DMAIC Approach to Address Non-compliances in 3D Feature Based Computer Generated Design Models

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Abstract

This project aims to address non-compliances in 3D feature based Computer Aided Design (CAD) models and drawings that are delivered to the customers under agreed Technical Data Packages (TDP's), at the various conceptual, developmental and production levels of a company. It has been found that over 20% of all models in the TDP has shown evidence of non-compliance. This results in profit losses, lost time and morale of employees. The DMAIC Six-Sigma approach was used to define the problem, measure the extent of the problem, analyze the problem, attempt to identify root causes, find solutions to reduce the effects of the problem, and finally, sustain the improvements made. Various six-sigma tools like project charter, operational definition, control charts, fish-bone analysis, etc. have been used to improve the non-compliance situation. After implementing the improvements discussed in this project, there has been a significant reduction in the number of non-compliances, validated through statistical quality control tools. On the whole, this project has helped acquire a deeper insight of the application of six-sigma DMAIC approach.

Keywords: DMAIC approach, Six-Sigma, 3D CAD models

1. Introduction

1.1 Background

This project is the actual case study of a concern in a company based in Michigan – USA. The company manufactures certain components for the defense industry and also produces 3D feature based Computer Aided Design (CAD) models and drawings under agreed Technical Data Packages (TDP's) for the components manufactured. These models are generated by personnel at many facilities remote to the main office, and a lot of detail and effort goes into making a CAD model. This increases the chance of errors in the model. Therefore, sometimes, some models develop few non-compliances with the customer's requirements. This situation may not be completely eliminated; however, the fraction of models non-complaint can be significantly reduced.

Currently, about 20% of the total models in a TDP are being rejected due to evidence of non-compliance. After evaluating the TDP and the costs involved, it has been found that the resultant cost incurred is about $231K based on the combination of part, assembly and installation files. In addition to the above mentioned Non-compliance the company's reputation is also vulnerable. The wasted effort to correct the TDP models also has an impact on profits.

1.2 DMAIC Approach

This project uses the DMAIC (Define, Measure, Analyze, Improve, and Control) Six-Sigma approach to improve the condition of this problem. The DMAIC improvement cycle comprises of 5 stages. Each of these stages is described below:

Define: This phase is the first step in the DMAIC approach. It is also a very important phase, because it helps outline the key problem. It helps be more effective by eliminating the wastes involved in addressing the wrong/irrelevant issue. In this phase, the main issue, project goals and objectives, opportunities for improvement, problem-solving time frame, customer requirements, etc are defined. It is critical that the right team is gathered and all potential causes are identified. An outlier which is not accounted for can become quite evident once the main causes have been eliminated.

Measure: This phase helps to measure the extent of the problem by collecting trust-worthy data in order to compare with the data collected after implementing changes for improvement. This phase has to ensure that un-biased, accurate, effective and relevant data is collected. Inaccurate data could lead to ineffectiveness of the project. In the event of multiple sites contributing to the CAD models, the measured data was a sampling from a total production lot (all models) generated by the company.

Analyze: The main objective of this phase is to comprehend and analyze the data collected. This is the most important phase as it identifies the root causes of the problem. This phase helps identify areas of the process where improvement initiatives could result in significant changes. Simple and complex analysis tools are used during this process to arrive at identifying the area for improvement.

Improve: The improve phase helps in identifying the possible improvement strategies and techniques to arrive at a better performance of the process. In this phase, the project team finalizes and validates a change which is designed to mitigate the problem. All improvements and all necessary feedback is recorded for future analysis.

Control: The control phase is the final stage of the cycle and this stage is equally important as the analyze phase as it helps maintain and sustain the improvements made and avoids the situation of the problem going back to the initial stage on which the DMAIC cycle was originally performed. Continuous improvements are a main part of this stage.

2. Literature Review

Several frameworks and methodologies were developed by researchers and practitioners around the world for improving the productivity, safety, quality, and reducing costs in a variety of sectors. Gamal Aboelmaged 2010 reviewed 417 journal articles and classified DMAIC as one of the major suggested approaches utilized and suggested for improving the existing processes as shown in Figure 1. This section discusses few of such studies along with their results.

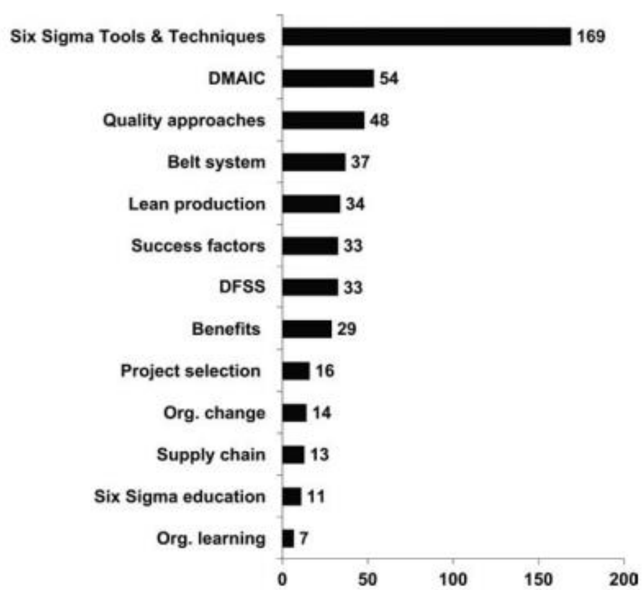

Figure 1. Distribution of Six Sigma articles by theme (Source: Gamal Aboelmaged 2010)

