be used for.

Finally, an analysis or research project should be done on the test parameters and/or the test specifications. It is not clear that appropriate things on the cards are being tested to predict the failure of an assembly. Furthermore, it is not clear if the test points on the assembly are sufficient for predicting the performance in the field.

5.1.3 Further Measurement System Analysis

A Measurement System Analysis should be completed on all test stations, whether automatic or manual. The process is taught in the statistics course at Raytheon and can be quite simple.

5.1.4 Lean Related Recommendations

Lean emphasizes lowering inventory and reducing the total time in system through single piece flow (along with other concepts) to improve the timeliness of feedback. It was said that the CCA produced cards in July or August for AC/DC test in December. Definitely, the lean principles should be further considered in this situation as they may improve yields. The goal is immediate feedback as this prevents additional boards from having the same defect, allows for repair before machine changeover occurs, and knowledge remains with the part throughout the rework process.

5.2 Organizational Change Recommendations

It is recommended that Raytheon use systems thinking as much as possible. This will help to manage the numerous stakeholder relationships, bring the AC/DC and CCA areas closer together through collaboration, encourage identification of true root cause of problems, and set project priorities. Management has the fortunate perspective of seeing the entire system. By sharing this view through emphasizing only the most critical projects, they can alleviate some stress at the lower levels.

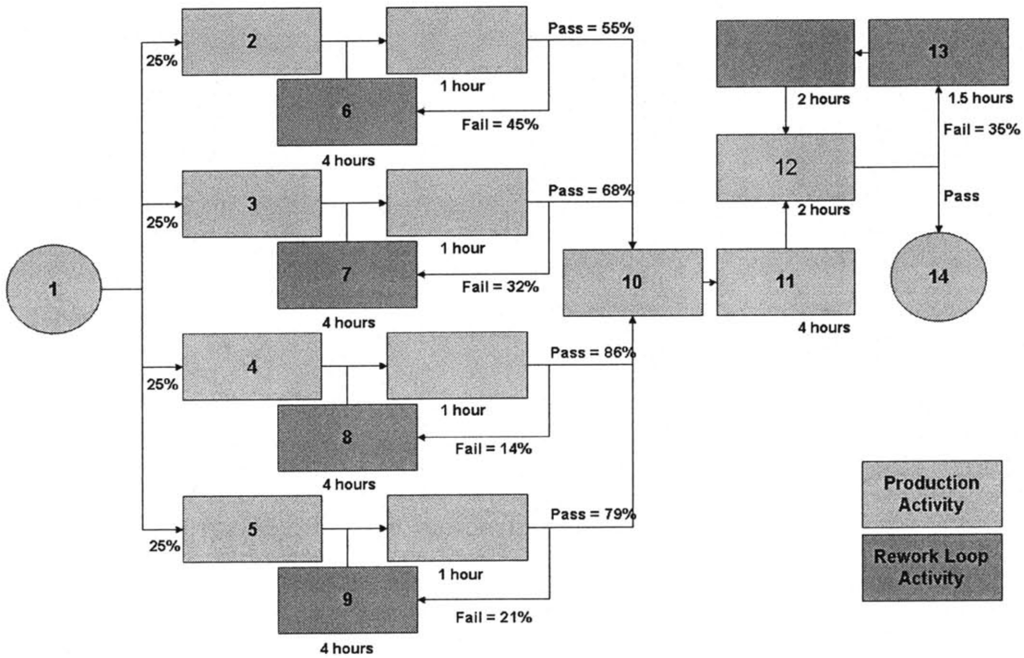
6 Conclusion

Manufacturing companies should create and encourage an environment of systems thinking. If successful in creating such an environment, the company will see improved returns on projects through a more effective project selection and implementation processes and increased employee satisfaction as project success is more visible. Tangible elements critical to maintaining such an environment include metrics, with control charts on critical metrics, a consistent project selection process that is driven by high level metrics and financials, and a post-implementation project evaluation. Intangible elements include employees maintaining an open mind and freely communicating across functions.

