Dmarc: A Framework For The Integration Of Dmaic And Dmadv

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DMARC: A FRAMEWORK FOR THE INTEGRATION OF DMAIC AND DMADV

by

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B.S. Embry – Riddle Aeronautical University, 2006

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ABSTRACT

The Lean Six Sigma methodology is being applied extensively to tackle many quality related issues in many processes of today’s industries. Various companies have benefited greatly from the adoption of Six Sigma and Lean engineering concepts since their introduction, and continue to do so. The DMAIC method that is traditionally adopted in the implementation of the Lean Six Sigma methodology has proven to yield cost – saving results in most cases. Yet, industries have found that just improvement of existent process and products to reduce defects, does not quench the customer’s growing thirst for greater quality. In order to tackle variation and defects pro actively, the initiative to achieve Six Sigma level of quality (3.4 DPMO) or greater is being infused into the design of new products using the Design for Six Sigma (DFSS) methodology, through systematic approaches such as DMADV. This research integrates the DMADV approach into the classic DMAIC methodology through a framework, DMARC, which details the improvement an existing process through re – design. It provides a systematic approach to avoid the mis – direction of projects into following the path of continued improvement of existing processes that are deemed to be beyond such efforts . A real – life industrial case: a successfully completed Lean Six Sigma project, tackling the downtime of the Launch Pad Meteorological System at Launch Pads 39A and B at the Kennedy Space Center, was studied to exemplify the possibility of the achievement of greater results from the implementation of the DMARC framework.
This research is dedicated to my parents, Prasad and Rani Vootukuru, who have provided unwavering support and encouragement throughout my M.S. program and my life. I also dedicate this research to my friends (too many to name) for their efforts in retaining my sanity.
ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

AHP   Analytic Hierarchy Process
BVA   Business Value Added
CBA   Cost Benefit Analysis
CCAFS Cape Canaveral Air Force Station
Cp    Process Capability Index
Cpk   Minimum Capability Index
CTQ   Critical – to – Quality
DFSS  Design for Six Sigma
DMADV Define, Measure, Analyze, Design, Verify
DMAIC Define, Measure, Analyze, Improve, Control
DMARC Define, Measure, Analyze, Re-design, Control
DPMO  Defects Per Million Opportunities
DOE   Design of Experiments
FMEA  Failure Mode Effects Analysis
GE    General Electric
HOQ   House of Quality
IDOV  Identify, Develop, Optimize, Verify
KPOV  Key Process Output Variables
KPIV  Key Process Input Variables
KSC   Kennedy Space Center
LCC   Launch Commit Criteria
LCL   Lower Control Limit
LPMS  Launch Pad Meteorological System
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>LSL</td>
<td>Lower Specification Limit</td>
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<tr>
<td>L6S</td>
<td>Lean Six Sigma</td>
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<tr>
<td>MARSS</td>
<td>Meteorological and Range Support Safety System</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<tr>
<td>NVA</td>
<td>Non – Value Added</td>
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<tr>
<td>OEE</td>
<td>Overall Equipment Effectiveness</td>
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<td>SPOC</td>
<td>Space Program Operations Contract</td>
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<tr>
<td>TRIZ</td>
<td>Toeriya Resheniya Izobreatatelskik Zadatch</td>
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<tr>
<td>QC</td>
<td>Quality Control</td>
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<td>QFD</td>
<td>Quality Function Deployment</td>
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<td>QM</td>
<td>Quality Management</td>
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<tr>
<td>UCL</td>
<td>Upper Control Limit</td>
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<td>USA</td>
<td>United Space Alliance</td>
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<td>USL</td>
<td>Upper Specification Limit</td>
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<tr>
<td>VA</td>
<td>Value Added</td>
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<tr>
<td>VOC</td>
<td>Voice of Customer</td>
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<tr>
<td>VSM</td>
<td>Value Stream Mapping</td>
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<tr>
<td>WIP</td>
<td>Work in Progress</td>
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Companies of every contemporary industry, major or minor, strive against fierce competition to stay afloat the ocean of product or service providers that cater to the quintessential customer. Even those companies that have been complacent of their position in their respective industries for a long time are realizing the threats to their dominance from advancing rivals. Managing for quality has exponentially risen in criticality as the demand in quality increased. Traditional management theories are being phased out to overcome the drawbacks that tag along.

Quality Management (QM) concepts have been adopted dramatically over the past few years to counter the rigidity of aged, classical management theories. Developing companies had realized that the primary weapon to stay in or ahead of competition is to please their customer by striving to make products or provide services that satisfy their demands or even exceed their expectations. It had dawned upon most sectors of industry, both service and manufacturing, that trying to reduce the current or persistent defects and variation was not enough to improve quality, but to tackle the problems at the root - during design. Thus, the concept of Designing for Six Sigma standards was born to take the Six Sigma methodology to new heights. Design for Six Sigma is implemented using approaches like IDOV (Identify, Develop, Optimize, Verify), TRIZ (Theory of Inventive Problem Solving) and DMADV (Define, Measure, Analyze, Design, Validate).
The traditional DMAIC method is used to solve issues dealing with current existence of defects and variation, whereas DMADV is used to design new products. In a real-life industrial environment, there might arise a case in which a project adopts the DMAIC approach to improve a process, only to realize that the best improvement gains will result from employing a Design for Six Sigma, or DMADV approach. The best solution then lies in the integration of the DMAIC model with DMADV tools and the concepts of design/re-design. An integration of the DMAIC and DMADV approaches, DMARC, is discussed in this research paper.

DMARC stands for Define, Measure, Analyze, Re-design, Control. It portrays a path that can be used in a case that follows a traditional DMAIC approach in the improvement of a process, product or service but upon recognizing that the process is beyond generic improvement, considers the alternative to re-design instead. Such a case will be explained further in this paper. DMARC is neither a novel nor an out-of-the-box concept, but a framework that explains one aspect of the DMAIC methodology. It provides an option for the consideration of the re-design of a process, product or service, which has been identified in the course of the Analyze or the Improve phase, to be beyond continued improvement efforts. DMARC integrates the DFSS approach and tools through DMADV into DMAIC, demonstrating a shift in the nature of the mindset of the project team as it employs the re-design alternative. The difference in the DMADV and DMAIC will discussed in a later chapter, but in order to have an understanding of the basic concepts of Six Sigma, a literature review is provided as follows.
CHAPTER 2
LITERATURE REVIEW

Quality has been an important issue for any organization for many years. Managing for quality has exponentially risen in criticality as the demand in quality increased. Traditional management theories, though, have been criticized for their drawbacks such as their incapability for self – criticism, the conservative and rigid approach to problem solving. Over the few years, the management revolution called Quality Management (QM) has become a paradigm shift from the traditional management theories, paving a way to improve total organizational performance. QM concepts include Lean manufacturing and Six Sigma methodology, which have been heavily adopted over the years by most industries to reduce waste and improve financial results by increasing the efficiency of involved processes.

The following are short introductions to the QM concepts:

2.1 Six Sigma

The Six Sigma methodology is a business management strategy, that was first developed by Motorola in the mid – 1980s, as a concept or a set of practices aimed at improving manufacturing processes and eliminating defects, but is now currently is applied in a broad spectrum of sectors of industry.

Six Sigma was developed based on preceding QM concepts such as Total Quality Improvement, Quality Control and Zero Defects. Incorporating elements from the work of many quality pioneers, such as Deming, Shewhart, Taguchi, Juran, Ishikawa etc, Six Sigma is a disciplined process that aims for virtually error free business performance. The methodology
measures a process in terms of defects, uses statistical tools to identify the vital factors that matter most for improving the quality of the process and attempts to eliminate defects.

Six Sigma asserts that continuous effort is to be made to achieve consistent and predictable results by reduction of variation. It identifies the characteristics in a manufacturing or service process that can be measured and analyzed for improvement that can be retained. The Six Sigma methodology also emphasizes that sustainable improvement in quality requires commitment from the entire organization, especially the management.

Six Sigma differs from the preceding quality improvement initiatives as in it focuses on achieving quantifiable financial returns from decisions made from concrete data rather than assumptions and an emphasized team structure of champions, black belts, etc. to spearhead the approach. Previous improvement strategies placed little, if any, emphasis on the repeatability and reproducibility of the measurement systems needed for operating the business. Six Sigma takes into account the fact that many companies have inadequate measurement and data collection systems to support modern statistical tools\(^1\).

Sigma (\(\sigma\)) is a Greek letter that represents the standard deviation of a sample population in statistics. When measuring process capability, the standard deviations between the process mean and the nearest specification limit is designated in sigma units. The term "six sigma process" comes from the notion that if one has six standard deviations between the mean of a process and the nearest specification limit, there will be practically no items that fail to meet the specifications. The greater the sigma value, more number of standard deviations fit between the mean and the nearest specification limit.
A Six Sigma process is defined as one that produces 3.4 defects per million opportunities (DPMO). Processes that operate with “Six Sigma quality” over the short term are assumed to produce long-term defect levels below 3.4 DPMO\textsuperscript{4, 5}. Six critical factors that are required for an organization to attain a quality level of Six Sigma are given as follows\textsuperscript{26}:

1. Customer focus
2. Fact-driven management
3. Process focus
4. Down to business management
5. Boundary-less group effort
6. Drive for excellence

In a more practical sense, processes do not perform in the long-term as well as in the short-term. Hence, a sigma shift of 1.5 is introduced to account for the variation in the process, over time, that will cause the sigma levels to drop. According to this idea, a process that fits 6 sigmas between the process mean and the nearest specification limit in a short-term study will in the long term only fit 4.5 sigma – either because the process mean will move over time, or because the long-term standard deviation of the process will be greater than that observed in the short term, or both\textsuperscript{29}. Hence, a Six Sigma process actually refers to a 4.5 sigma level minus the 1.5 sigma shift that is introduced to account for the long-term variation.
2.1.1 Roles in a Six Sigma implementation

In the Six Sigma methodology, key roles are identified to define a hierarchy that carries out the approach, thus professionalizing the different quality management functions. The project team consists of a Sponsor, a Champion, who is capable of selecting, reviewing and evaluating projects. The team leader of a Six Sigma Black Belt project team is usually called a Master Black Belt or Black Belts and team members are known as Green Belts.

2.1.2 Benefits of Six Sigma

The primary benefit of implementing the Six Sigma initiative in a process is that it reduces the number of defects that ultimately reach the customer. Also, it reduces variation in the process, thus allowing sustenance of gains and improvements. Reduction of variation also aligns the process or product to the customer’s requirements, thus satisfying the customer. “The goal of six sigma is that only 3.4 of a million customers should be unsatisfied.” A Six Sigma initiative involves significant support from management and the usage of implementation roles for a Six Sigma project, e.g. black belt, green belt, etc. also builds professionalism in management functions and teamwork. The financial savings are the bottom line savings, which have been evident in many major companies as discussed in the following text.

2.1.3. Implementation of Six Sigma in Industries

In 1988, Motorola received the Macolm Baldrige National Quality Award for launching in the Six Sigma program. Motorola achieved great success in the form of financial saving of billions of dollars from the implementation the Six Sigma concept. The success of Motorola lead
to a widespread interest in the Six Sigma concept that has increased over the years and is now ingrained in almost every industry.

As quoted by Anthony Velocci, Jr, Editor-in-Chief of Aviation Week & Space Technology, “The process-improvement system known as Six Sigma is fast becoming the Swiss Army Knife of aerospace manufacturing: a growing number of contractors see it as a multipurpose tool of choice for reducing costs and improving customer satisfaction.”

In the aerospace industry, there has been a long history of efforts to improve quality, but most of them were not well directed or received till the 1990s, when imminent competition and growing demands of the customer led companies to apply the Six Sigma initiative to their manufacturing operations, and gradually towards services and support functions too. Some programs were successful, whereas others failed.

General Electric and Honeywell International (previously known as Allied Signal), are amongst the companies who have achieved great financial success from the adoption of Six Sigma initiatives. General Electric reports saving approximately $500 - $600 million worth of costs annually as a result of its Six Sigma initiative. By January 1997, no one in GE could be considered for any management job without basic training in the Six Sigma methodology. Similarly, the Six Sigma initiative adopted by Honeywell International has been saving $500 - $550 million worth of costs annually. The companies that have had successful results from implementing the Six Sigma methodology have provided adequate training and experience in the concept and have also applied the approach on a larger scale throughout the organization. Lessons learnt from those whose efforts failed say that the Six Sigma initiative proves to be more
successful if applied with focus on the customer and if the objectives of the implementation are linked to overall business objectives.

2.2 Lean

Lean manufacturing, or lean production, also simply known as “lean”, is a production strategy that has been wider-spread and accepted than any other QM concept. The National Institute of Standards and Technology (NIST) defines “lean” as a systematic approach to identifying and eliminating waste through continuous improvement, flowing the product at the pull of the customer in pursuit of perfection. Lean manufacturing is also known as “lean enterprise” in the service industry.

2.2.1 History

The lean concept has been believed to have begun in Japan, when introduced in a big manner by Toyota in the 1950s\(^1\), but evidence of the following quote shows that Henry Ford has been using some of the lean concept since the 1920s:

“One of the most noteworthy accomplishments in keeping the price of Ford products low is the gradual shortening of the production cycle. The longer an article is in the process of manufacture and more it is moved about, the greater is its ultimate cost.” Henry Ford, 1926\(^1\).

2.2.2 The Eight Wastes

The aim of the lean production concept is the elimination of waste in the process. Waste in the process refers to the activities that are involved in the process that do not provide any value to the objective of the process function.
The lean concept was introduced by the Toyota Production System (TPS) as an effort to reduce their Eight original ‘Wastes’ and to improve the value of the company’s products to the customer. According to Taiichi Ono, the co-developer of the TPS, the Eight Wastes stated below, were suggested to account for 95% of all costs in non–lean manufacturing environments 11:

- Overproduction
- Waiting for logistical supplies
- Transportation
- Non–Value added Processing e.g. reworks, inspection
- Excess Inventory
- Defects
- Excess Motion – poor workflow, poor housekeeping
- Underutilization of mental, creative and physical skills

2.2.3 Lean Toolkit

Lean production provides a lot of tools such as Value Stream Mapping, 5S, poke–yoke (error – proofing), Kanban (pull systems) and Lean Building Blocks to identify and eliminate waste, i.e. the activities in the process that do not contribute any value to the overall result 11. The Lean Building blocks are stated as follows:

- **Pull system:**

  Historically, manufacturers have operated on a Push system – building products per sales forecast, and without any firm impending sales order. Lean production advocates the Pull system technique for production upon customer demand.
- **Kanban:**
  A method for the maintenance of the smoothness of process “flow”. It maintains improvement levels i.e. it is a signaling system that calls for a need for action when the level of improvement is to be addressed. Kanban became an effective tool to support the running of the production system as a whole. In addition, it proved to be an excellent way for promoting improvements because reducing the number of Kanban in circulation highlighted problem areas.