Aguilar-Duque et al., 2016 implemented DMAIC approach to improve the productivity of a die casting process which also resulted in material wastage of approximately 60% and a cost savings of $25,958 per year. Furthermore, Barbosa et al. applied the same approach to improve quality, reduce rework, and also check the ergonomic and safety requirements of the aircraft painting process. The learnings from a case study application in this paper not only suggest improvements in the overall process but also boost the technological innovation thereby giving an edge in the ever growing competitive market.

Ficatier 2015, utilized this approach to identify the factors that result in the non-compliance of a treatment process. That is, investigate the control process and determine the main causes that are responsible for the low compliance rate in the glaucoma treatment. On the other hand, Cunhaa and Dominguez (2015) discussed a case study implementation that measured the non-compliance, analyzed the root causes, improved the process, and controlled compliance. Tong and Tsung applied this to improve the screening process in the production of printed circuit boards (PCB). Specifically, design of experiments was used in the improve phase to determine the optimal settings that maximize the quality of the product. Other studies that discuss the advanced statistical quality techniques to improve the processes include Tsung and Shi (1999), Tsung et al. (1999), Tsung (2000), and Tsung and Apley (2002).

Lynch et al., 2003 studied the importance of scoping DMAIC projects. It is stated that scoping in the define stage of a six sigma project is very essential. Arriving at the particulars of the project and obtaining a clear and concise objective with effective restrictions for timely execution of the project is necessary in order to achieve visible improvements. It was also stated that one of the significant characteristics of a Six Sigma project is to gain quantifiable benefits in cost, quality and time. It is also mentioned that long duration projects involving a higher budget and risk should be handled by experienced Six-Sigma black-belt or master black-belt professionals.

3. Objectives

This project is done as a requirement of a Six-Sigma course. The main objectives of this study are outlined below:

a. To get a detailed understanding of the use and application of the DMAIC six-sigma approach.
b. To help reduce non-compliances in 3D CAD models using the DMAIC approach.

4. Six-Sigma Techniques

Various six-sigma tools were used in order to address the defined concern. Below are the tools split phase-wise.

4.1 Define

a. *Project Charter*: The project charter is a powerful tool that helps to outline the key concern. Various components of the project charter include project name, purpose of the project, main stakeholders, authority of project manager, team members, estimated time-frame, functional areas, project scope, goals, objectives, estimated cost of carrying out the project, estimated savings and returns, deliverables, etc.
b. *SIPOC:* The SIPOC diagram identifies the major suppliers, inputs, process, outputs and customers of a project. It is a visual tool that helps quickly arrive at the concern. They are higher-level process maps that do not usually contain much detail. The main purpose is to identify the concern.

4.2 Measure

a. *Operational Definition:* The tool helps define a clear, concise, comprehendible description of the parameters to be measured and observed. This tool is important as it standardizes the parameters to be measured, such that different entities working on the data would be able to measure and collect the same data.
b. *Data Collection:* This tool refers to the actual gathering of data from various reliable sources. All data gathered has to be reliable, un-biased, relevant, accurate and easily accessible. All the data collected has to be represented in an easily understandable form to be able to visually observe the extent of the problem.
c. *Control Chart:* Control charts are an effective tool to represent the variations of the performance of a process. Control charts help to study the process over time. A control chart has a center line for depicting the average and two control limit lines (lower and upper control limits) on either side of the average line. All these lines

are determined from historical data. There are different types of a control chart, like the mean and range control chart (x-bar and R), p-chart, np-chart, etc. different charts are used for different scenarios.

d. *Pareto Analysis:* The Pareto analysis is a depiction of the main possible root causes that result in defects in a set of products. The Pareto principle is based on the idea that solving 20% of the causes of problems would result in 80% of the advantages. All possible causes of the defects are plotted in a Pareto chart and usually the main two or three causes that cause majority of the defects are chosen to implement improvements on.

4.3 Analyze

a. *Current Process Flow Diagram*: The existing process flow diagram is an important visual tool to help us identify the steps in the process. The number of steps and the significance of each step is further analyzed to evaluate and differentiate non-value added activities from the value-added.
b. *Fishbone or Ishikawa Diagram:* This is a cause and effect diagram that helps to identify the possible root causes of the main concern.

4.4 Improve

a. *5S:* It is a Japanese methodology that helps to organize all relevant and necessary information. 5S stands for sort, straighten, shine, standardize and sustain. Research suggests that a clean, safe and organized environment motivates employees and improves the overall productivity.
b. *Benchmarking:* This refers to looking up to an entity belonging at a higher standard and evaluating our performance with respect to the higher standard. This tool helps to compare and improve the processes as against a leader in the same field.
c. *Brainstorming:* This refers to generate problem-solving solutions usually by engaging in a high order group discussion.
d. *Improved process flow diagram:* This diagram shows the number of non-value added steps eliminated from the process and helps to identify how much we have travelled from the original scenario.
e. *Value stream mapping:* This is a similar tool as a process flow map that is used to document, analyze and improve the process flow.