Appendices

Appendix 1 – Process Flow Model Formulas and MatLab Code [17]

Below is the process model with the nodes labeled.



f_{ij} = flow from node *i* to *j*
p_{ij} = probability of going from node *i* to *j* (the sum of all "*p*"s for one *j* must equal 1)
y_i = flow out of node *i*
x_j = new assemblies entering the network

$$f_{ij} = y_i p_{ij}$$

To conserve flows at *j*:

$$y_i = y_j p_{ij} + \sum_{k \neq j} y_k p_{kj} + x_j$$

Arrange p_{ij} into matrix *P*
Arrange y_j into vector *Y*
Arrange x_j into vector *X*
Arrange f_{ij} into vector *F*

To conserve flows at *j* (matrix math):

$$Y = P^T Y + X = [I - P^T]^{-1} X$$

$F = box(YY, P)$ where *YY* is a square matrix whose columns are each vector *Y* and *box(A,B)* is a matrix whose *i, j* entry is $A_{ij} * B_{ij}$

MATLAB Code for the Network

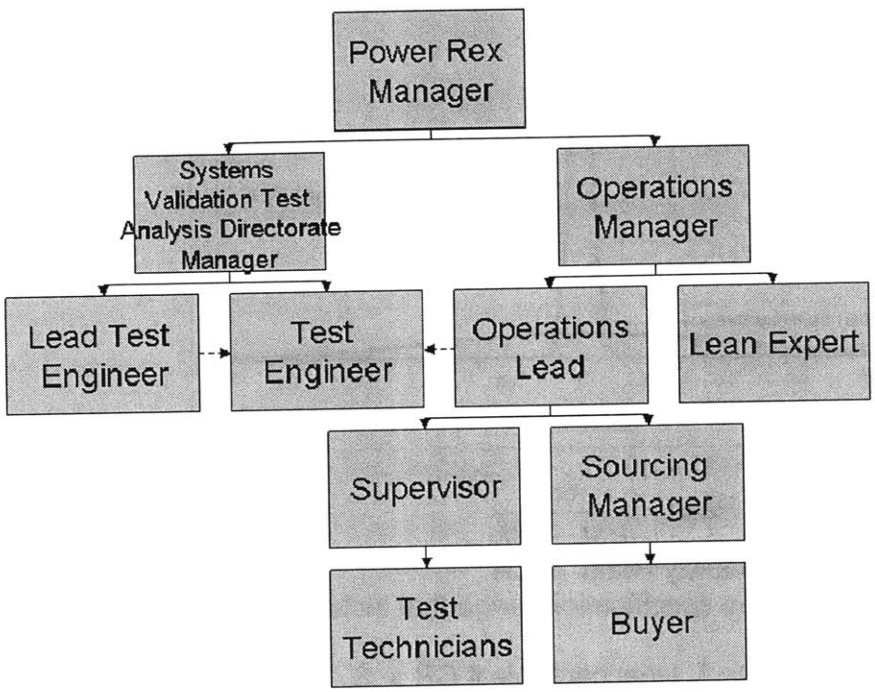
```
P=zeros(14)
C=zeros(14)
P(1,2)=.25
P(1,3)=.25
P(1,4)=.25
P(1,5)=.25
P(6,2)=1
P(7,3)=1
P(8,4)=1
P(9,5)=1
P(2,6)=.45
P(3,7)=.32
P(4,8)=.14
P(5,9)=.21
P(2,10)=.55
P(3,10)=.68
P(4,10)=.86
P(5,10)=.79
P(10,11)=1
P(11,12)=1
P(12,13)=.35
P(12,14)=.65
X=[1 0 0 0 0 0 0 0 0 0 0 0 0 0]
X=X'
Y=inv(eye(14)-P')*X
YY=[Y Y Y Y Y Y Y Y Y Y Y Y Y Y]
F=YY.*P
FF=sum(sum(F))
EX=FF/5
```

Appendix 2 – AC/DC Converter Processes Flow for RSSS Area

Step	Operation Name
20	S-ASY1
30	S-INSPECT1
40	S-ASY2
50	S-INSPECT2
60	S-HIPOT1
70	S-ASY3
80	S-PRETST
90	S-VIBTST
100	S-THERMTST
110	S-ASY4
120	S-ESSINS
130	S-HIPOT2
140	S-ASY5
150	S-INSPECT5
160	S-ASY6
170	S-PRELMTST
180	S-SNAPSTRT
190	S-BURNIN
200	S-FINALTST
210	S-ASY7
220	S-FINISP
9999	S-COMPLETE