- **Total Productive Maintenance:** TPM advocates the use of preventive maintenance to reduce unplanned and planned downtime, better quality production with lower maintenance cost.

- **5S:** A program that tries to improve productivity and quality through organization, cleanliness and standardization.

  The Five S stands for:\n
  - **Sort** - Clean up and organize
  - **Set in Order** – Identify and organize in the work area
  - **Shine** – maintain cleanliness
  - **Standardize** – Simplify process to make it easy to maintain
  - **Sustain** – Ensure that the organization is maintained.
• **Concurrent Engineering:** A technique of using cross-functional teams (rather than sequential departmental assignments) to develop and bring new products to market\(^\text{11}\).

### 2.2.4 Benefits of Implementation of Lean

The benefits of implementing the lean concept can be seen not just on the operational level, but also throughout the organizational structure. Cycle time, work-in-process (WIP) inventory, processing errors, unnecessary accumulation of documentation, human resource issues are some of the areas where a reduction will be visible. An increase in overall productivity and quality and streamlining of flow will be evident.

### 2.2.5 Barriers to Successful Implementation

Companies that apply the Lean initiative do not experience the benefits to the full effect or sustain the results, due to some of the following reasons:\(^\text{11}\):

- The company does not convert the improvement results to monetary gain, which is the primary advertisement for management to provide support to continue the efforts for maintaining the improvement.
- The company implements the lean building blocks in an incorrect sequence, which worsens the problem instead of alleviating.
- Over emphasis on training than the actual implementation adds no value to the process, thus retarding the lean efforts.
- Lean implementation is done on a small-scale or narrowed into certain projects, instead of expanding it throughout the organizational structure.
The adopted lean culture fails to expand to the supply chain, which is responsible for delays caused in receiving logistics, hence detracting the lean efforts.

Thus, the lean concepts are not to be confined to a small scale within the company, but throughout the organization in order to secure support for continuous improvement in order to sustain the results that are reaped from implementation.

### 2.3 Lean Six Sigma

The Six Sigma methodology is aimed at the reduction of variation in the process, which in turn reduces or eliminates production of defects. The stand-alone methodology does not tackle the issues with the process flow though. On the other hand, lean thinking is aimed at identification and elimination of non-value added activities, which smoothen the process flow. Six Sigma uses statistical tools to define and identify process variation, whereas Lean uses descriptive tools such as flowcharts, value stream process mapping etc to visualize the flow of the process and isolate the waste (non-value added activities).

The limitations of the Six Sigma methodology, with respect to smoothening of process flow, are removed by the integration of Lean thinking and its tools into the approach. The fusion of Lean and Six Sigma, known as Lean Six Sigma, is being adopted widely by many industries in their efforts to refine their processes into providing maximum value at a Six Sigma quality level. The DMAIC methodology is traditionally adopted by many organizations to practice the Lean Six Sigma (L6S) approach.
2.4 DMAIC methodology

The Six Sigma methodology is traditionally applied through a five- phased approach called the Define – Measure – Analyze – Improve – Control (DMAIC) model, which is analogous to the Shewhart’s ‘Plan – Do – Study – Act’ cycle of continuous improvement. An overview of the DMAIC model is as follows:

2.4.1 DEFINE Phase

In this phase of a Lean Six Sigma project, a process is identified to be in need of improvement and the goals of the improvement activity are stated based on the needs of the customer, which are obtained through various forms of communication. The project goals are aligned with the strategic objectives of the company. The problem is clearly defined in concrete measurable terms with the help of tools such as Pareto charts and histograms, which are used to shortlist the target issues. The scope of the project is also charted along with an estimate of the expected results. A stakeholder analysis is performed to identify the key stakeholders involved in the project and a project team is identified in a project charter. Basically, the necessary foundation needed for the implementation of the project is laid out in this phase.

2.4.2 MEASURE Phase

In this phase, the current performance of the process is measured for identified to find the Key Process Variables - the critical measures that affect the success of the project. The L6S team first tries to understand the process through pictorial representations like flowcharts, and then determines the capability of the process and its stability in order to set a baseline for
measurement. After the project has been clearly defined and the process is considered measurable from a set of indicators, the Critical – to – Quality characteristics, also known as Key Process Output Variables (KPOV) are identified by the customer. A clear data collection plan is formed to measure the factors that affect the KPOV and shortlist the Key Process Indicator Variables (KPIV). If the process can be perceived as a \( Y = f(X) \) function, then \( Y \) represents the KPOV and \( X \) represents the KPIV.

![Figure 2.1 Example of a \( Y = f(X) \) function](image)

After the KPIV list is shortlisted, the input variables are prioritized for investigation based upon the magnitude of their effect on the KPOVs, with respect to the defects generated.

With a prioritized list of inputs in hand, the team leader will determine the potential ways the process could go wrong or how the input could go wrong. The best method to do this is an Failure Mode Effects Analysis (FMEA). Once the reasons for input failure are determined, preventative action plans are put into place.
2.4.3 ANALYZE Phase

This phase of the project is the beginning of the attempt to bridge the gap between the desired level of performance of the process and the existing level. It involves the determination of the causes of the problem requiring improvement and analysis of how to tackle those causes, which will help reduce the defects and process variation. This is done through the detailed study of the KPIVs that have been short listed as the factors that are possibly contributing to process variation and affecting the KPOVs most. The prioritization of the KPIVs performed during the Measure phase helps identify which amongst the factors to tackle first. Based on the information found through the Analyze phase, the Improvement phase that follows will see the project team develop various improvement initiatives that are expected to affect the current process dramatically for the better. Although seeking the solutions in the Improvement phase takes more effort and time, due to the magnitude of the change expected to be brought, some quick solutions are implemented during or before the Analyze phase to mitigate the current situation, however minor they may impact.

2.4.4 IMPROVE Phase

The Improve phase is where the project team evaluates the information from the Analyze phase about the major causes of the problem and puts forth various solutions to eliminate or reduce those causes. Of those, the team analyzes and evaluates the solutions through testing, possibly simulation and design of experiments and selects the optimal one(s). The team then develops the implementation plan for the improvement with an approach that encompasses a
management approach that helps the organization to accept, implement and adapt to the changes brought upon by the solution.

2.4.5 CONTROL Phase

In this phase, the project team develops measures to sustain the improvement from the implementation of the solutions during the Improve phase. If the preceding four phases were successful, then the new and improved process with variation eliminated or reduced, is to be made robust against recurrence of problems, may they be of the same or new. In order to ensure that robustness, a stringent monitoring plan that identifies the key stakeholders, a project hand-off process, reaction plans and adequate training resources are the vital activities performed in this phase. Lessons learned are now implemented and tools are put in place to ensure that the key variables remain within the acceptable ranges over time so that process improvement gains are maintained. In order for the improvements to be incorporated into the process accurately and be useful to the whole organization, the original project and the changes are to be well-documented. At the end of the Control phase, the project team transfers ownership and knowledge to the process owner, the customer, with appropriate documentation and a cost benefit analysis of the effort. The final step of the phase is to provide an insight on future improvement opportunities by identifying replication and standardization of opportunities and plans.
2.5 DMAIC Toolkit

The following are some of the tools used in the five phases of DMAIC approach:

2.5.1 DEFINE Phase

- **Affinity Diagrams**: A tool that refines and organizes raw data or ideas (from brainstorming) into categories. In Seven New QC Tools, Ishikawa recommends using the affinity diagram when facts or thoughts are uncertain and need to be organized, when preexisting ideas or paradigms need to be overcome, when ideas need to be clarified, and when unity within a team needs to be created\(^\text{10}\).

- **Interrelationship Diagraphs**: A tool that organizes disparate ideas and defines how they influence one another. For organization of ideas from a brainstorming session, it is best to use both affinity diagrams and Interrelationship diagraphs.

- **Histograms**: A statistical tool that consists of bars (tabulated frequencies of data) that collectively depict a distribution.

- **Project Charter**: Statement of the scope of the project, its goals and its participants. It identifies the roles and responsibilities of team members, stakeholders, the primary objectives and boundaries. A project can be successful with a project charter that clearly defines the resources needed and the scope of the project, or it can fail if the information is not gathered or delineated properly, due to confusion in team efforts and lack of direction.
• **Process Flowchart:** A tool that depicts the activities in a process either in the current state before the improvement effort or the state post-improvement.

• **SIPOC:** SIPOC stands for Suppliers, Input, Process, Output, Customer. It is a flowchart used to show the links between the key elements of a project.

• **Stakeholder Analysis:** A technique for identification of key people that are ‘stakeholders’, or likely to be affected by the outcomes of a project. A stakeholder analysis is performed, typically at the start of a project, to inform the project team of the consequences of any changes being made, who is at the receiving end and how much will they be affected.

• **VOC:** Information gathered from customers on their expectations of a process, product or service.

2.5.2 **MEASURE Phase**

• **Benchmarking:** A process of comparison of an organization’s internal processes, using standard measurements, with other organizations that are considered best in-class, to get a perspective of the organization’s performance. Benchmarking is the identification of best practices that, upon implementation, improves the performance of the organization.

• **Brainstorming:** A creativity technique designed to generate ideas in a free, unstructured manner or in a formalized manner called Nominal Group Technique, which is a method of generating a “short list” of items to be acted upon.\textsuperscript{18}
• **Check sheets**: Data collection tools help understand the problems in a process and measure the effect of process improvement.

• **Cost – Benefit Analysis (CBA)**: A process by which business decisions are analyzed to be monetarily profitable or not. The overall positive and negatives are added up in the financial perspective to identify the option that provides more value to the decision maker.

• **Control Charts**: Also known as Shewhart charts (originated by Walter Shewhart and extended by W. Edward Deming). Control chart is a graph used to study process variation over time and detect special causes of variation. The points plotted are compared against control limits. Any point or a pattern of points that cross the control limits indicates that the process is out of control and requires attention. Control charts are extremely useful in assessing the stability of the process before the improvement and monitoring the stability post improvement. Control charts form part of the monitoring procedures placed in the Control phase.

• **CTQ**: Key measurable characteristics of a product or process [or service] whose performance standards or specification limits must be met to satisfy the VOCs. They align improvement or design efforts with customer requirements.

• **CTQ tree**: The focus of a CTQ tree is to discover measurable critical – to – quality requirements. It decomposes a general, hard to measure, requirement on the left, into more specific, easy to measure variables on the right.
• **Kano Analysis**: A quality measurement tool that classifies and prioritizes customer needs based on their impact to customer satisfaction. Not all customer needs are same or carry the same importance hence this tool is useful to identify the customer needs that carry the most importance in affecting the satisfaction of the majority of the customers\textsuperscript{10}.

• **Pareto Chart**: A histogram that categorizes the data from the largest frequency to the smallest\textsuperscript{6}, which helps in prioritizing the investigation of the causes of a problem. The Pareto Chart illustrates the 80 – 20 Rule, which says that 80\% of the problems stem from 20\% of the various causes.

• **Run charts**: A line graph that helps to understand the level and variation of a quality characteristic over time\textsuperscript{6}.

• **Value Stream Mapping (VSM)**: A vital tool of Lean, that is a visualization tool used to identify and decrease waste in a process. It is a variation of process mapping that analyzes the flow of materials and information that is required to deliver a product or process to a customer. Hence, it is also known as Material and Information Flow Mapping\textsuperscript{18}.

2.5.3 **ANALYZE Phase**

• **Cause – and – Effect Diagram**: Also known as the Ishikawa diagram, after its inventor, Kaoru Ishikawa. It is a graphical method for presenting a chain of causes and effects and for sorting out causes and organizing relationships between variables\textsuperscript{6}.
• **Failure Mode and Effects Analysis (FMEA)**: A systematic approach that is used to identify all possible failures, the effect they have on the system, the frequency and likelihood of occurrence, and the probability that the failure might go undetected. It should be used in the Analyze phase of DMAIC.

• **Process Capability**: A measurement index of a process’s ability to perform within its specification limits. Various indicators are used to measure process capability – some address overall performance, some address potential performance. $C_p$ and $C_{p_k}$ are such estimates of process capability, after the process is found to be in control.

$C_p$ measures the capability of the process with respect to its specification limits and is calculated as follows:

$$C_p = \frac{USL - LSL}{6\sigma}, \text{ where } USL \text{ and } LSL \text{ are Upper and Lower Specification limits of the process respectively}$$

$C_{p_k}$ measures the shift in the process mean ($\bar{X}$) and is calculated as follows:

$$C_{p_k} = \min[C_{p_{upper}}, C_{p_{lower}}] \text{ where } C_{p_{upper}} = \frac{USL - \bar{X}}{3\sigma}, \quad C_{p_{lower}} = \frac{\bar{X} - LSL}{3\sigma}$$
2.5.4 IMPROVE Phase

- **ANOVA Gage R & R**: The Analysis of Variance Gage Repeatability and Reproducibility is a technique that measures the amount of variability induces in the measurements that come from the measurement system itself and compares it to the total variability observed to determine the viability of the measurement system\(^9\).

- **Design of Experiments (DOE)**: Series of tests that are designed to assess the factors that impact the output or the response variable of a process.

- **Poka – Yoke**: An approach for mistake – proofing processes by eliminating simple human error by using automatic devices or methods.

- **Regression Analysis**: A statistical tool for approximating the parameters in a regression model, which is used to predict future observations of the mean response variable.

2.5.5 CONTROL phase

- **Cost – benefit Analysis (CBA)**: A process by which business decisions are analyzed to be monetarily profitable or not. The overall positive and negatives are added up in the financial perspective to identify the option that provides more value to the decision maker.

- **Control Charts**: Also known as Shewhart charts (originated by Walter Shewhart and extended by W. Edward Deming)\(^{22}\). Control chart is a graph used to study process variation over time and detect special causes of variation. The points plotted are compared against control limits. Any point or a pattern of points that cross the control
limits indicates that the process is out-of-control and requires attention. Control charts are extremely useful in assessing the stability of the process pre and post-improvement.