4.5 Control

a. *Standard Operating Procedures (SOP):* These refer to standard instructions that help in performing a task in the most correct way possible. SOPs usually consist of set-by-step instructions to carry out complex tasks. They are important in an organization in order to standardize the procedures being followed to carry out complex tasks.
b. *Training Plans*: This is another great tool to sustain improvements. Training helps to convey and communicate improvements to a wider audience and helps in a united approach to sustain them.
c. *Communication:* Communication is the key to reaching out to everyone in the organization and involving the relevant to help maintain the improved condition.
d. *Implementation:* This tool ensures that all necessary documents and relevant information is available to all the staff involved. A strong implementation strategy is definitely instrumental in bringing about a wide-range change.
e. *Support Team:* This is essential in addition to a good implementation strategy. No employee must feel unequipped with any information or data that stops him/her from contributing to an improvement.

In summary, the phase-wise split of the six sigma tools used in this project are listed below in the following table, Table 1.

Table 1. Six Sigma tools used

Define	Measure	Analyze	Improve	Control
• Project charter • SIPOC diagram	• Operational definition • Data collection • Control charts • Pareto analysis	• Current process flow diagram • Fishbone diagram	• 5S • Benchmarking • Brainstorming • Improved process flow diagram • Value stream mapping	• SOP • Training plan • Communication • Implementation • Support team

5. Data

Data collection is sub-divided into three stages: Pre-data collection, during data collection and post data collection. During the pre-data collection stage, list of all applicable file types to be included in the TDP are obtained. The file readiness is approved by project management and designers/engineers. And, configuration management conserves revision and version level of CAD files. Further, during data collection, part, assembly and installation CAD files are audited by modeling and drawing compliance team. Audits validate a distributed checklist that is communicated by stakeholders. Compliant and noncompliant components are recorded and submitted for corrections. Finally, post data collection, the designer/engineer confirms audit results and implements CAD corrections. Compliance reviewers verify CAD models. Configuration management collects final CAD models as compliant TDP.

6. DMAIC Application

6.1 Define

The problem was identified with the help of a project charter and the SIPOC diagram as shown in Table 2 and Figure 2 respectively. The Project Charter in Table 2 is crucial for project cohesion and eliminating opportunity for project scope creep. The charter should provide clear support for upper level sponsorship and lay the foundation to support solutions for questions for team members. The project purpose is to establish the need for a model compliance process and a path to provide Technical Data Packages acceptance by the customer. The Charter also identifies the rules and what data (drawings) will not be included in the project.

Table 2: Project Charter

Prepared by	Ramani Ayyagari/Ramon Banuelos
Date Issued	03.17.2018
Project Name	Technical Data Package CAD Model Compliance
Purpose of Project	To provide modeling compliance to all new feature based Computer Aided Design (CAD) part and assembly models. Currently non-compliance is causing a delay in Technical Data Packages (TDP) which serve as a contract deliverable to the customer at the end of the program/project. The TDP has been a focus of for all new programs and projects with specific measurements for compliance. Currently TDP's are being rejected by the customer with an average of 20% errors in regard to non-compliance. This rejection equates to $1K per part, $2K per assemblies, and $5K per installation. The purpose of the Six Sigma project will be to implement the DMAIC phases to reduce non-compliance in all CAD models for 100% customer acceptance of TDP's.
Business Case/Need (Business reasons for the project)	The cost of prototyping errors when the latest revision is not provided creates delays in timing and additional cost effecting the prototype build.
Team Members	Ramon Banuelos, Ramani Ayyagari and compliance team
Estimated project duration	Three months
Functional Areas Involved	Design, Engineering, Checking, Project Management, Supply Chain, Configuration Management and IT services
Suppliers to the Process	Customers, team responsible for identifying non-compliances.
Project Scope (start/end)	Start: 1.19.18 End: 5.18.18
Not included in Scope	All drawing types will not be included in this project. Upon successful compliance mapping to all CAD model types, drawings will be included in a similar project.

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Project Goal(s) (What is it intended to achieve?)	The project goal will be to establish compliance measures for all CAD models (part, assembly and installations) to meet TDP acceptance at any of the three defined TDP levels.
Estimated Cost $	Cost estimation for the 4 month project is: 160(4)*4*75= $192K 1 month =160 hrs 4 heads per month $75 per hour
Timeline and estimated project completion date	Start of Project 1.19.18 Measure 2.19.18 Analysis 3.22.18 Improve 4.12.18 Control 5.10.18
Estimated Savings $	The latest rejected TDP was for 847 drawings consisting of: 758 parts/37 assemblies/52 installations. By reducing the model defects a 20% savings equates to $231,000 plus company reputation.
Final Deliverable(s)	The six sigma DMAIC process will establish a compliance method for all modeling to result in full acceptance of all TDP's with the customer
Team Leader Signature	Ramon Banuelos
Management Signature	TBD

The SIPOC diagram as shown in Figure 2, captures the flow of generating the models from the suppliers and inputs to the process, and then the final outputs and customers at a high level. It is important that all criteria be reviewed. Using these six-sigma tools provide a safety net to ensure all causes that could affect the inputs and outputs are being defined. It can be costly if an outlier not captured will become visible once the known causes are removed.