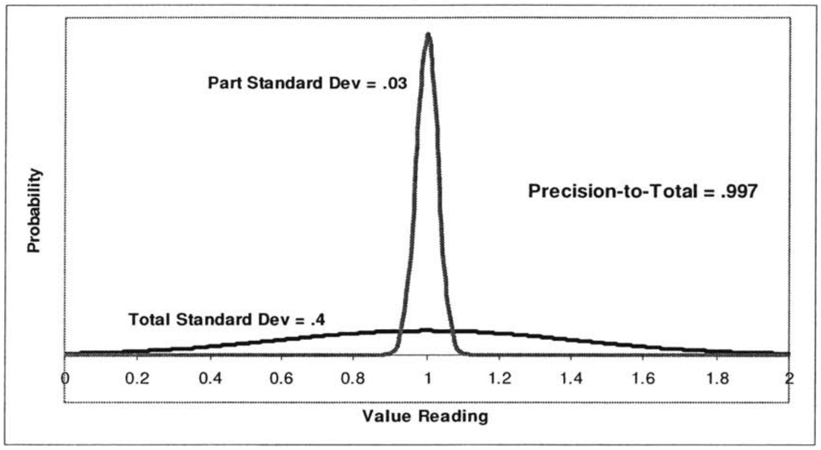
Appendix 3 – Organizational chart of AC/DC test (Power Rex) area

There are many additional dotted lines that are not included in this chart.

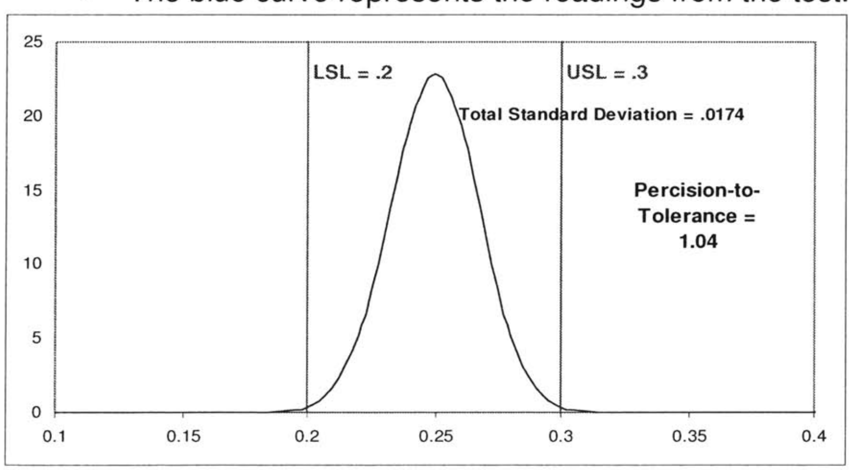


Appendix 4 – Precision-To-Total and Precision-To-Tolerance Ratios

- Precision-to-Total Ratio $= \frac{\sigma_{measurement}}{\sigma_{total}} = \frac{\sigma_{total} - \sigma_{part}}{\sigma_{total}}$
  - Process is capable if Precision-to-Total $\leq .1$
  - Picture of a bad Precision-to-Total
    - The pink curve is the readings if the parts were measured on perfect equipment. The blue is what the readings look like if measured on bad equipment.



- Precision-to-Tolerance Ratio $= \frac{6\sigma}{USL - LSL}$
  - Also called "Capability Ratio" = CR
  - Percentage of the specification range that includes 99.98% of test data
  - Adequate if CR $\leq .1$, Unacceptable if CR $\geq .3$
  - Picture of bad Precision-to-Tolerance
    - The blue curve represents the readings from the test.



Appendix 5 – Measurement Systems Analysis Calculations [10]

These calculations can be done automatically in many software packages including MatLab and SPC XL. The calculations were done in an Excel spreadsheet in this case because only one parameter can be run at a time using the software available to the team.