2.6 Design for Six Sigma (DFSS)

The DMAIC methodology has been widely accepted by most industries as the traditional and best practice for the Six Sigma process improvement methodology. A Lean Six Sigma project has become synonymous with the DMAIC approach. However, when the DMAIC approach is being followed in a project for a very long time or in numerous cycles, it becomes apparent that a better approach is needed to address the issue\textsuperscript{24}. Six Sigma is an excellent process improvement methodology that reduces the process variation and strives to eliminate defects. The DMAIC approach is effective in implementing that methodology, but the application of its order and tools is limited to existing, functioning processes that are failing. For brand new processes or services that are being designed to meet the quality standards of Six Sigma, a different method called Design for Six Sigma (DFSS), has been developed.

Design for Six Sigma (DFSS) is a process management strategy that implements the Six Sigma methodology in the design/redesign of processes or services. It is a generic term used to define the approach of different individual methods that try to achieve the Six Sigma level of quality. According to Tennant, it is “a rigorous approach to the design of a new product or service to reduce delivery time and development cost and to increase the effectiveness of the product or service and hence customer satisfaction\textsuperscript{24}”. The objective of designing for Six Sigma is to meet the specific needs and expectations of the customer. Designing a process or service that has a high sigma level, or a very low DPMO, helps achieve that objective. According to
Harry and Schroeder (2000), organizations which have adopted principles and concepts of the six sigma methodology have realized that once they have achieved five sigma quality levels (i.e. 233 defects per million opportunities) the only way to surpass the five sigma quality level is to redesign their products, processes and services by means of DFSS\textsuperscript{2}. This statement has not been supported with concrete data or assumptions used to formulate it, hence it is arguable, but it has been agreed upon by other authors (Chowdhury, 2001; Tennant, 2001). A sigma level of 4.5 (no more than 1 defect per thousand opportunities) is expected of a DFSS process or service, but can be higher than 6 sigma level if the process demands it.

Of the various design methodologies employed by DFSS, \textit{IDOV} is a well-known one, particularly in the manufacturing industry. IDOV is the acronym for Identify, Design, Optimize and Validate. The phases are elaborated as follows:

\textbf{IDENTIFY} - The customer and the needs of the customer, i.e. critical-to-quality (CTQ) specifications are identified at this stage.

\textbf{DESIGN} - In this phase, the CTQs are translated into functional requirements and solutions / concepts are developed. The best solution is selected through a systematic selection process.

\textbf{OPTIMIZE} - This stage involves the optimization of the selected design and its performance through simulation, modeling and advanced statistical tools

\textbf{VALIDATE} - The design chosen, developed and optimized is validated to meet the customer requirements (CTQs) in this stage.

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2.6.1 Typical Improvement projects versus DFSS’s IDOV

Typical improvement projects that implement Six Sigma strive to improve the processes by gradual, continuous improvement, but are bound by the framework of existing processes in the company. These projects are developed from today’s perspective and constrained by the assumptions made during development and design stages. According to Nave, improvement projects generally assume that the design of the product or service is correct and most economical. Another assumption is that the current specification of the process or service satisfies the current market and the design fulfills the customer’s needs. DFSS projects, on the other hand, predict the quality even before the products or services are launched by using the IDOV model.

The IDOV model attempts to design processes and services that are resource efficient, robust to process variability and most importantly, tailored to meet customer demands.

Since, DFSS is a common community term of Six Sigma, IDOV is just one of the models that strive to achieve DFSS goals. Companies employ different methodologies that suit their needs to design / re – design processes of six sigma quality. Of the methodologies, the favorite of most industries is one that does not stray heavily from the classic DMAIC model, called DMADV.
2.6.2 DMADV

DMADV is an acronym for Define – Measure – Analyze – Design – Verify. It is a five phased methodology that is drawn on parallel lines to DMAIC, except that the typical DMAIC approach deals with existing processes that are failing, while DMADV deals with the design / re - design of processes or services.

The five inter – connected phases of DMADV are elaborated as follows:

**DEFINE** - This phase encompasses the definition of the goals of the design activity, per the customer’s demands and in consistency with the company strategy and goals.

**MEASURE** - In this phase, the customer’s needs or the Critical – to – Quality requirements from the customer’s perspective, are measured from customer input. These metrics are translated to project goals. The product capability, risk assessment and the capability of the production process are also measured.

**ANALYZE** - This phase consists of the analysis of innovative concepts and alternatives (benchmarking) for the feasibility of aligning them to the customer requirements, DMAIC’s analyze phase consists primarily of data analysis while it deals with the research and selection of concepts that provide the best value to the customer.

**DESIGN** - The Design phase involves the design of the product, process or service. The design is optimized and its effectiveness in meeting the customer requirements is validated using simulation, prototype testing, DOE etc.
**VERIFY** – This final phase involves the verification of the design to adapt to the real-world environment, before it enters full production.

A slight modification of the DMADV methodology is the *DMADOV* model (O representing Optimize), which has formed the current DFSS approach adopted by GE, Corp\(^{26}\). It enforces more measurement and optimization regulations to the design.

"This may take a few people by surprise, but per Piet van Abeelen (GE Corporate VP of Six Sigma), DMADV is 'Six Sigma for poets', therefore no longer in the eyes of GE a valid roadmap for transactional companies to circumvent the measurements required by DMAIC (most often by simply replacing baseline measurements with a QFD)\(^{26}\). The roadmap for DFSS at GE is now DMADOV, with measurements and optimization steps strictly enforced. Because of the nature of the newly re-defined DMADOV, it is used for new product introduction or large enterprise-wide processes\(^{26}\).

### 2.6.3 DFSS Toolkit

DFSS methodologies share many tools with the DMAIC model e.g. Affinity Diagrams, check sheets, brainstorming and FMEA, but the focus of DFSS tools is primarily on customer analysis (identification of needs and expectations), the translation of customer requirements to process requirements, defect and cost reduction. Some tools used are fundamental in any DFSS approach, while others vary with respect to the type of design effort – product, process or service.
• **Voice of Customer (VOC) analysis**: Analysis of the needs of the customer in a much more detailed manner in an attempt to tailor the product or process to meet the customer’s expectations. The VOC is gathered through surveys, focus groups, letters etc.

• **Measurement System Analysis (MSA)**: An experimental and mathematical method of determining the variation within the measurement process that contributes to overall process variability. The five parameters to investigate in an MSA: bias, linearity, stability, repeatability and reproducibility.

• **Quality Function Deployment (QFD)**: A structured process that establishes customer value using the VOC and transforms that value to design, production and manufacturing process characteristics. QFD is used to record the VOC info, prioritize, weigh and link with technical and benchmark attributes in matrices that are fitted together like a house. Hence, QFD is also known as House of Quality.

• **Pugh Selection Matrix**: A decision analysis tool that can be used to select a solution amongst alternatives, based on chosen performance metrics. A list of alternatives that are compared to one another based on the customer requirements taken from CTQs and the concept that aligns best with the requirements is determined to be the best solution.

• **Monte Carlo Simulation**: A method that uses computer algorithms that use repeated random sampling to simulate a model that can be used to identify, measure and root out the causes the variability in production and service processes and designs. Monte Carlo simulation performs and optimizes tolerance analysis – it simulates and predicts potential
percentage of scraps, depending upon combinations of nominal design values and process variation\(^{16}\).

- **TRIZ**: Acronym for Toeriya Resheniya Izobreatatelskik Zadatch, or Theory of Invention Problem Solving\(^3\). TRIZ is an evolving tool set and methodology that was developed in the Soviet Union in the 1940s, by Genrich S. Altschuller\(^3\). It is a problem solving method based on logic and data. TRIZ is a systematic approach, contrary to random approaches like brainstorming, which are based upon intuition and the knowledge of team members and typically produce unrepeatable results. TRIZ emphasizes repeatability and predictability through its algorithmic approach\(^3\).

- **Design of Experiments (DOE)**: Series of tests that are designed to assess the factors that impact the output or the response variable of a process.
CHAPTER 3
REASON FOR RESEARCH

Companies have associated DMAIC as the generic methodology in the implementation of Lean Six Sigma. Since the advent of DFSS, approaches like DMADV and IDOV are being gradually adopted as alternatives to DMAIC, but the question arises as in when to use a traditional DMAIC process or DMADV.

3.1 DMAIC vs DMADV

In order to understand which methodology, DMAIC or DMADV, to follow for a fruitful success of the project, it is important to understand the differences between the two. The following table shows a detailed description of those differences:

Table 3.1: DMAIC versus DMADV

<table>
<thead>
<tr>
<th>Phase</th>
<th>DMAIC</th>
<th>DMADV</th>
</tr>
</thead>
</table>
| DEFINE | **Project Objectives** - Defect and process variation reduction in an existing process or product  
  **Scope** - Defined and bound by the existent problem  
  **Returns** - Returning savings to the bottom line; reduction of cost of poor quality  
  **Customers** - Those impacted by the problem  
  **Key Requirements** - the critical and satisfying requirements are that the solution to the problem improves the primary output variable (Y), while ensuring the consistency of improvement  
  **VOC data gathering** - of a investigative nature | **Project Objectives** - Identification and development of a new process, product or service that provides best customer satisfaction  
  **Scope** - Broad, defined by potential opportunity  
  **Returns** - Generating increased revenue to the top line  
  **Customers** - Prospective market, internal or external, that the process or product can cater to  
  **Key Requirements** - Critical and satisfying requirements are considered baseline, but latent requirements are to be paid attention to  
  **VOC data gathering** - of an exploratory nature |
<table>
<thead>
<tr>
<th>Phase</th>
<th>DMAIC</th>
<th>DMADV</th>
</tr>
</thead>
</table>
| MEASURE    | **Key Variables (output and input)** - Categorization based on the location of existent problem and existent effects  
**Data collection** - Data is collected, using the current state of the process as the basis of facts, is used to identify the root causes for the problem | **Key Variables (output and input)** - Categorization based on the potential problem and predicted effects  
**Data collection** - Data is collected, with or without a current state of the process, to identify and prioritize requirements, including latent ones. |
| ANALYZE    | **Process Capability determination** - The capability of the process is determined directly from the performance of the process in its current state.  
**Key sources of data** - Current and historic process data  
**Verification of root causes** - The relationships between KPIVs and KPOVs are known, hence the focus is on quantification of the relationship | **Process Capability determination** - The capability of the process is predicted from the performance of a relevant process in its current state.  
**Key sources of insight** - Benchmarks, prototypes  
**Verification of root causes** - The relationship between the KPIV and KPOV is new and may vary by the design selected. Modeling of designs enables estimation of the relationship |
| IMPROVE    | **Improvement verification** - Pilot testing of improvements | **Improvement verification** - Modeling and simulation results |
| CONTROL    | **Methods** - Control Procedures | **Methods** - Control Procedures |

The main answer to the question – “DMAIC or DMADV” lies in defining the main purpose of the project: if it is improving an existing process or creating a new process or service, or even re-designing an existing process that is pointless to improve upon because the fundamental design is discrepant.

As stated in the table above, the difference in the DMAIC and DMADV methodologies is not just in the tools that are being used or the purpose they are used for, but also in the nature of the project employing either of them. The two methodologies have the first three phases (D, M, A) with the same names – Define, Measure and Analyze. What does vary, is the mindset and focus of the project team that applies one approach versus the other, as it goes through the three phases of the project. The focus in the data collection, analysis of the problem, and the nature of
the problem solving are quite different through the DMAIC approach, compared to that of DMADV’s. DMAIC problem-solving calls for a "detective" orientation, looking for clues and focusing on specific root causes, whereas innovation/design calls for an "anthropologist" orientation, looking for how people do things (or could do things), clues about latent requirements and measures that identify performance drivers. While both of these orientations move through a "D, M and A" stage, they have a different scope and flavor.

In a real–life industry environment, a Lean Six Sigma project is typically synonymous with the DMAIC approach. There exists a danger of not realizing that it truly is of a DFSS / DMADV approach, until improvement efforts are developed based on the analysis of the problem and realizing that the customer requirements are not met completely. In such cases, the improvement efforts of the project might not seem to reap adequate results or the project might just fail if the process is beyond improvement over its current state. The Define, Measure and Analyze phases of a DMAIC project shed light on the cause(s) of the variation in the process, hence a team has to go through the three phases to understand the problem clearly, in measurable terms. If during the Improvement phase, there is a conscious decision made based on quantified data and financial assessment, to either improve on the existing process or re–visit its design, an integration of the DMAIC and DMADV phases will bring out a DFSS perspective to the project. Employing DFSS tools to assist in the re–design of the existing and failing process, product or service will help eliminate chronic maintenance of improvement efforts. The purpose of this research is to present a framework that integrates the DMADV and DMAIC methodologies to provide an option for the re–design of an existing process, product or service using the DMADV approach, in a project that is typically DMAIC.
CHAPTER 4
DMARC

This framework describes the approach of a typical DMAIC project, dealing with an existing process, product or service that has completed the Define and Measure phases and is in the Analyze phase, considering options for improvement as it progresses into the Improve phase. The analysis of KPIVs and process variation leads to the development of initiatives that attempt to improve the process by elimination of variation, but when improvements made / projected do not satisfactorily achieve the goals of the project or leaves scope for persistence of variation, revisiting the fundamental design of the process is to be considered. A design change to a process, product or service means more expenditure of resources, a shift in the nature of the project and request for support from the management and most importantly, the customer. A decision to re-design the process or product should be proposed based on numerical, statistical data. Decision-making tools, such as Analytical Hierarchy Process (AHP), benchmarking or cost-benefit analysis of a design / equipment change assist in assessing the value of such an effort in comparison to viable initiatives of improvement to the existing system.

In the case of a decision to re-design being considered to be more fruitful, then the classic DMAIC methodology takes a different path, one that incorporates the DFSS approach for re-designing purposes, called DMARC.
DMARC stands for five phases - Define, Measure, Analyze, Re-Design, Control. The Re-Design phase is a collective term for the Measure-Analyze-Design-Verify phases of DFSS perspective, borrowed from DMADV methodology. The Define phase of the DMADV methodology is not necessarily to be re-lived, as the main project objective is unchanged from the beginning of the project, to provide what the customer has asked for.