The modeler faces many decisions and it becomes apparent that the opportunities to freelance and establish modeling conditions can be unique across the company's location. Multiple programs will have unique requirements and non-compliant models can be generated quite easily. It is important to note that establishing a standard that applies to all programs/projects is required and formal Standard Operating Procedures must be written and applied to all company locations.

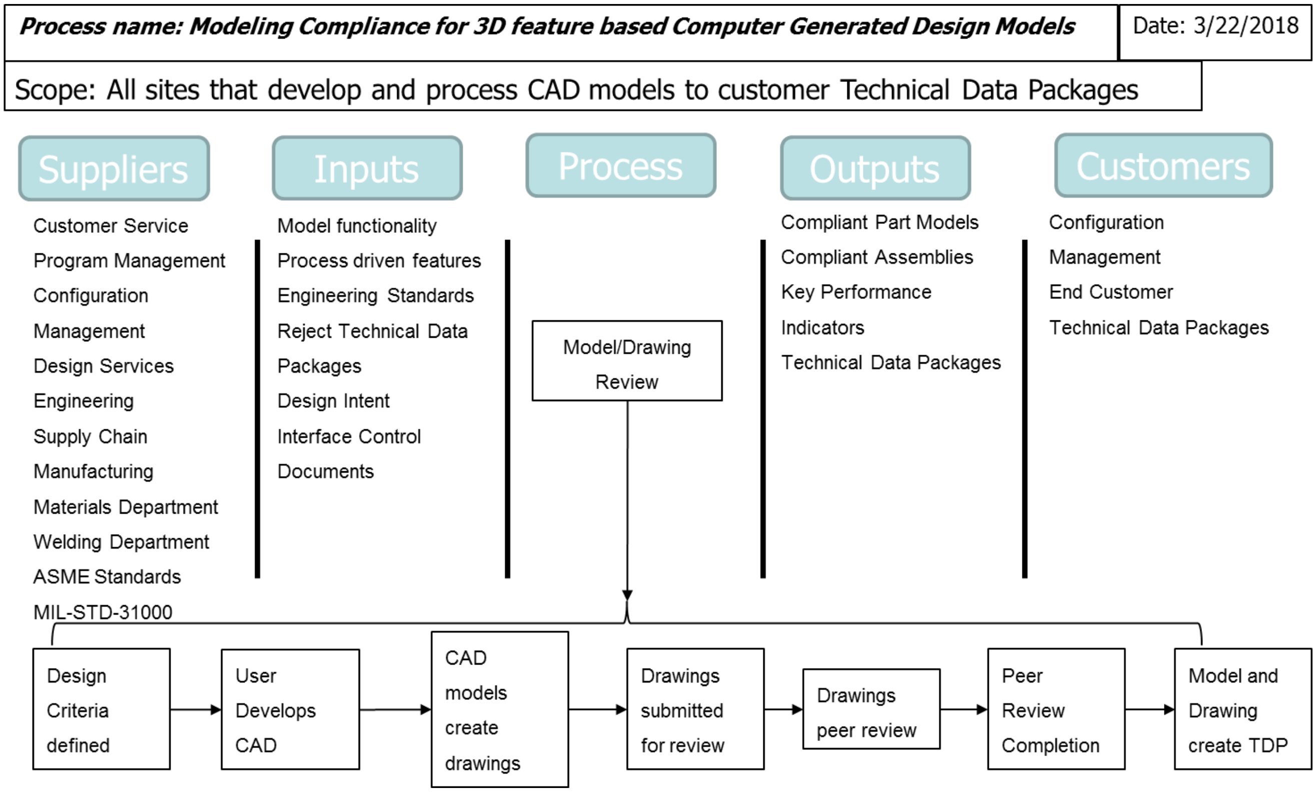

Figure 2: SIPOC diagram

6.2 Measure

The tools used to measure the performance of the process were operational definitions, data collection, control chart and Pareto analysis.

6.2.1 Operational Definition

The file checks that constitute an approved TDP were collected by reviewing the TDP sub-packages representing the complete TDP delivery. All files within each sub-package were reviewed upon delivery into the Product Lifecycle Management (PLM) upon the receipt of the TDP full package by the customer. Part, Assembly, and Installations were evaluated to the following non-compliance which resulted in a TDP non-compliance.

To collect data on all TDP CAD files, a complete compliance check had occurred and metrics were identified and logged for analysis. Re-occurring noncompliance issues were addressed for correction through training or specific correspondence addressing the issues.