s = station number (number of stations = ns)
u = test unit number (number of test units = nu)
r = replication number (number of replications = ur)

$$SSA = \sum_{s=1}^{ns} \frac{\left(\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{nu + nr} - \frac{\left(\sum_{s=1}^{ns}\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{ns + nu + nr}$$

$$SSP = \sum_{u=1}^{nu} \frac{\left(\sum_{s=1}^{ns}\sum_{r=1}^{nr} x\right)^2}{ns + nr} - \frac{\left(\sum_{s=1}^{ns}\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{ns + nu + nr}$$

$$SSAP = \sum_{u=1}^{nu}\sum_{s=1}^{ns} \frac{\left(\sum_{r=1}^{nr} x\right)^2}{nr} - \frac{\left(\sum_{s=1}^{ns}\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{ns + nu + nr} - SSA - SSP$$

$$SST = \sum_{u=1}^{nu}\sum_{s=1}^{ns}\sum_{r=1}^{nr} x^2 - \frac{\left(\sum_{s=1}^{ns}\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{ns + nu + nr}$$

$$SST = \sum_{u=1}^{nu}\sum_{s=1}^{ns}\sum_{r=1}^{nr} x^2 - \frac{\left(\sum_{s=1}^{ns}\sum_{u=1}^{nu}\sum_{r=1}^{nr} x\right)^2}{ns + nu + nr}$$

SSR =

$$SSE = SST - SSAP - SSP - SSA$$

$$MSA = \frac{SSA}{ns - 1}$$

$$MSP = \frac{SSP}{nu - 1}$$

$$MSAP = \frac{SSAP}{(nu-1)\times(ns-1)}$$

$$MSE = \frac{SSE}{nu \times ns \times nr}$$

$$P = Max(\frac{MSP - MSAP}{nu \times ns \times nr},0)$$

$$A = Max(\frac{MSA - MSAP}{nu \times ns \times nr},0)$$

$$A \times P = \frac{MSAP - MSE}{nu \times ns}$$

$$\sigma_{\mathrm{Re}\,producability} = A \times P + A$$

$$\sigma_{\mathrm{Re}\,peatability} = MSE$$

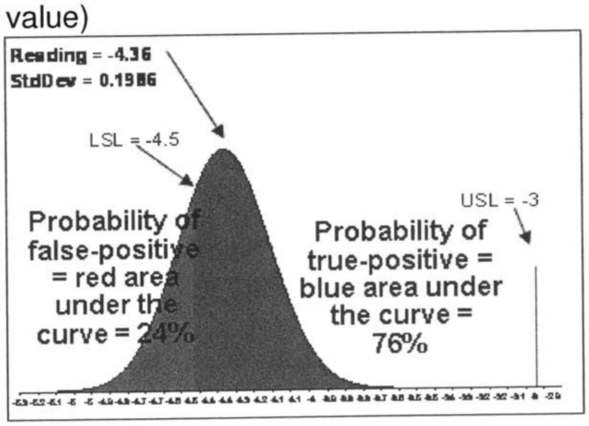
$$\sigma_{MeasurementSystem} = \sigma_{\mathrm{Re}\,producability} + \sigma_{\mathrm{Re}\,peatability}$$

$$\sigma_{Total} = \sigma_{\mathrm{Re}\,producability} + \sigma_{\mathrm{Re}\,peatability} + P$$

Appendix 6 – Probability of False-Positive or False-Negative

The purpose is to find the probably that the test station has historically generated a false-positive or false-negative (also commonly called a type I or type II error) result on the parameter. These are the steps to calculate this value:

1. Using all historical data (or as much as makes sense), find the following values (for each parameter if there are multiple parameters):
    a. The maximum reading that has passed = ap
    b. The maximum reading that has failed = af
    c. The minimum reading that has passed = ip
    d. The minimum reading that has failed = if
2. Find the measurement system variation by performing a measurement system analysis = s
3. Using the normal distribution, calculate the probability that the actual mean falls outside the specification limits (for a false-positive) by using the reading as the mean, the measurement standard deviation. Below are the formulas from Microsoft Excel and an English explanation:
    a. Maximum probability of false-positive
        i. = MAX (NORMDIST(LSL,ip, σ,1)+1-(NORMDIST(USL,ip, σ,1)), NORMDIST(LSL,ap,standard deviation from measurement,1)+1-(NORMDIST(USL,ap,standard deviation,1)))
        ii. = Maximum(area to the left of the LSL + area to the right of the USL for the minimum passing value, area to the left of the LSL + area to the right of the USL for the maximum passing value)
    b. Maximum probability of false-negative
        i. = MAX(1-NORMDIST(LSL,if,σ,1)-1-(NORMDIST(USL,if,σ,1)), 1-NORMDIST(LSL,af,σ,1)-1-(NORMDIST(USL,af,σ,1)))
        ii. = Maximum(area to the right of the LSL - area to the right of the USL for the minimum failing value, area to the right of the LSL - area to the right of the USL for the maximum failing value)



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