The following figure describes the framework in the form of a process flow:

Figure 4.1: Flowchart of the phases of DMARC
The DMARC phases can be summarized as follows:

**Table 4.1: Description of DMARC phases and tools**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activity</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define</td>
<td>Problem, project objectives, scope are defined.</td>
<td>Project Charter, Process Map, VOC tools, Stakeholder's Analysis</td>
</tr>
<tr>
<td>Measure</td>
<td>Current performance of process is measured. Data is plotted and analyzed for variation causes</td>
<td>Typical DMAIC Measurement tools e.g. Control charts, Run Charts, MSA, Process Capability Analysis</td>
</tr>
<tr>
<td></td>
<td>KPOVs, KPIVs are measured</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Process Capability, Stability (Control) are measured and baseline is established.</td>
<td></td>
</tr>
<tr>
<td>Analyze</td>
<td>KPIVs are analyzed to identify causes and major contributors of process variation, defect analysis.</td>
<td>DMAIC Analysis tools e.g. Cause and effect chart, FMEA, X and Y analysis, Brainstorming</td>
</tr>
<tr>
<td></td>
<td>Improvement concepts are developed and analyzed for impact on the process. If continuous improvement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>on existing process is found to be pointless or inadequate, re-design options are put forth for</td>
<td></td>
</tr>
<tr>
<td></td>
<td>consideration.</td>
<td></td>
</tr>
<tr>
<td>Re - Design</td>
<td>Decision to re-design is made based on numerical and statistical data, management and customer</td>
<td>Decision analysis tools e.g. Analytical Hierarchy Process, Cost - Benefit Analysis, Benchmarking</td>
</tr>
<tr>
<td>Measure</td>
<td>The VOC is captured in a DFSS perspective to capture customer needs in further depth, in alignment</td>
<td>DFSS approach VOC tools, Kano Analysis, QFD - HOQ, Risk Assessment, Process and product capability</td>
</tr>
<tr>
<td></td>
<td>with the company and project objectives.</td>
<td>measurement</td>
</tr>
<tr>
<td>Analyze</td>
<td>Selection of best solution amongst alternatives</td>
<td>TRIZ, Hypothesis Testing, DFSS approach, Decision analysis tools e.g. Pugh Matrix, AHP</td>
</tr>
<tr>
<td>Design</td>
<td>Re-design current process / Design the corrective process</td>
<td>Prototypes, pilot runs</td>
</tr>
<tr>
<td>Verify</td>
<td>Verification of performance of design change and ability to satisfy customer needs</td>
<td>Predictive models, simulation, pilot testing, Taguchi's robust engineering</td>
</tr>
<tr>
<td>Control</td>
<td>Establishment of control procedures for sustenance of gains</td>
<td>Control charts, written procedures</td>
</tr>
</tbody>
</table>
4.1 Decision to Re-design

How do companies make the decision on whether an existing process or service can be improved upon, or it is beyond improvement such that the very design has to be looked into for change? Initiating an effort to design / re-design requires management support and customer approval, which is acquired only through the use of numerical evidence. The benefits of undertaking such is to be ascertained through thorough study of the expenditure (financial and resources) involved and adequate comparison of the alternatives. Tools like Analytical Hierarchy Process (AHP) help determine the suitable use of redesign alternative over the improvement option.

Analytic Hierarchy Process is a multi-criteria decision making tool that was developed by Saaty. It can be used to make critical decisions based on numerical evidence in the form of the comparison of alternatives against one another to select the one that carries most weight. In AHP, a hierarchic or network structure is used to simplify and represent the decision problem with its criteria and alternatives. At each level of the network or hierarchy, pairwise comparison values of decision elements are used to determine the priority weights of the criteria.

AHP uses the following five steps to solve decision problems:

1. The decision problem is broken down to a hierarchy of decision elements. In other words, fundamental objectives of the process in question are identified as categories carrying weight against one another.
2. A pair-wise comparison, is performed for each decision element (and for criteria and sub-criteria).
3. The relative weights of the decision elements are calculated.

4. The input data is verified if it satisfies a consistency index and if it does not, the process re-iterates back to Step 2.

5. The relative weights are aggregated to obtain the final scores to see if the initiative to re-design outweighs the initiative to improve upon the existing design.
The following figure is a flow chart of the overview of the steps involved in the AHP process:

Figure 4.2: AHP Flow Chart\textsuperscript{2}
The following figure describes a generic AHP network that can be used to make the decision (based upon priority weights of the factors) on whether to pursue the re-design of an existing process or to improve upon it:

![Generic AHP network for decision-making on re-design](image)

Figure 4.3: Generic AHP network for decision-making on re-design
CHAPTER 5
CASE STUDY

5.1 Launch Pad Meteorological System

Since the late 1960s, Pads A and B at have served as backdrops for America's most significant manned space flight endeavors - Apollo, Skylab, Apollo-Soyuz and Space Shuttle.

Of all the numerous launch pads that have been used since the advent of America’s space flight endeavors, Pads A and B at the Kennedy Space Center, located in Cape Canaveral, Florida, are the operational ones from which the Space Shuttle is being launched.

Both the launch pads are equipped with a meteorological system that provides constant weather data that is used to make a decision on a space shuttle launch and landing, provide weather warnings and advisories for the Kennedy Space Center and Cape Canaveral Air Force Station Operations and many more. The meteorological system at each pad consists of equipment mounted on two 60 foot weather towers, located at Camera Sites 3 and 6, as shown in the figure below:
Figure 5.1: Location of LPMS
5.2 Company Profile

United Space Alliance (USA) is a limited liability company that was formed in 1995 by The Boeing Company and Lockheed Martin under equal ownership. It serves as the Space Program Operations Contractor (SPOC) to NASA in handling human space operations, including the Space Shuttle and the International Space Station. USA is headquartered in Houston, Texas and has employees working in Florida, California, Washington D.C., Alabama and Russia.

The Launch Pad Meteorological System and the data produced are primarily handled by the Ground Instrumentation Engineering department of the Ground Operations division, located at Kennedy Space Center, Cape Canaveral, Florida

Source: United Space Alliance Intranet Home Page
5.3 Equipment

The Meteorological System’s equipment mounted on each weather tower are of the following types:

The following equipment, or transducers (excluding cables and power supply equipment) consist the Launch Pad Meteorological System (LPMS) at each of the launch pads A and B.

Table 5.1: List of Met. System Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Transmitter Purpose</th>
<th>Quantity Required at each Pad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climet 011-4</td>
<td>Wind speed</td>
<td>2</td>
</tr>
<tr>
<td>Climet 012-16</td>
<td>Wind direction</td>
<td>2</td>
</tr>
<tr>
<td>Rotronic I-200</td>
<td>Relative Humidity</td>
<td>4</td>
</tr>
<tr>
<td>Rotronic HT205</td>
<td>Temperature</td>
<td>4</td>
</tr>
<tr>
<td>ORG-815</td>
<td>Rain gauge</td>
<td>2</td>
</tr>
</tbody>
</table>

The data obtained from these equipment is used for the following:

- To determine if conditions qualify the Launch Commit Criteria prescribed per NASA 16007 document
- Support the Meteorological and Range Support Safety System (MARSS)
- Support daily operations for safety analysis
- Weather warning advisories to KSC, Cape Canaveral Air Force Station (CCAFS) operations.
5.4 Problem Statement

It is an absolute NASA requirement that the Launch Pad Meteorological System be operational during all launch operations. The meteorological system experiences downtime when an unplanned event causes the system to go offline or for scheduled preventive maintenance of the equipment. Over the few years, the LPMS saw an excessive amount of downtime due to field equipment defects. Baseline data gathered between years 2001 – 2003 from United Space Alliance’s Maximo Database showed that there has been a worrying increase of system downtime, with a record high of 134 days in 2003.

Figure 5.2: Comparison of Met. System downtime (in days) from 2001 – 2003
The downtime data was used to determine the Overall Equipment Effectiveness (OEE), which is the amount of time the system is producing credible and accurate data.

For around – the – clock operation, the LPMS has to have an optimum OEE of 98%. Cumulative data from years 2001 to 2003 indicated an actual OEE of 71% for the three year span, identifying a need for improvement. In order to increase the OEE to an optimal level, the system downtime period required effective reduction.

Analysis of downtime occurrences showed that in 2003, 70 % of the system downtime was due to field equipment related defects resulting in unscheduled downtime for either maintenance or repairs or transducer replacements. It seemed critical that the factors for unplanned and planned downtime be studied and analyzed for providing solutions to the overall improvement of the effectiveness of the system.

5.4.1 The Project Team

A Six Sigma team was formed by United Space Alliance system engineers and technicians, headed by a Six Sigma black belt, to undertake the initiative to improve the effectiveness of the LPMS in reporting accurate and reliable data with decreased downtime. The project was sponsored by the Ground Operations division of United Space Alliance at Kennedy Space Center. As part of the Six Sigma culture that has been adopted by USA for problem solving and continuous improvement, the traditional DMAIC path was utilized as the approach to this project. Upon approval of the project, it was classified as a Green Belt project with an expected lifespan of seven months. The DMAIC method phases shall be described as follows:
5.5 DEFINE Phase

The Define phase of the DMAIC methodology involved the identification of the project purpose and scope, its goals, the benefits of the desired results, organization of the team and process descriptions.

Following the typical Define phase, the project goals, scope, team members and stakeholders were identified.

5.5.1 Project Scope

The LPMS downtime reduction project was constrained by its boundaries, such as it dealt only with the meteorological system at pads consisting of the humidity measurement transducer, wind direction and speed transmitters. It did not account for change in support requirements. Special causes such as wild life collisions or tampering, lightning, or facility power issues were also not taken into consideration when analyzing the data acquired. It is important to note that a change in equipment or design change was neither out of scope nor considered as an initial option. The project nature was towards analyzing the current state of the system and developing improvement solutions.
5.5.2 Project Goals

The basic goals of the project were as follows:

- Eliminate unplanned downtime due to common causes
- Reduce planned downtime to 30% of current amount.
- Improve the Overall Equipment Effectiveness (OEE) from 71% (as derived from the cumulative data of three years, 2001 – 2003) to 90%
- Establish a more accurate / detailed resource tracking method, which includes the logistics and labor resources used.
- Support USA Vision Support Plan (VSP) goals
  - VSP Goal 1: Provide safe operations for all aspects of the business of United Space Alliance
  - VSP Goal 2: Achieve excellent customer satisfaction and program performance
  - VSP Goal 3: Achieve outstanding quality in all aspects of United Space Alliance’s business

(A full list of USA’s VSP goals can be found in Appendix A).
5.5.3 Project Benefits

The overall benefits expected upon project completion was projected and summarized in as follows:

- Financial

  This project will provide for a significant type C soft Savings that will result in reduced labor resource use that can be reallocated to other work/needs.

- Safety

  Reducing downtime will provide for more accurate weather monitoring used for warnings, and watches for center wide operations.

  Reducing the amount of times the weather tower is raised/ lowered will reduce the number of times the technicians are exposed to the hazards of the operation.

- Customer Satisfaction

  A reduction in downtime will increase the quality of our data, and the satisfaction of weather data customers.
A SIPOC was drafted to identify the key stakeholders in the project as follows:

![SIPOC model of Met. system](image)

**Suppliers**

- The Calibration Lab that calibrates the Relative Humidity and performs the preventive maintenance and calibration of the equipment
- The Logistics department that supplies the equipment spares and tools needed for preventive maintenance.

**Inputs**

- The major inputs that are involved with the Met. System are the observations / data provided by the system and calibration cycles, which are scheduled periodically for the calibration of the equipment.

**Process**

- The function of the Met. System in acquiring and recording data in the Maximo system
- Preventive and corrective maintenance process of the LPMS equipment
Output

Valid Weather Data is considered the ultimate output. As described earlier, the weather data is necessary to be accurate for the various purposes used for at Kennedy Space Center.

Customers

There are both external and internal customers, who benefit from the valid weather data provided by the LPMS.

- The Launch Commit Criteria, which is used by NASA and its space flight contractors at KSC, formulates forecast based on the weather data, made available by all the meteorological sensors at pads A and B (camera sites 3 and 6) and selectively uses the data provided by the wind tower sensors to represent the most consistent wind velocity effect on the Space Shuttle Vehicle.
5.5.5 Process Maps (As – is condition)

In order to understand the basic processes that involve investigation of defective equipment and re-calibration of replaced equipment as performed at the beginning of the project, process maps were drawn in the form of flowcharts.

Calibration R & R Process Map

Calibration of replaced equipment was performed as displayed in the following process map:

![Calibration R & R Process Map](image)

Figure 5.4: The Calibration R & R Process Map (current)
**Defect process map**

The following map shows the process that is involved when equipment is reported or suspected to be defective:

![Defect investigation process map](image)

Figure 5.5: Defect investigation process map
5.5.6 Voice of Customer

In a traditional DMAIC project, the Voice of the Customer is obtained and the result is oriented based upon those expectations, but most projects do not emphasize acquiring an assessment of the customer’s expectations as detailed as in the Define phase of a DFSS project. The customer’s expectations are usually vague when initially obtained. In this case, the VOC that was obtained from the customer(s), who were identified collectively in the SIPOC, proved to be a typical example.

The primary concern of the customer was that the LPMS must be operational during all launch operations as required by the Launch Commit Criteria specified by NASA document, NSTS 16007, and that it should report accurate, valid data on relative humidity, ambient temperature, and wind speed that would be used to formulate forecast conditions for launch.

Other concerns included that the overall downtime period be reduced to increase the quality of the data being received, the need for 24/7 coverage of weather, proper organization of scheduled maintenance and the general mindset that had been inculcated amongst the people who are involved in handling the LPMS, in accepting that there will be problems associated with the current state and functionality of the system.

On the other hand, some of the positive comments that were received about the pre-project functionality of the LPMS included the accuracy of the system at the launch pads, the responsiveness of engineering staff, and that the system status was well communicated by team members to one another.
5.5.7 KPOV and KPIV

Based on the VOC that was obtained and the process maps, the Key Process Output Variable (KPOV) to be measured was determined. All the equipment defect issues, calibration cycles, scheduled preventive maintenance cycles etc. contribute to the downtime of the LPMS. Hence, it was appropriate to choose the KPOV to be the amount of support downtime.

The Key Input Variables of the LPMS to be analyzed were determined to be the calibration cycles, the preventive maintenance schedule that caused planned system downtime, maintenance methods, resource (time / labor) tracking methods, and special tests.

KPOV:

- Amount of System downtime

KPIV:

- Calibration cycle
- Maintenance schedule
- Maintenance methods
- Resources ( labor / time) tracking methods
- Special causes
5.6 MEASURE Phase

The Measure phase involved the identification of the Critical to Quality parameters that are influenced by the KPIVs and the measurement of those KPIV processes, by generating detailed task specific process maps that help determine and distinguish value added time from non-valued added time. Also, the Mean Time Between Failures (MTBF) was determined for those measurements. Other important measurements that were taken were the amount of false defects, and variation in specific measurements.