6.2.2 Control Charts

The P-chart is a category of control charts that can monitor the variation of proportion non-conforming/non-compliant units in a sample. Figures 3, 4 and 5 show the P-charts for rejected parts, assemblies and installations respectively. In the below Figures, we can see that the average proportion non-compliant is the center line. The LCL (lower control limit) and UCL (upper control limit) are 3 standard deviations above and below the average (center) line. There is a varying UCL and LCL due to the varying sub-group sizes of the non-compliant proportion data available.

In Figure 3, the average non-compliant proportion of the P–chart of rejected parts is 0.197. There are a total of 26 technical data packages (TDPs) or points plotted on the control chart. In Figure 4, the P-chart of rejected assemblies has a center average proportion defective of 0.289. There were assemblies available for only 9 of the 26 TDPs, which were plotted on the control chart in Figure 4. In Figure 5, the P-chart of rejected installations has a center line at 0.231. Again, only 11 TDPs had installations as components. In all the three Figures, it can be seen that there are no points lying outside of the control limits. This tells us that the proportion defective (non-compliant) are in control. However, this does not mean the variation in proportion non-compliant is acceptable. There could always be room for improvement, the fluctuation could be minimized and, the average proportion non-compliant could be reduced.

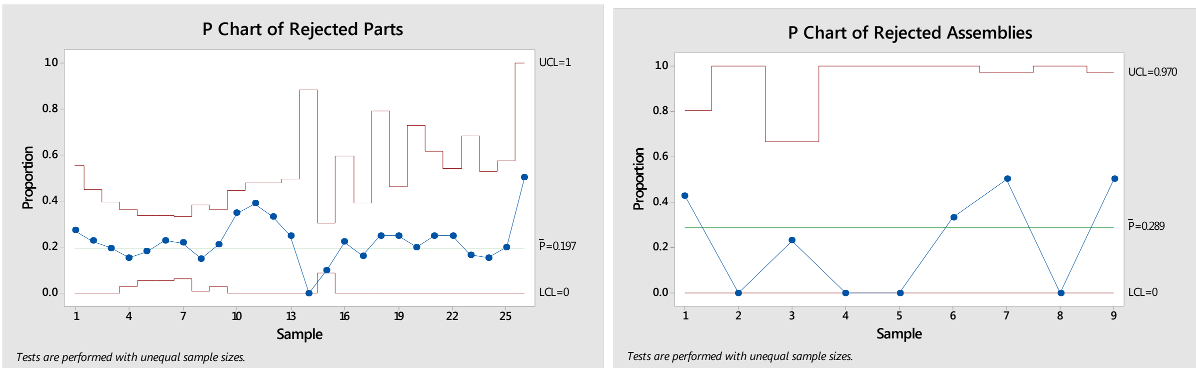

Figure 3 and 4: p-charts of rejected parts and assemblies

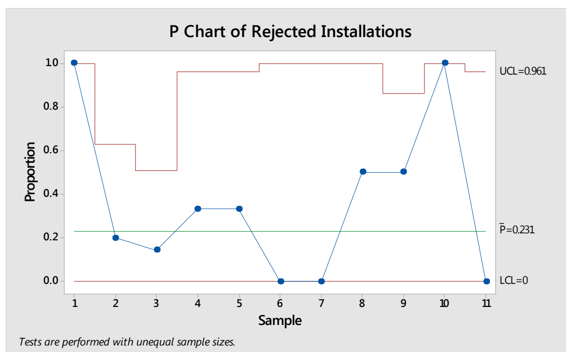

Figure 5: p-chart of rejected installations

6.2.3 Pareto Analysis

The Pareto chart depicts the main factors causing defects in the CAD models. The Pareto analysis is mainly based on the principle that eliminating 20 % of the root causes can solve 80% of the problems. Figures 6, 7 and 8 show the Pareto analysis for parts, assemblies and installations respectively. The vertical blue bars refer to the histogram of defects arranged in the order of largest to smallest number of defects caused by particular root causes; and the green lines represent cumulative percentage of the defects.

As can be seen, the main root causes in Figure 6 are layers and suppressed features, followed by the rest of the causes. In Figure 7, Pareto chart for assemblies, external references is the major root cause, followed by the rest of the root causes resulting in the same number of defects. Figure 8 shows the main root causes in non-compliances in installations, which are component order and external references.

The Pareto analysis suggests that by solving these main root causes resulting in a larger number of defects, the total non-compliances/defects can be significantly reduced.