The Gage Repeatability and Reproducibility Test (Gage R & R) was performed on field standards used for the set-up of field measurements, and validation of the calibrations of the wind speed and wind direction transducers by the Calibration Lab.

5.6.1 Critical to Quality Characteristics

The CTQs were identified from the received feedback through surveys sent through e-mail and verbal conversation with the external customers, primarily the NASA KSC Weather Office, the Range Operation Control Center (ROCC) and ATK Thiokol (involved in Solid Rocket Booster processing).

Critical to Quality factors are defined as the measures or proxies (related measure(s) predictive of what is desired) of the what is important to a customer (8).
In this case, the CTQs were identified as follows:

- Maintaining 24/7 operation of system
- Maintaining Launch Commit Criteria (LCC) status on system.

It is important to note that the requirements to maintain the Launch Commit Criteria status on the system and its round–the–clock operation is more necessary than the accuracy of the data provided by the system. That fact was asserted by one of the key members of the project, that the disparity in the measurements of the transducers at Camera Sites A and B at each Pad, was originally not allowed much leeway, thus scheduling more downtime in the process of tackling the discrepancy or defect.

5.6.2 KPOV Measurement

The KPOV for this project was identified as the amount of downtime of the system. In the Define phase, the amount of downtime that occurred from years 2001 – 2003 was measured and discussed. In the Measure phase, the number of downtime events, both planned and unplanned, that occurred from years 2001 – 2003 were measured as follows:
As inferred from the chart above, there has been a gradual increase in the number of downtime events happening over the three years. To identify the locations of the occurrences, the patterns of the downtime events were charted out for the three years. The events were seen to be dispersed in a similar manner for the three years. In 2003 though, there were 5 special cases – four lightning strikes and a bird strike that were omitted from the measurement of the downtime as per the scope of the project.
5.6.3 **KPIV Measurement**

The Key Process Input Variables affecting outputs were selected as follows:

- Transducer calibration cycles
- Maintenance of field equipment
- Transducer defects
- Field equipment defects

5.6.4 **KPIV Process Maps**

A Value Stream Map (VSM) was charted for each KPIV. The VSM is used to separate the Value Added (VA) activated from the Non – Value Added (NVA) activities. The identified Non – Value Added activities are analyzed for minimization or even elimination.

The Value Added activities are of two types:

- Customer Value Added (CVA) activities are those that accomplish the customer expectations.
- Business Value Added (BVA) activities are those that are required by law or regulations.
The typical calibration cycle for the transducer was mapped out in the form of a Value Stream Map (VSM) as follows:

![Value Stream Map of calibration cycle]

Figure 5.7: Value Stream Map of calibration cycle

From the process VSM that was charted out, it was determined that it took an estimated 12 hours to replace a transducer, calibrate it and validate the calibration.
The typical process for scheduled maintenance of field equipment (non-transducers) was mapped out in the form of a Value Stream Map (VSM) as follows:

![Value Stream Map]

Figure 5.8: Value Stream Map of scheduled maintenance of field equipment

From the process VSM that was charted out, it was determined that it took an estimated 5 hours to perform scheduled maintenance of field equipment (non-transducers).
The typical process for the investigation of field equipment (non-transducers) and transducer defects, was mapped out in the form of a Value Stream Map (VSM) as follows:

Figure 5.9: Value Stream Map of transducer defect investigation

From the process VSM that was charted out, it was determined that it took an estimated 5 hours if no equipment was replaced, and took 15 hours if there was an equipment replacement performed.
5.6.5 *KPIV Pie – Chart*

The number of downtime events that resulted from each of the KPIVs were measured and charted as a pie – chart as follows:

![Pie Chart]

**Figure 5.10: KPIV Pie Chart**

Reduction of the number of defects is critical to achieving the project’s goal of increasing the OEE. From the pie – chart, it was noticed that 48 %, i.e. 74 out of 154 downtime events, was due to calibration issues, which provided the team an indication that the reduction of the number of calibration cycle events would have a significant impact of number of downtime events. On
the overall, 80% of the total downtime events were noted to be due to equipment defects and calibration issues.

The huge contribution of downtime by equipment defects was further analyzed by plotting the variation of defects, amongst the transducers involved in the LPMS, in the form of a pie–chart as follows:

![Pie-Chart of Transducer-Caused Defects](image)

**Figure 5.11: Pie-chart of transducer - caused defects**

Of the transducers, the relative humidity and wind direction sensors contribute most for the defect caused downtime, which indicated that analyzing the related discrepancies could significantly impact the downtime.
5.7 ANALYZE Phase

The ANALYZE phase involved the study of the factors that were identified, during the measurement of the KPIVs in the MEASURE phase, as the larger contributors to the LPMS downtime. The focus of the Analyze phase was to analyze the following issues:

- The calibration cycle and the maintenance process for set – up reduction opportunities
- The primary common causes of defects

5.7.1 KPIV – Calibration Cycle

As the Calibration Cycle is the largest KPIV to the amount of downtime, its current state was analyzed and noted as follows:

- Relative Humidity – 5 months
- Wind Direction – 12 months
- Wind Speed – 12 months
- Barometric Pressure – 17 months
- Rain Rate – 24 months

According to a downtime event pattern charted out for the year 2003, it took approximately 12 man hours to change out a transducer on a calibration cycle. 9 of those hours were for the setting up of the equipment or breaking it down.
The stated problem with the calibration cycle was that it was not synchronized, which caused a scattered pattern in the indication of the downtime events and time traps in the set up or breakdown of a transducer change – out process. The proposed solutions were to synchronize the calibration and tower Preventive Maintenance cycles and to eliminate the variation in the cycles to take advantage of the reduction of the setup time through the synchronization.

Some changes to the calibration cycle were suggested as follows:

Since there are 4 towers with 5 – 7 transducers each, synchronization of the calibration cycle and preventive maintenance downtime to 5 months, or multiple of 5 months would greatly reduce the amount of planned downtime events, as well as the number of man hours used through the setup process.

A projection of the implementation of the 5 month calibration cycle theory, in the year 2003, showed that there would be 22 less downtime events and a 38% reduction in events for approximately 264 man hours based on process map estimates.

Application of the suggested calibration cycle in the year 2003 would’ve increased the OEE significantly from 64% to 74%. That would contribute in achieving one of the project goals of improving the OEE from 71% to 90%. Also, it was projected that there would be a 68% reduction in planned downtime, which achieves the project goal of reducing planned downtime by 30%.

It was also projected from a chart, as shown below, a 5 month cycle would have prevented 10 defects over all, barring the possibility of defects of replacement transducers.
An overall projection of the impact of the synchronization of calibration cycles, showed the following:

- A reduction of man-hours spent by 48% through set-up reduction (450 from 891, years 2001-2003 data)
- Elimination of the WAD creation step provided a slight gain of time using set-up reduction.
- 4% increase to the OEE

The benefits of using an auto-generated Preventive Maintenance cycle, through the Maximo server interface system, were identified to be as follows:

- No special induction of system needed due to the system already being used.
- The automatic generation of the PM cycle eliminated the time and need of an engineer to create a Word Authorization Document (WAD).
- The variation caused by defects skewing the cycle, was eliminated because the ideal conditions are reset each time the PM cycle WAD is generated.
- The auto-generation could schedule multiple transducers at once, hence inducing set-up reduction in the process.
- The PM had a window of 6 weeks, allowing enough flexibility to manage the process.
- A benchmark is created for controlling the process
5.7.2 KPIV – Defects

Defects, being the second largest KPIV for the amount of downtime, were analyzed in detail next.

5.7.2.1. Cause and Effect Analysis of Defects

A cause-and-effect analysis was performed in this phase to investigate the reasons behind the defects that trigger the downtime of the system.

The fishbone diagram that was charted by the team is as follows:

![Fishbone Diagram](image-url)

Figure 5.12: Cause-and-effect analysis of defects
The defects that are categorized as erroneous measurements taken are caused by the following:

- Wire corrosion at the Remote Terminal Unit (RTU)
- Failure of transducers
- Loose connections at the RTU, or transducer.
- Incorrect calibration settings

Defects that come under issues related to materials are caused by the following:

- Power supply failure
- Battery failures
- Voltage regulator failure
- Faulty cables

Defects that were induced by personnel involvement are caused by the following:

- Inadequate investigation
- Lack of a maintenance plan
- Lack of proper communication
- Set-up data is not saved
- Power outages
Environmental reasons that caused downtime are as follows:

- Water intrusion causing damage to connectors
- Lightning strikes
- Bird strikes

Inference from the cause and effect analysis shed light on the fact that personnel involvement, malfunction of materials and equipment and erroneous measurement were common cause defects, whereas the bird strikes and environmental issues such as lightning strikes were special causes. The scope of the project excluded the special causes because of their high uncertainty in occurrence. The common cause defects, however, could be addressed through implementation of improvement initiatives.

5.7.2.2. Tackling Common - Causes Defects

To prevent the common cause defects, improvement ideas proposed by the team were as follows:

“*Poka - Yoke*” the system.

“Poka - Yoke” is the method of “engineering and instrument an activity, so it is incapable of supplying a defective product, or service “(George, M. 2002)

The existing tools of the system that would smoothen and standardize the process are as follows:

- The Corrective Maintenance (CM) job plans in the Maximo system would help to further investigate and refine the causes of defects by incorporating steps that would call for inspections on the voltage of the instruments and cable connections.
• The Preventive Maintenance (PM) job plans in the Maximo system would help eliminate common cause issues by incorporating preventive steps (in the tower structural plan), such as inspection of cables to check for their structural integrity, prevention of corrosion of wires, application of torque seal on applicable connections

• SLA Batteries that are estimated a life of 3 years (36 months) @ 90 deg.F were being encased in an unventilated metal box, which shortens their life span to 25 months. Checking the life of the batteries at prescribed intervals, with the reduced life span in consideration, and replacing them would eliminate battery failures.

The team identified the benefits of incorporating the inspection steps to the CM job plans as follows:

• With a systematic process for further investigation of the root cause being provided, there was a chance for identifying and reducing false defects

• The incorporation reduced re-work, with respect to the extra steps being added to the job plans for further investigation on an individual case basis.

The team identified the benefits of incorporating the additional preventive steps to the tower structural PM job plans as follows:

• Elimination, or at least, reduction of defects caused by corrosion.

• Elimination, or at least, reduction of defects caused by loose connections in cables

• Elimination, or at least, reduction of defects caused by battery failure.

• Provision of a non-intrusive visual inspection because of the torque seal installation
The following fishbone diagram demonstrates the improvement efforts (CM and PM job plans) that tackled the identified causes:

![Fishbone Diagram](image)

Figure 5.13: Fishbone diagram showing solutions
To summarize the benefits of the improvement initiatives that were proposed by the team, the additional steps to the CM job plans were added to assist in the identification of the root cause of the defects, while the steps to the PM job plans were added to reduce or eliminate the occurrence of defects.

5.7.3 Quick Fixes

Along with the major factors being further analyzed, some other improvements that could easily be implemented from field observations, and did not require any major investments, were proposed as follows:

5.7.3.1 False Defects

- The Calibration Lab was suggested to use the temperature range when calibrating Relative Humidity, resolve some issues on false defects

5.7.3.2 Set – up Reduction

Changing out a transducer only took a half – hr out of a twelve man – hour process and maintenance while the tower was being lowered, eliminating set – up time of two hours.

- A longer interface cable was fabricated for laptop set – up to use in the van, thus elimination the rigging of an umbrella that provides reduction of screen glare.

- A power inverter was purchased and installed for the laptop in the van, providing quick reliable power source and eliminating the extension cord setup
• Instead of needing an engineer to write a calibration work order each time for a transducer, the calibrations being written as Preventive Maintenance work orders in Maximo would eliminate a step in the process. While writing the work orders, it was important that the calibration dates be kept the same regardless of defect interference.

5.7.3.3 Troubleshooting

During troubleshooting, simple issues such as lack of reference material also contributed to some waste of time. Hence, a quick – fix solution was suggested and implement as follows:

• Installed a copy of the drawing in each TD for quick reference when troubleshooting.

5.8 IMPROVE Phase

From the findings of the Analyze phase, the improvement initiatives that were adopted and implemented by the project team were summarized as follows:

1. Creation of new job plans for Corrective Maintenance and Preventive Maintenance

   • 32 new job plans for preventive maintenance were written, although none were created for corrective maintenance.

   • The intervals for preventive maintenance were synchronized scheduled for each site.

   • Additional steps in the job plans were added for resource tracking purposes ( e.g. serial numbers, signatures) for traceability purposes
This improvement initiative contributed to the addressing of the project goals of establishment of an efficient resource tracking method and reducing the Planned Downtime by 30%.

2. Identification of time line for implementation of calibration cycle schedule

- The calibration cycles were staggered for each site to reduce multiple downtime events
- Batteries were replaced
- Torque values were applied for RTU terminations to prevent loose cable connections

5.8.1 Synchronization of Calibration and Maintenance Cycles

The transducer calibration R & R cycle was done 5-6 times per year, per site. Maintenance of each site was performed twice a year. Synchronization of the two activities combines the steps so that both the activities can be scheduled simultaneously at every site. The improvement steps combined the two activities to be done at 5 month intervals.

5.8.1.1 Benefits

The synchronization estimated a 68% reduction in planned downtime. It allowed for set-up reduction in the process (multiple transducer replacement, calibration and maintenance). Auto-generation of PM eliminated the need for an engineer to create a WAD. The PM window of 6
weeks provided enough flexibility to effectively manage the process. In short, the improvement contributed to creating a known benchmark for controlling the process.

5.8.2 Identification and elimination of common cause defects

Reducing unplanned downtime through the identification and elimination of common cause defects was proposed in the Analyze phase. The initiative was studied and implemented in the Improve phase. The data analysis, though, did not provide any significant record of the common cause defects hence the preventive steps taken were based upon institutional knowledge.

5.8.2.1 Actions taken

- The calibration of the Relative Humidity transducer used to be performed at the lab only at ambient temperature. The calibration process was then changed to include temperature ranges.
- The wire termination points in the RTU were cleaned to address possible corrosion.
- To prevent loose connections of the RTU cables, a torque value was applied.
- A torque seal was applied to applicable terminations to prevent corrosion and loose connections.
- The back-up batteries in the RTU were changed.
- A Maximo PM Job Plan was written, to change batteries on manufacturer recommended intervals, and check for corrosion/verify set torque values implemented.
5.8.3 Results from Improvement Initiatives

The following describes the savings that were reaped upon implementation of the improvement actions:

- The Auto generated PM Job Plans eliminated the need for the engineer to create a WAD for transducer calibration R&R.

  \textit{27 Calibration R&R WADs in CY03 (28 average a year, 2001-2003)}

  \textit{Savings: 13-14 Engineer labor hours}

- Combining, and synchronizing maintenance, and transducer calibration R&R decreased the number of times that the towers are lowered for planned downtime.

  \textit{25 times (total, all towers) in 2003 to 8 times a year, 12 every 3 years.}

  \textit{Savings: 17 events}

- Set up reduction cut down the number of man hours spent on transducer calibration R&R, and tower maintenance

  \textit{25 times in 2003 approximated at 272 man hours versus 8 times a year approximated at 148 man hours}

  \textit{Savings: 124 Technical staff labor hours}

The following table summarizes the gains from the improvement initiatives and the comparison of the actual improvements to the expected.
Table 5.2: Summary of gains from improvement initiatives

<table>
<thead>
<tr>
<th>Improvements</th>
<th>Was</th>
<th>Goal</th>
<th>Actual Improvement</th>
<th>Improved by</th>
<th>Type</th>
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</thead>
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<td>8</td>
<td>17</td>
<td>68%</td>
<td>D</td>
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<tr>
<td>Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planned Downtime</td>
<td>272</td>
<td>148</td>
<td>124</td>
<td>46%</td>
<td>C</td>
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<td>Hours</td>
<td></td>
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<td>events</td>
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</tbody>
</table>

5.8.4 Savings

From the list of type of savings defined by United Space Alliance, the following were achieved through the implementation of the improvement initiatives from the project.

Type D Non-Quantifiable Savings:

- No identifiable dollar cost savings, but produces a measure improvement in quality, safety, or customer satisfaction.

Type C Soft Savings:

- The use of labor resources are reduced, enabling reallocation to other work, with no reductions to current budget/operating resource levels.

(A full list of the definition of the type of savings can be found in Appendix B)

5.9 CONTROL Phase

The project entered the final phase, the “Control” phase, to sustain the results of the improvement initiatives implemented. Though the team did not fulfill the objective of increasing the OEE to 90% from 71%, some improvement was achieved (e.g. an overall increase of 4%).
5.9.1 Control Measures

The following control measures were developed in order to sustain the improvements made:

- Maintenance of Preventative Maintenance job plans:

  The Job Plans are auto generated by Maximo 6 weeks before completion date, which gives the flexibility to plan, schedule and work around operations. Maintaining a consistent PM Cycle would control scatter effect of defects. Auto generated job plans would be issued, regardless of actual cal due date of transducer in order to correct scatter effect of a defective transducer replacement. A control plan schedule prescribing periodic maintenance of every 5 months was laid out for the preventive maintenance at each of the sites as follows:

<table>
<thead>
<tr>
<th>ID</th>
<th>Location Work to be Completed</th>
<th>PM Auto Generated date</th>
<th>PM Due Date</th>
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<th>2007</th>
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<td>Valuation 1</td>
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<td>12/5/2005</td>
<td>6w</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Valuation 2</td>
<td>5/20/2006</td>
<td>5/20/2006</td>
<td>6w</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Ped B C/S 3 R/H (2), A Tower Maint.</td>
<td>6/22/2005</td>
<td>7/31/2005</td>
<td>6w</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Ped B C/S 3 R/H (2), W/B, Tower Maint.</td>
<td>4/22/2006</td>
<td>5/31/2006</td>
<td>6w</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Ped B C/S 6 R/H (1), &amp; Tower Maint.</td>
<td>10/21/2006</td>
<td>11/30/2006</td>
<td>6w</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.14: Control plan schedule
5.9.2. Project Validation

To conclude the Control Phase, measure(s) were devised to validate the project’s efforts. The team decided on bi-annual and annual reviews of data gathered, starting from the end of the Control Phase.

The team decided that data, gathered from the Maximo database, will be reviewed 6 months and 12 months from the end of the Control Phase, in order to validate the project’s efforts.

The following data would be measured:

- Overall Equipment Effectiveness (OEE) - Days the system is operating at 100% over total days.
- Amount of Unplanned Down Time (UPDT) - Amount of time (days) system has a defect until it is resolved.
- Amount of Planned Down Time (PDT) - Amount of time (days) the system is down for planned maintenance from completion of the control Phase.
- Defects by Transducers - Transducers indicating defects.
- Amount of False Defects - Transducers removed for an indicated defect where no defect was found upon return to the lab.
CHAPTER 6
DISCUSSION

The project team had used the DMAIC approach in the efforts to reduce the downtime of the Met. System and achieved some successful results through the improvement initiatives. The results, as admitted by the Green Belt leading the project, were only partially fulfilling the goals of the project i.e. the Overall Equipment Effectiveness (OEE) was improved to 75% from 71% whereas the goal was 90%. In the Analyze phase, realizing that achieving full efficiency of the system is beyond continuous improvement, the team had stated its recommendations that a change in the design / equipment of the process, i.e. replacement of the transducers with more advanced models, would solve many maintenance issues, reduce defects and help achieve the goals of the project. They had also stated that a change in the design of the process was not in the scope of the project and should be performed as a separate effort due to budget constraints for the project. If the team decided to consider a design change, they would have to get the approval of the customer and management for that effort, which would be based on providing numerical evidence that a design change of the process would actually be financially beneficial in the long – run and yield more effectiveness of the system.
6.1 DMARC Implementation

By implementing the DMARC framework, the team would apply the findings of the Define, Measure, Analyze phases as basis for the re-design of the process using DFSS approach and tools. In order to convince the customer and management of the validity of such an initiative, the team could use benchmarking tools and Decision – making tools like Analytic Hierarchy Process (AHP).

The following shows how the AHP can be used to decide whether an existing process is to be improved or re-designed:

In AHP, a hierarchic or network structure is used to simplify and represent the decision problem with its criteria and alternatives. At each level of the network or hierarchy, pairwise comparison values of decision elements are used to assess the weights carried by the attributes to determine the preference amongst alternatives.

Pairwise comparison is done as follows:

The relationship is assessed between two elements (criteria or attributes) that connect to a common parent in the hierarchy.

Weights are assigned to the pairwise comparison of the elements using a scale devised as follows:
If two elements, “i” and “j” are being compared,

Table 6.1: Pairwise comparison values

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>i and j are equally important</td>
</tr>
<tr>
<td>3</td>
<td>i is weakly more important than j</td>
</tr>
<tr>
<td>5</td>
<td>i is strongly more important than j</td>
</tr>
<tr>
<td>7</td>
<td>i is very strongly more important than j</td>
</tr>
<tr>
<td>9</td>
<td>i is extremely more important than j</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Used for intermediate values</td>
</tr>
<tr>
<td>Reciprocals of above</td>
<td>Degree of importance of j over i</td>
</tr>
</tbody>
</table>

The following is an example of a hierarchy that can be used to make a decision on whether to improve upon an existing process or opt for re-designing it to get maximum benefits:
The criteria that the decisions will be based on are as follows:

Minimizing expenditure (Criterion A)

Minimizing risk (Criterion B)

Maximizing financial returns (Criterion C)

Maximizing process capability / performance (Criterion D)
Suppose the objective of minimizing risk (Criterion B) is **strongly more important** than minimizing expenditure (Criterion A) and maximizing financial returns (Criteria C) is **weakly more important** than maximizing process capability (Criterion D), then the relationships will be represented in the form of a matrix as follows:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>1/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The ratings of the elements should be consistent in the matrix, i.e. since A is more important than C, and C is more than B, A should be more important than B.

For “n” elements, there will be \( \frac{n(n-1)}{2} \) pairwise comparisons.

For 4 criteria, there will be \( \frac{4(4-1)}{2} = 6 \) pairwise comparisons.

Hence, the criteria are compared to each other pairwise as follows:

AB, AC, AD, BC, BD, CD
Suppose the data matrix (10) for the comparisons is given as follows:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1/5</td>
<td>1/3</td>
<td>1/2</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1/4</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

The first step is to normalize the A matrix so that the sum of the values in each column equals 1. This is done by dividing each entry in a column of the A matrix by the sum of the entries in that specific column. The average of each criteria row is taken to form:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.091</td>
<td>0.102</td>
<td>0.091</td>
<td>0.059</td>
<td>0.086</td>
</tr>
<tr>
<td>B</td>
<td>0.455</td>
<td>0.513</td>
<td>0.545</td>
<td>0.471</td>
<td>0.496</td>
</tr>
<tr>
<td>C</td>
<td>0.273</td>
<td>0.256</td>
<td>0.273</td>
<td>0.353</td>
<td>0.289</td>
</tr>
<tr>
<td>D</td>
<td>0.182</td>
<td>0.128</td>
<td>0.091</td>
<td>0.118</td>
<td>0.13</td>
</tr>
</tbody>
</table>

This allows the prioritization of the criteria based upon the relative importance.

Based on the values assigned in the pairwise comparisons, minimizing of risk (Criterion B) holds most importance.
The alternatives (Re – design (26) or Improve (25)) are compared with respect to each of the criteria.

Pairwise comparison with respect to Criteria A,

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>J</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

Upon normalization and taking averages of the rows, the matrix is as follows:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>J</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Pairwise comparison with respect to Criteria B,

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>J</td>
<td>1/5</td>
<td>1</td>
</tr>
</tbody>
</table>

Upon normalization and taking averages of the rows, the matrix is as follows:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>J</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Pairwise comparison with respect to Criteria C,

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>1/5</td>
</tr>
<tr>
<td>J</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Upon normalization and taking averages of the rows, the matrix is as follows:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>J</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Pairwise comparison with respect to Criteria D,

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>1/9</td>
</tr>
<tr>
<td>J</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Upon normalization and taking averages of the rows, the matrix is as follows:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>J</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>J</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>
After obtaining the priority weights of alternatives with respect to a criterion (e.g. criterion A), the weights of those alternatives with respect to the overall objective are calculated as follows:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Criterion A</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>0.086*0.75</td>
</tr>
<tr>
<td>j</td>
<td>0.086*0.25</td>
</tr>
</tbody>
</table>

Weighing the alternatives with respect to all the criteria, finally produces a data matrix as shown:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Criterion A</th>
<th>Criterion B</th>
<th>Criterion C</th>
<th>Criterion D</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>0.0645</td>
<td>0.412</td>
<td>0.0491</td>
<td>0.013</td>
<td>0.538</td>
</tr>
<tr>
<td>j</td>
<td>0.0215</td>
<td>0.084</td>
<td>0.241</td>
<td>0.117</td>
<td>0.462</td>
</tr>
</tbody>
</table>

Evaluation:

This is just an example of how AHP can be used to make such decisions. It is important to note that the priority weights for the criteria and the alternatives are based upon subjective assessment of the customer and the project team. Based on the priorities given to each of the criteria, the first alternative, (i) or re-design, holds more weight (0.538 > 0.462) than the second one (j), which is to improve upon the existing process. Hence, the decision to re-design the existing process gains more importance in this case. If approval is received to pursue the chosen alternative to re-design the process, the DMARC path can be utilized to proceed. In this case, re-design would involve the replacement of existing equipment with better models, test for system compatibility and re-design applicable processes and procedures.
Embarking upon the re-design phase, the team could perform the following actions in the Measure, Analyze, Develop and Validate phases:

**MEASURE phase**

Since the project has adopted a DFSS approach, capture the Voice of the Customer, in a more detailed manner, about the expectations and needs from the system. Using Quality Function Deployment (QFD), the baseline measurements are assessed for value that is translated into the CTQ characteristics that are to be achieved by the re-design. The House of Quality tool helps to identify the crucial customer requirements and the relative priorities that need to be satisfied with the technical requirements of the equipment. The requirements act as references in the benchmarking and design activities. A sample House of Quality capturing the customer requirements is shown as follows:

![House of Quality Example](image-url)

Figure 6.2: Example of House of Quality based on customer requirements of the LPMS

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ANALYZE phase

Analyze the requirements based on past information and implement benchmarking techniques to explore alternatives.

The project team had recommended that changing the transducers and replacing the models with better equipment would solve many calibration and maintenance issues, which would help realize the goal of reduction or near-elimination of planned downtime of the LPMS. In pursuit of finding replacements, they performed benchmarking exercises and named replacements. An example of the benchmarking exercise is as follows:

For the wind speed and direction equipment, they had recommended the Vaisala WINDCAP® WS425 Ultrasonic Wind Sensor as the ideal replacement to the current Climet 011-4 wind speed and 012-16 wind direction sensors.

Advantages:

Some advantages of the Vaisala WS425 wind sensor over the existing sensors (Climet 011-4 and Climet 012-16) are as follows:

- No moving parts
  - Reduces the damage to the equipment
  - Resistant to contamination and corrosion
  - No housing required
- Elimination of periodic maintenance
  - PM is eliminative, hence planned downtime is eliminated
• In-place calibration
  - No need to travel to site, unlike field calibrated 011-4 and 012-16 transducers
• Combination of both wind direction and wind speed sensors
  - 4 transducers (2 wind direction and 2 wind speed sensors) are combined into 2
• 1 year in-place calibration cycle
  - In comparison to the 5 month calibration cycles that the project team had prescribed in the Analyze and Improve phases of the DMAIC project
  - Calibration is done by vendor with certification, hence sensor does not need calibration lab involvement.

Disadvantages:

Some disadvantages of the Vaisala WS425 wind sensor over the existing sensors (Climet 011-4 and Climet 012-16) include:

• Requires initial investment expenditure to replace the existing equipment.
• No prior data of compatibility with the current system
• Less accurate than the existing 011-4 and 012-16 transducers

According to the Voice of Customer, accuracy of the equipment is important, but is less important than the requirement that the system should be 24/7 operational with as minimum downtime as possible. Hence, the Vaisala WS425 wind sensor seems a prospective replacement to the existing wind direction and wind speed sensors, if it proves cost-effective over the existing configuration.
Process change visualization:

To visualize the change in process flow and a projection of savings in labor hours by the induction of the benchmarked equipment, the process map can be re-charted. The following process maps represent the flow of the process of the transducer calibration cycle before the equipment replacement and after.

Figure 6.3: Transducer (Climet 011-4 and Climet 012-16) calibration cycle process map
Due to the in-place calibration feature, non-value added activities such as travel to the field location and equipment set-up in the field are eliminated, saving nearly 4 hours out of the estimated 12 hours of labor per transducer. This reflects in a significant reduction of downtime in the long-term.
A Cost – Benefit Analysis can be performed to realize the savings (long – term) of inducting alternative product into the system.