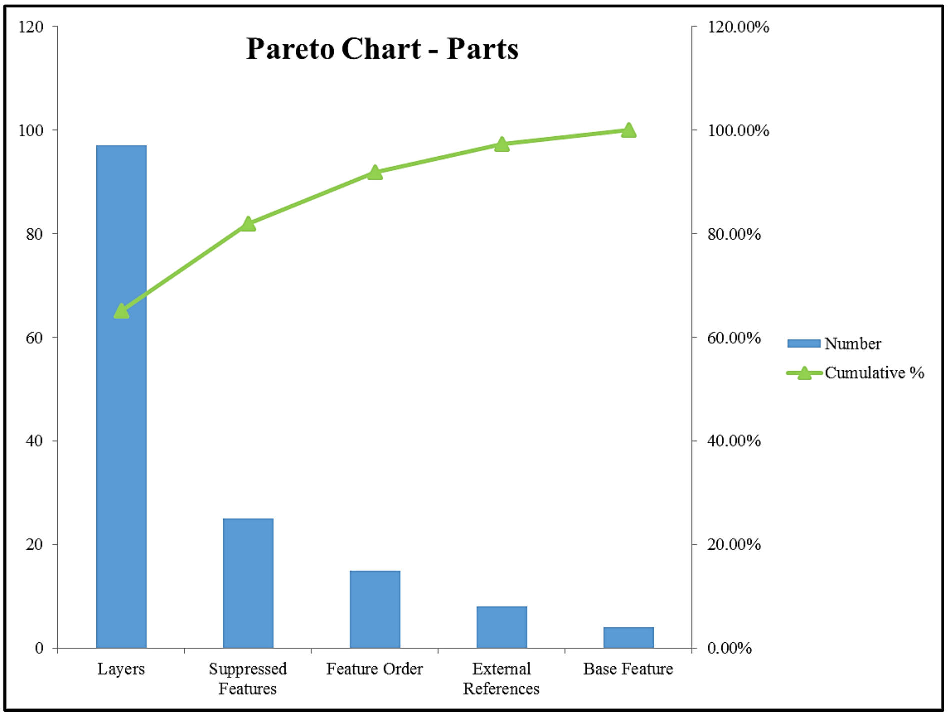

Figure 6: Pareto analysis - Parts

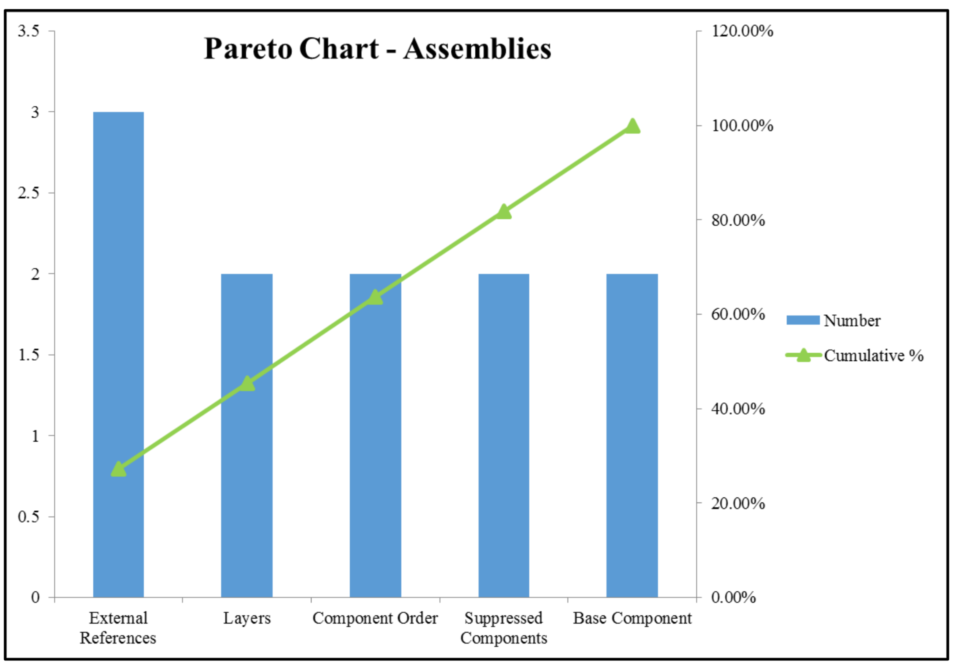

Figure 7: Pareto analysis – Assemblies

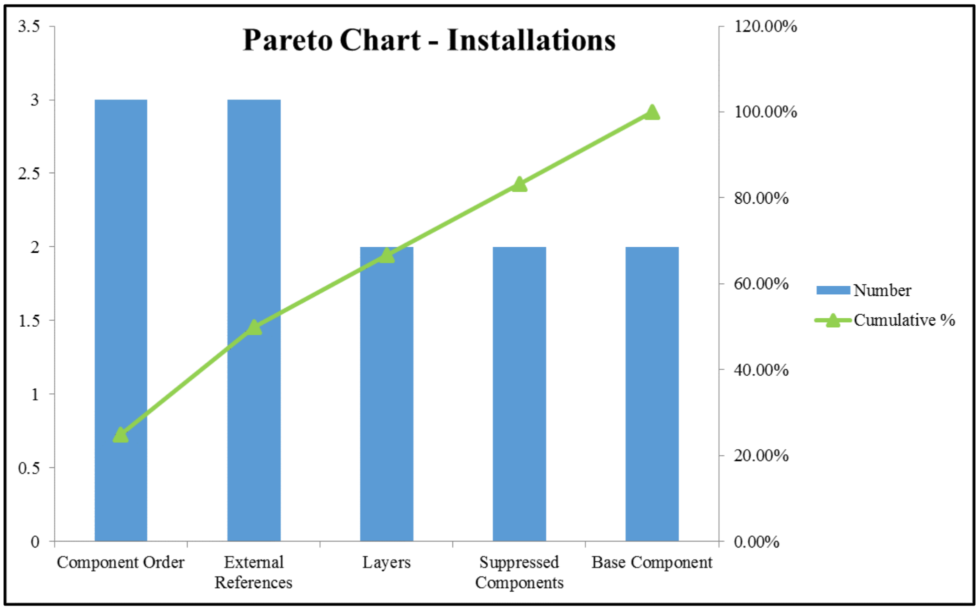

Figure 8: Pareto chart – Installations

6.3 Analyze

Process flow diagram, and the fish bone analysis were used as effective tools to analyze and identify potential root causes of the problem. They are shown below in Figures 9 and 10 respectively.

6.3.1 Current Process Flow

The current process flow in Figure 9 captures the re-work of rejected CAD files from rejected TDP's. Not only is there a CAD model repair, but data must be transferred from Configuration Management (CM) and processed outside the Data Management system. This creates an un-parallel link to the company's current version and