Table 6.2: Example of Cost – Benefit Analysis of an alternative

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Vaisala WS425</th>
<th>Climet 011-4</th>
<th>Climet 012-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity required (each Pad)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Moving Parts</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Periodic Maintenance</td>
<td>None</td>
<td>5 months</td>
<td>5 months</td>
</tr>
<tr>
<td>Protection</td>
<td>None</td>
<td>Housing</td>
<td>Housing</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 3% of true value or ± 0.30 mph</td>
<td>± 1% of true value or ± 0.15 mph</td>
<td>± 1% of true value</td>
</tr>
<tr>
<td>Wind Velocity Range</td>
<td>0-144 mph</td>
<td>0 - 100 mph</td>
<td>N/A</td>
</tr>
<tr>
<td>Threshold</td>
<td>0 mph</td>
<td>0.6 mph</td>
<td>0.75 mph</td>
</tr>
<tr>
<td>Wind Direction Range</td>
<td>0-360 deg</td>
<td>N/A</td>
<td>0-540 deg</td>
</tr>
<tr>
<td>Unit cost</td>
<td>$1,800</td>
<td>$475</td>
<td>$625</td>
</tr>
<tr>
<td>Housing cost</td>
<td>0</td>
<td>$1,250</td>
<td>$1,250</td>
</tr>
<tr>
<td>Total transducer cost</td>
<td>$1,800</td>
<td>$1,725</td>
<td>$1,875</td>
</tr>
<tr>
<td>(housing and sensor only)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cal Cycle labor hours</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>saved (out of 12) per</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transducer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savings at $300/ labor</td>
<td>$1200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>hour per transducer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At an estimated $300 per labor hour, which includes the cost of planning, scheduling, manpower etc, $1200 are saved per calibration cycle performed on one transducer. Considering that one Vaisala WS425 replaces both a Climet 011-4 wind speed and Climet 012-16 wind direction transducer, the savings are doubled to $2400 per calibration cycle performed at each launch pad, due to the number of wind speed and wind direction transmitters cut down from 8 to
4. The improvement efforts originally proposed by the team called for performing synchronized calibration cycles every 5 months, which meant that there will be 2.4 calibration cycles performed in an year, on the Climet models. The Vaisala WS425 will ideally require only 1 calibration cycle annually, which multiplies the savings to $5400 annually, at each launch pad. An initial overall investment of inducting one Vaisala WS425 transducer into the LPMS, estimated at $3600, will mean that the cost incurred to induct the required 4 transducers at each launch pad ( $14,400) would be compensated within just 3 years of operation (savings of $16,200).

DESIGN phase

Induct the replacement equipment as prototypes and perform pilot runs to understand the behavior of the new process. Design experiments to assess the variables that impact the response variable of the process.

VERIFY phase

Through predictive models, simulation, pilot testing, verify that the design change adapt to the system real – time. If the pilot runs prove successful to have improved the system, implement the re – design of the process and provide all necessary documentation.

CONTROL Phase

In order to sustain the improvements that are achieved from the design change, establish control procedures to monitor process capability and variation of the process. Provide detailed and accurate instructions on operation and maintenance.
CHAPTER 7
SUMMARY / CONCLUSION

7.1 Major Findings

The Launch Pad Meteorological System downtime reduction project had adopted the DMAIC approach to produce the best sustainable improvements through their efforts. They had set high goals to achieve, such as the increase of the Overall Equipment Effectiveness (OEE) from 71% to 90%, elimination of unplanned downtime etc. At the end of the Improvement phase the project team had reported an OEE increase of only 4%, which was far below the expected goal. The team had recommended in the Analyze phase that in order to achieve project goals of 90% and avoid recurring maintenance problems, a design change i.e. replacement of the transducers with benchmarked models. The recommendations were not followed probably due to apprehension of the idea of re – design of the process and uncertainty of the compatibility of the replacement equipment with the current system, overshadowed by budget constraints.

The possibility of the project team having pursued the DMARC framework was discussed after reviewing the case study. Based upon the conclusions of the Define, Measure and Analyze phases, the team could have weighed the priorities of the customer and project to make a decision, quantitatively, on whether to pursue continued improvements on the existing system retaining the current configuration, or the alternative, i.e. re – design of the process by testing and inducting benchmarked alternative equipment. Weighing the alternatives based upon customer requirements favored the re - design alternative with an assigned value of 0.538, over the improvement option (0.462). By employing the Re-design phase, team would have used Design for Six Sigma tools and methods as they would progress through the Measure, Analyze,
Design and Verify (M,A,D,V) phases that consist the Re-design path. Using QFD to translate detailed customer expectations into product specifications and performing benchmarking activities, the team would have compared the alternative models of the equipment to the existing ones, tested and verified the expected gains from the configuration change. An example of the projected benefits was demonstrated where the Climet 011-4 wind speed and Climet 012-16 wind direction transducers were compared with a benchmark replacement, the Vaisala WS425 wind speed and direction sensor. If the current models were to be replaced with the alternative (Vaisala WS425), an average of $5400 per calibration cycle would be saved annually, eventually compensating for the costs incurred during initial investment.

7.2 Resistance to Re-design

The DMARC approach is useful when a typical DMAIC project shifts its nature from an initiative dwelling on just improvement, to the modification or re-design of an existing process. An initiative to re-design an existing process often, if not always, is confronted with initial skepticism and apprehensions of exorbitant expenditure, project failures etc. Some companies do realize the imperative need for the re-design of a process or product or service, but steer clear of embarking on such efforts probably due to a hefty investment price tag and uncertainty of compatibility with the current system etc. A typical example is the industrial conglomeration at Kennedy Space Center where most processes or operations affect multiple systems or even organizations in varying magnitude that any change in design of a process would have to conform to the function of many. An improvement initiative is assumed to be economical compared to an approach that changes the design of the process or product, which is the reason for apprehensiveness of supporting a design change. The argument is true in many cases, but if
numerical or simulation evidence proves that the overall value of the design / re – design effort might be more fruitful than an initiative to improve a process, that is beyond improvement in its current configuration, then the project team and the team leader should overcome the apprehension of implementing a DFSS approach and embrace its benefits. If a process is essentially functioning, though it has errors, it becomes the responsibility of the pertaining system to weigh the importance of a modification with respect to long – term benefits. It is always preferred that a process be improved upon its current configuration and nature without a design change, but if such an initiative does bring about long – term benefits, then an initial investment might be worth the effort. The resistance to the re – design effort is to be broken down through solid assurance of the expected gains.

In cases of persistent problems with equipment and systems, an attempt to modify / upgrade the equipment is a re – design effort that comes with benefits such as reduction of maintenance issues and increased efficiency, but also with a higher price tag and resource expenditure. Whether such an effort is worth the time and money is for the project team and customer to decide.
APPENDIX A
USA’S VISION SUPPORT PLAN GOALS
**Goal 1:** Provide Safe Operations for All Aspects of Our Business

**Goal 2:** Achieve Excellent Customer Satisfaction and Program Performance

**Goal 3:** Achieve Outstanding Quality in All Aspects of Our Business

**Goal 4:** Improve, Innovate, and Diversify

**Goal 5:** Be the Company of Choice for Our Employees and for Our Communities

**Goal 6:** Provide Excellent Financial Returns and Extend Our Core Business

*Source: United Space Alliance Intranet Home Page*
APPENDIX B
USA’S L6S SAVINGS DEFINITION
**Type A Hard Savings:**

Type A savings occur when costs incurred by the applicable USA operating unit are reduced, by accepting future budget reductions from current levels.

**Type B Hard Savings:**

Type B savings occur when costs incurred by the applicable USA operating unit are reduced, enabling the applicable operating unit to meet already established reductions/challenges in future year budget targets, or to eliminate or reduce an existing budget overrun condition.

**Type C Soft Savings:**

Type C savings occur when the improvement results in the avoidance of a future cost (such as the addition of headcount or an expenditure of funds), or the use of labor resources are reduced, enabling reallocation to other work, with no reductions to current budget/operating resource levels.

**Type D Benefits:**

Type D benefits occur when the improvement results in no identifiable dollar cost savings, but produces measurable improvement in quality, safety, or customer satisfaction.

*Source: United Space Alliance Intranet Home Page*
Equipment info on: Climet instruments, Climet 011-4, Climet 012-16 and Vaisala WS425

---

### Wind Speed (W/S) & Wind Direction (W/D) Sensors

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Price</th>
<th>PCB Model*</th>
<th>Range</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>011-4</td>
<td>Wind Speed Sensor w/ Cups &amp; 50' Cable</td>
<td>$475.00</td>
<td>05-8005-26</td>
<td>-50 to 120 KnuV</td>
<td>$220.00</td>
</tr>
<tr>
<td>012-16</td>
<td>Wind Direction Sensor w/ Vane &amp; 50' Cable ($40°)</td>
<td>$625.00</td>
<td>05-8019-2</td>
<td>0-540°</td>
<td>$220.00</td>
</tr>
</tbody>
</table>

### Translators with Power Supply

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Price</th>
<th>PCB Model*</th>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>060-5</td>
<td>5-Channel Transmitter</td>
<td>$450.00</td>
<td>05-8005-1</td>
<td>Delta Temp</td>
<td>$275.00</td>
</tr>
<tr>
<td>060-10</td>
<td>10-Channel Transmitter</td>
<td>$510.00</td>
<td>05-8016-2</td>
<td>Sigma Computer</td>
<td>$355.00</td>
</tr>
<tr>
<td>060-15</td>
<td>15-Channel Transmitter</td>
<td>$575.00</td>
<td>05-8059</td>
<td>Sigma Calibr.</td>
<td>$375.00</td>
</tr>
<tr>
<td>060-20</td>
<td>20-Channel Transmitter</td>
<td>$625.00</td>
<td>05-8061-1</td>
<td>ThA, 300 Sec.</td>
<td>$350.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05-8061-2</td>
<td>ThA, 60 Sec.</td>
<td></td>
</tr>
</tbody>
</table>

### Optional Sensors

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Price</th>
<th>PCB Model*</th>
<th>Range</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-3x1</td>
<td>Calibrated Temp Sensor w/50' Cable</td>
<td>$175.00</td>
<td>05-8004-15</td>
<td>-30°C/30°C</td>
<td>$165.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05-8004-30</td>
<td>-30°F/120°F</td>
<td></td>
</tr>
<tr>
<td>016-44</td>
<td>Relative Humidity</td>
<td>$115.00</td>
<td>05-8002-30</td>
<td>0 - 100%</td>
<td>$165.00</td>
</tr>
<tr>
<td>0501-5</td>
<td>Rain Gauge, Tipping Bucket</td>
<td>$690.00</td>
<td>05-8157-4</td>
<td>0 - 1&quot;</td>
<td>$400.00</td>
</tr>
<tr>
<td>0501-4</td>
<td>Rain Gauge, Tipping Bucket - Heated</td>
<td>$1160.00</td>
<td>05-8157-6</td>
<td>0 - 10&quot;</td>
<td>$400.00</td>
</tr>
<tr>
<td>0502-2</td>
<td>Pressure Sensor (Std)</td>
<td>$925.00</td>
<td>05-8002-6</td>
<td>28.0&quot; to 32.0&quot;Hg</td>
<td>$165.00</td>
</tr>
<tr>
<td></td>
<td>(Other pressure ranges available on request)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0503</td>
<td>Pyranometer</td>
<td>$1055.00</td>
<td>05-8002-8</td>
<td>0-2 gm Cal/ cm²/min,</td>
<td>$165.00</td>
</tr>
</tbody>
</table>

### Temperature Shields - Mounting Devices - Tower J-Boxes

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>016-1</td>
<td>Motor Aspirated Temperature Shield w/50' Cable</td>
<td>$790.00</td>
</tr>
<tr>
<td>091-1</td>
<td>Instrument Mks. Arm Fum 011-4, 012-16</td>
<td>$5.00</td>
</tr>
<tr>
<td>091-9</td>
<td>Quick Disconnect</td>
<td>$75.00</td>
</tr>
</tbody>
</table>

Standard DC Analog outputs 0-1mA & 0-IV; others to a max. of 0-10mA & 0-10V on request.

Prices are F.O.B. Redlands, California.
<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>093-1</td>
<td>(95009301) Instrument J-Box w/Decell P.S.</td>
<td>$200.00</td>
</tr>
<tr>
<td>093-2</td>
<td>(95009302) Instrument J-Box</td>
<td>200.00</td>
</tr>
<tr>
<td>B-4910</td>
<td>(00495002) Retractable Boom, 10'</td>
<td>Approximately 600.00 (Consult Factory)</td>
</tr>
<tr>
<td>B-4910</td>
<td>(00495001) Retractable Boom, 16'</td>
<td>Approximately 650.00 (Consult Factory)</td>
</tr>
</tbody>
</table>

PRICES ARE F.O.B. REDLANDS, CALIFORNIA

Page 2 of 2

4/83 - D

SUBJECT TO CHANGE WITHOUT NOTICE
WIND SPEED TRANSMITTER

- THRESHOLD: 0.6 MPH
- INDIVIDUAL CALIBRATION: N.B.S. Traceable
- ACCURACY: ±1% of true or ±0.15 mph, whichever is greater
- SENSING TECHNIQUE: Light Beam Chopper

INTRODUCTION

Climet Model 011-4 Wind Speed Transmitter is the best research-grade sensor available for obtaining precise wind velocity measurements. A 3-cup anemometer of integrally molded Lexan plastic provides an accuracy of one percent over a calibrated range of 0.6 mph to 90 mph. The instrument uses a phototransistor-LED chopper circuit to generate the wind speed proportional output signal which is suitable for both digital and analog recording applications. Model 011-4 Transmitters are high reliability instruments of comparatively light weight but extremely rugged design and operate in almost any environment from temperatures of 50°F to +155°F over extended periods of time and with wind velocities up to 110 mph.

HOW IT WORKS

The 011-4 Wind Speed Transmitters are comprised of a 3-cup anemometer, stainless steel drive shaft and precision ball bearing assembly, 100-slot light beam chopper, phototransistor-LED circuit, and solid state amplifier.

The 3-cup anemometer and coupled drive shaft respond to wind and rotates the 100-slot light beam chopper. Rotation of the chopper alternately masks and exposes the phototransistor to an LED. The phototransistor responds to the light passing the chopper wheel and generates electrical pulses which are then amplified to provide a resultant 10 volt (0 to peak) squarewave output with the frequency proportional to wind velocity.

CONSTRUCTION AND DESIGN FEATURES

To preserve the exceptional threshold and linear characteristics of the Model 011-4 Wind Speed Transmitter, only the anemometer cups are exposed to the environment. The bearings, light chopper, and amplifier assembly are shielded by a heavy-anodized housing, protected from moisture and particulate contamination by an “O” ring seal. The weatherproof cable connector further guarantees the integrity of the output signal.

The cups are of a special beaded design which significantly reduces the effects of wind turbulence. Less than 0.05 feet of air must pass the cups to produce an output signal, thus providing resolution even at wind speeds of less than 1 mph. Special lubrication is used in the shielded bearings to insure a low and continuously reliable threshold in extreme environments where conventional lubricants congeal and fall. Bearing replacement, when required, is easily accomplished in the field without special tools.
CERTIFICATION OF PERFORMANCE

Climet's anemometer cup assemblies have been certified by the National Bureau of Standards as secondary standards accurate to within 1 percent (or 0.15 mph) from threshold to 90 mph. Each anemometer cup assembly supplied with the 011-4 Wind Speed Transmitter is dynamically calibrated against a secondary standard and is guaranteed to an accuracy of one percent. No higher assurance of accurate wind speed measurement capability can be provided by modern instrumentation.

SPECIFICATIONS

Performance Characteristics

Operating Range: 0 mph to 110 mph
Threshold Level: 0.6 mph
Calibrated Range: Threshold to 90 mph
Accuracy: ±1% or 0.15 mph, whichever is greater
Temperature Range: −50°F to +155°F
Response: Distance constant equals 5 feet of flow

Electrical Characteristics

Power Requirements: 12VDC at 20 MA
Output Signal: 10 volt (c-p) squarewave audio signal with frequency proportional to wind speed.
Less than 90 ohms
Use with: Climet Instruments Wind Translator, Series 060

Physical Characteristics

Weight: 14 ounces
Height (overall): 13¾ inches
Housing Dimension: 3½ (H) x 2¼ (D) inches
Cup Diameter: 7¾ inches
Finish: Clear Anodize
Cable: 4 conductor #20 wire, 25 feet long, terminated in pigtail connections. Extra cable up to 1500 feet long can be provided on special order.
Mounting Fixture: Climet Instruments Mounting Arm, No. 091-1

*The distance constant is a measure of the lag characteristics of an anemometer defined by Shubauer and Adams as "the distance travelled by the air after a sharp-edged gust or portal has occurred for the anemometer rate to reach (1−t)/d or 63% of the new equilibrium." Ref. Shubauer and Adams, "Lag of Anemometers." N.B.E. Report 3246, 4/16/54.

Climet Instruments Company
A DIVISION OF WEHR CORPORATION

P.O. Box 151
Redlands, CA 92373
Phone AC 714/793-2788
WIND DIRECTION TRANSMITTER

FEATURES

- THRESHOLD: 0.75 MPH
- ACCURACY: ±1% of true
- SENSING TECHNIQUE: Micro-Torque Potentiometer
- TEFLON SEALED BEARINGS
- ORIENTATION LOCKING DEVICE

INTRODUCTION

Climet Model 012-16 Wind Direction Transmitter is the best research-grade sensor available for obtaining precise wind direction measurements. The Model 012-16 Wind Direction Transmitter measures wind azimuth plus the amplitude and frequency variations in wind direction. The output from the Wind Direction Transmitter is a very stable analog voltage which is proportional to horizontal wind direction. A symmetrical airfoil vane of durable molded foam plastic responds to winds as low as 0.75 mph over a continuous mechanical range of 360 degrees and provides a damping ratio of 0.4 to allow a fast rise time with minimum overshoot. For extremely critical micrometeorological studies, the Wind Direction Transmitter may be optionally supplied with Climet's 0.6 damping ratio vane assembly. The Model 012-16 Wind Direction Transmitter is a high-reliability instrument of lightweight but extremely rugged design and operates in almost any environment from temperatures of −50°F to +155°F over extended periods of time.

Model 012-16 includes Climet's patented Ambiguous Point Logic Feature and is recommended where a very precise output is required over a continuous range of 0 degrees to 540 degrees.

Climet's patented Ambiguous Point Logic Feature (APL) produces a single continuously variable DC voltage proportional to wind direction. Conventional equipment produces an output voltage with discontinuities caused by the vane-driven wiper passing over the gap in the sensing potentiometer. APL resolves circular position into uninterrupted linear coordinates over the full azimuth range thereby eliminating crossover discontinuities. This option is a desirable feature for use when mathematical operations such as signal averaging and variance computations are performed on the output signal. Refer to Ambiguous Point Logic data sheet for further particulars.

HOW IT WORKS

The Model 012-16 Wind Direction Transmitter is comprised of a symmetrical airfoil vane and integral drive shaft, a precision potentiometer assembly, an electronics module, and the housing with related fittings.

The wind vane is directly coupled to the precision potentiometer assembly by the drive shaft and causes the potentiometer wiper to directly follow movements of the wind vane. A self-contained regulated power supply is included in the electronics module and provides a constant DC voltage to the potentiometer. The electronics module is adjusted to exactly match the resistance and gap width of the potentiometer, thereby causing the output signal to be a fixed ratio of volts per degree. It is this fixed ratio feature which allows the Wind Direction Transmitter to be interchanged without any recalibration requirements.
CONSTRUCTION AND DESIGN FEATURES

To preserve the exceptional threshold and dynamic characteristics of the Wind Direction Transmitter, only the vane is exposed to the environment. The bearings, potentiometer and power supply module are shielded by a heavy-anodized housing, protected from moisture and particulate contamination by an "O" ring seal. The weatherproof cable connector further guarantees the integrity of the output signal.

The 0.4 damping ratio vane airfoil is an integrally-molded skin of polyurethane. The 0.8 damping ratio vane airfoil is constructed of expanded bead polystyrene and coated with a moisture resistant sealant. Special lubrication is used in the sealed bearings to insure a low and continually reliable threshold in environments where conventional lubricants congeal and fail. Bearing replacement, if required, is easily accomplished in the field without special tools. The self contained power supply insures the sensor calibration is independent of any associated translating electronics and allows the Model 012-16 Wind Direction Transmitter to be directly interchanged without recalibration.

DYNAMIC RESPONSE

The Climet Model 012-16 Wind Direction Transmitter employs sensitive wind vanes to provide immediate response and negligible overshoot to guarantee a reliable dynamic response even with very slight variation in wind direction. The dynamic response of wind vanes is primarily determined by their damping ratio. The three curves in the figure indicate relative damping ratios of a conventional wind direction sensor, the Climet Wind Direction Transmitters with the standard 0.4 damping vane, and the optional 0.8 damping vane.

*The damping ratio is the percent of critical damping, which is defined as the logarithm to the base “e” of the successive amplitudes of the decay curve described by the vane in obtaining a final direction when an abrupt change in wind direction is applied to it. The damping ratio is defined by the following equation:

\[ \text{Damping Ratio} = \frac{\ln(x_2/x_1)}{\ln(x_1/x_0)} = \frac{\ln(x_2/x_1)}{\ln(x_1/x_0)} \]

where \( x \) is the damping ratio and \( x_0 \) and \( x_1 \) are successive amplitudes.

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Performance Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range: (1) Electrical, 0-539°</td>
</tr>
<tr>
<td>(2) Mechanical, 360° Continuous</td>
</tr>
<tr>
<td>Accuracy: 0.75 µm</td>
</tr>
<tr>
<td>Linearity: 3% of full scale</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Requirements: 12 VDC at 15 ma</td>
</tr>
<tr>
<td>Output Signal: 0-600 volts (corresponding to 0-640°)</td>
</tr>
<tr>
<td>Use with: Climet Instruments Wind Translators, Series 060</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight: 14 ounces</td>
</tr>
<tr>
<td>Height (overall): 16½ inches</td>
</tr>
<tr>
<td>Housing Dimension: 3½ x 2½ (D) inches</td>
</tr>
<tr>
<td>Mounting Fixtures: Climet Instruments Mounting Arm #901-1</td>
</tr>
<tr>
<td>Cable: 4 conductor #20 wire, 25 feet long, terminated in female connections. Extra cable up to 1,500 feet long can be provided on special order</td>
</tr>
</tbody>
</table>

Climet Instruments Company
A DIVISION OF WEHR CORPORATION
P.O. Box 151
Redlands, CA 92373
Phone AC 714/793-2788
WS425 Ultrasonic Wind Sensor for Critical Wind Measurement Applications

The Vaisala WINDCAP® Ultrasonic Wind Sensor WS425 gives meteorologists an alternative to the cup and vane mechanical sensors. With its continuous data availability, the WS425 is also ideal for a variety of wind measurement applications in aviation, road and railway safety and energy production.

Accurate and maintenance-free
The WS425 has no moving parts, and is resistant to contamination and corrosion. In addition to improving accuracy and the reliability of data in all wind conditions and climates, the WS425 eliminates on-demand and periodic maintenance.

Measurement based on ultrasound
The WS425 uses ultrasound to determine horizontal wind speed and direction. The measurement is based on transit time, the time it takes for the ultrasound to travel from one transducer to another, depending on the wind speed.

The transit time is measured in both directions for a pair of transducer heads. Using two measurements for each of the three ultrasonic paths at 60° angles to each other, the WS425 computes the wind speed and direction.

The wind measurements are calculated in a way that completely eliminates the effects of altitude, temperature and humidity.

Features/Benefits
- Superior data availability and accuracy in all wind directions due to the patented three transducer layout
- No maintenance needed
- Theoretical mean time between failures (MTBF) 28 years
- Effects of temperature, humidity and pressure fully compensated
- Large transducer heads are insensitive to rain
- RS232/485/422, SDI-12 and analog outputs
- Operates with 10...15 VDC, additional 30 VDC required for heated model
- Stainless steel as standard sensor material
- Field verification device available
- Can be mounted upside down
- US National Weather Service relies on Vaisala ultrasonic technology

Standard and heated models
The heated model has thermostatically controlled heaters in the transducer heads to prevent freezing rain or snow build-up. The standard model operates with a low current 10...15 V supply. For the heated model, an additional 36 V supply is used for heating.

Outputs
SDI-12 provides the most extensive set of commands and calculations. The standard RS-232/485/422 protocol supports NMEA and three other message formats. Analog outputs are available as an option.
Technical Data

Wind speed

<table>
<thead>
<tr>
<th>Measurement range</th>
<th>0.45 m/s (8.8 mph, 0.155 knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial output</td>
<td>0.56 m/s (1.2 mph, 0.197 knots)</td>
</tr>
<tr>
<td>Analog output</td>
<td>virtually zero</td>
</tr>
</tbody>
</table>

Starting threshold virtually zero
Delay distance virtually zero
Resolution 0.1 m/s (0.1 mph, 0.1 knots, 0.1 km/h)

Accuracy (range 0.45 m/s) ± 0.15 m/s (±0.3 mph, ±0.26 knots)
or 3% of reading, whichever is greater

Wind direction

<table>
<thead>
<tr>
<th>Measurement range</th>
<th>0.20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial output</td>
<td>0.27°</td>
</tr>
<tr>
<td>Analog output</td>
<td>0.5°</td>
</tr>
</tbody>
</table>

Starting threshold virtually zero
Delay distance virtually zero
Resolution 0.1°

Accuracy (wind speed over 1 m/s) ± 0.2°

Outputs

<table>
<thead>
<tr>
<th>Digital outputs</th>
<th>type</th>
<th>RS232, RS422 or RS485, four different message formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>adjustable from 1200 to 19200 bit/s</td>
<td></td>
</tr>
<tr>
<td>Available averages</td>
<td>RS232: 1 to 9 seconds</td>
<td></td>
</tr>
</tbody>
</table>

SEI-12 Standard Interface

<table>
<thead>
<tr>
<th>Type</th>
<th>3 wires for ground, signal and supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>1200 to 19200 bit/s</td>
</tr>
<tr>
<td>Available averages</td>
<td>1 to 9999 seconds</td>
</tr>
</tbody>
</table>

Analog outputs

| Wind speed | 5 Hz/mph |
| Voltage    | 80 mV/mph |
| Output impedance | 10 kohm |

Wind direction

| Simulated potentiometer | 0.1° or represents 0.25° |
| Reference voltage | 1.0 V, 0 V |
| Output impedance | 20 kohm |

Response characteristics

| Maximum reading rate | 1 per second |
| Data measurement time | 0.2 s |
| Signal processing time | 0.15 s |
| Response time | 0.15 s |

General

<table>
<thead>
<tr>
<th>Operating power supply</th>
<th>10...15 VDC, 12 mA typical (analog)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>WSN25 non-heated -40...+55 °C (-40...+131 °F)</td>
</tr>
<tr>
<td>WSN25 heated -55...+55 °C (-57...+131 °F)</td>
<td></td>
</tr>
</tbody>
</table>

Material

<table>
<thead>
<tr>
<th>Body</th>
<th>Stainless steel (AISI 316)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor housing</td>
<td>Stainless steel (AISI 316)</td>
</tr>
<tr>
<td>Transducer housing</td>
<td>Silicone rubber</td>
</tr>
</tbody>
</table>

Dimensions

| Height | 355 mm (14") |
| Width  | 250 mm (10") |
| Depth  | 206 mm (8")  |

Weight

| 1.7 kg (3.7 lbs) |


Generic Environment

Accessories

| Cable supplying analog outputs, 10 m | ZZ112004 |
| Cable supplying RS-232 outputs, 10 m | ZZ11203 |
| Cable supplying RS-485/422 outputs, 10 m | ZZ114001 |
| Cable supplying SEI-12 outputs, 10 m | WSN25GB2001 |
| Adaptor for 33-35 mm (1 1/4") diameter vertical tube | WSN25FPC20 |
| Adaptor for 50 mm (2 1/4") diameter vertical tube | WSN25FPC25 |
| Field verifier | WSN25VERIFIER |

Specifications subject to change without prior notice.

©Vaisala Oy
Abhishek,

I reviewed the attachment, L6S Green Belt "Launch Pad Meteorological System Support Downtime Reduction" Project, to confirm that it contained no cost data and no training material restricted by USA copyright. With this done, I stripped the "USA Restricted" and "USA Proprietary" labels from the slides. As far as USA L6S is concerned, we are satisfied with the release of this information. Good luck on your Thesis.

Don Johnston
Lead Master Black Belt
United Space Alliance

Abhishek,

Our office received the required approvals for you to release your paper enclosed. Thanks for coordinating with our office.

Teresa Parrish
USA Export Control Office

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LIST OF REFERENCES