revision models and the customers. This dis-association will required future laborious updates for any future revision changes.

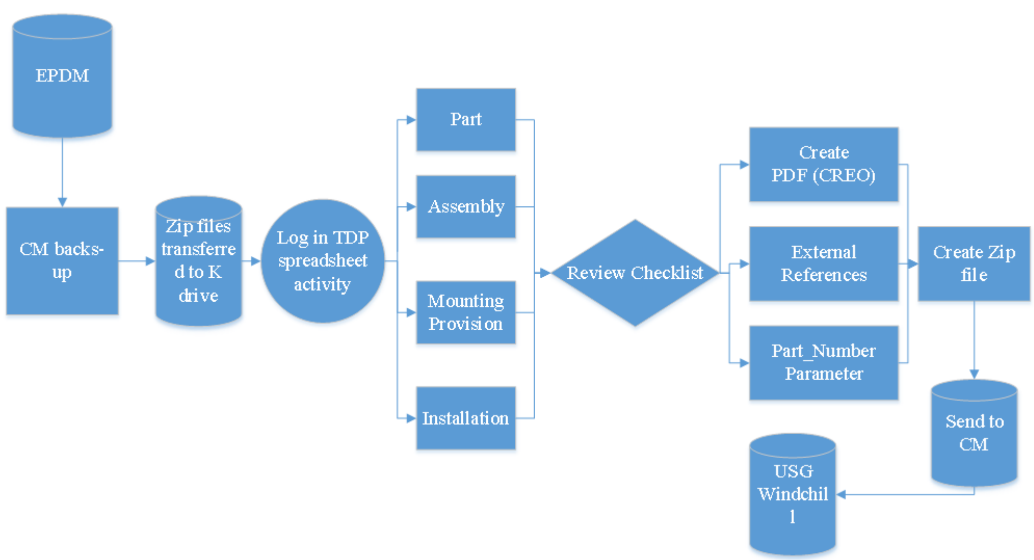

Figure 9: Current process flow diagram

6.3.2 Fishbone Diagram

The Fishbone Diagram, also known as a Cause and Effect Diagram in Figure 10 is extremely helpful visual tool to identify inputs that provide opportunities for modeling non-compliance. This allows the team to look beyond the modelers capabilities and seek possibilities for modeling errors from external sources. The customer can create conditions when providing direction or suggestions that may seem contrary to modeling standards. Following the ASME and MIL-Standards can also relate to modeling non-compliance due to when only the standards are partially adhered too.

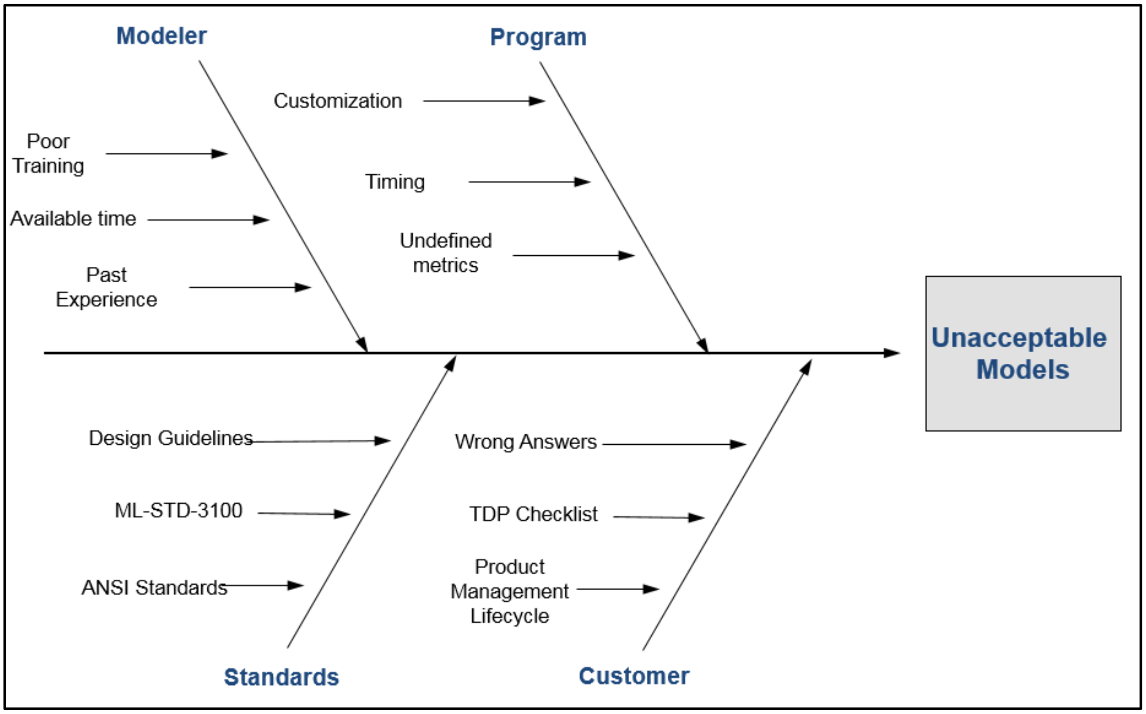

Figure 10: Fish-bone diagram

6.4 Improve

5S, benchmarking and brainstorming, improved process flow and value stream mapping were used to arrive at improvements to the existing process. The improved process flow diagram and value stream napping for the improved process are shown in Figures 11 and 12 respectively.

The Improved Process flow in Figure 11, captures the compliance check for TDP's prior to customer delivery. With the introduction of the Standard Operating Procedures (SOP) and supported by previous established Modeling Standards, the modeler and compliance team can establish a baseline for model compliance.

All non-compliance issues will be monitored and data collection will result in metrics that will be used to identify trends in non-compliance to be either reinforced by SOP revisions or additional training. The initial data collection will be a manual process, and will eventually be replaced with a more automated checklist that will be developed by Engineering Services IT.

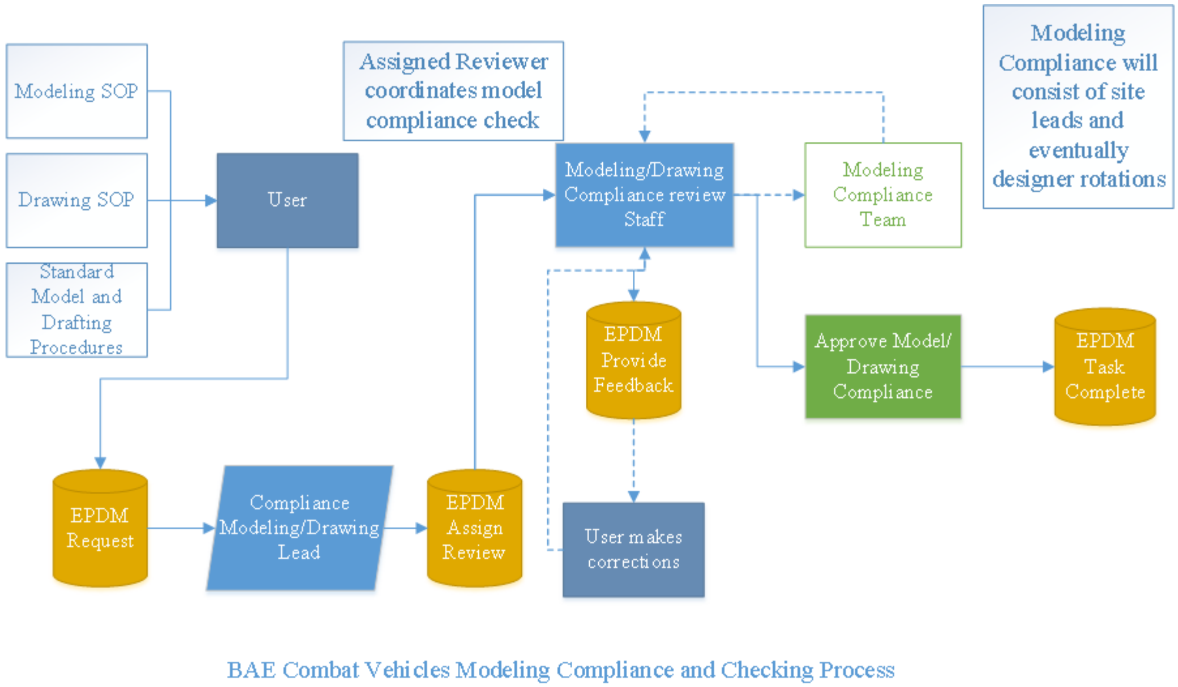

Figure 11: Improved process flow

Value Stream Mapping was used to define a final process flow to capture real work in process (Figure 12). This will be the final solid state compliance review in which model compliance can be reviewed prior to any official release and metric tracking will be available to all stakeholders. The ultimate goal was to establish a process where the compliance checks can occur simultaneously with the models progression towards drawing release. It should be noted that due to manpower the compliance would still be a sampling of the population, due to resources and workflow.

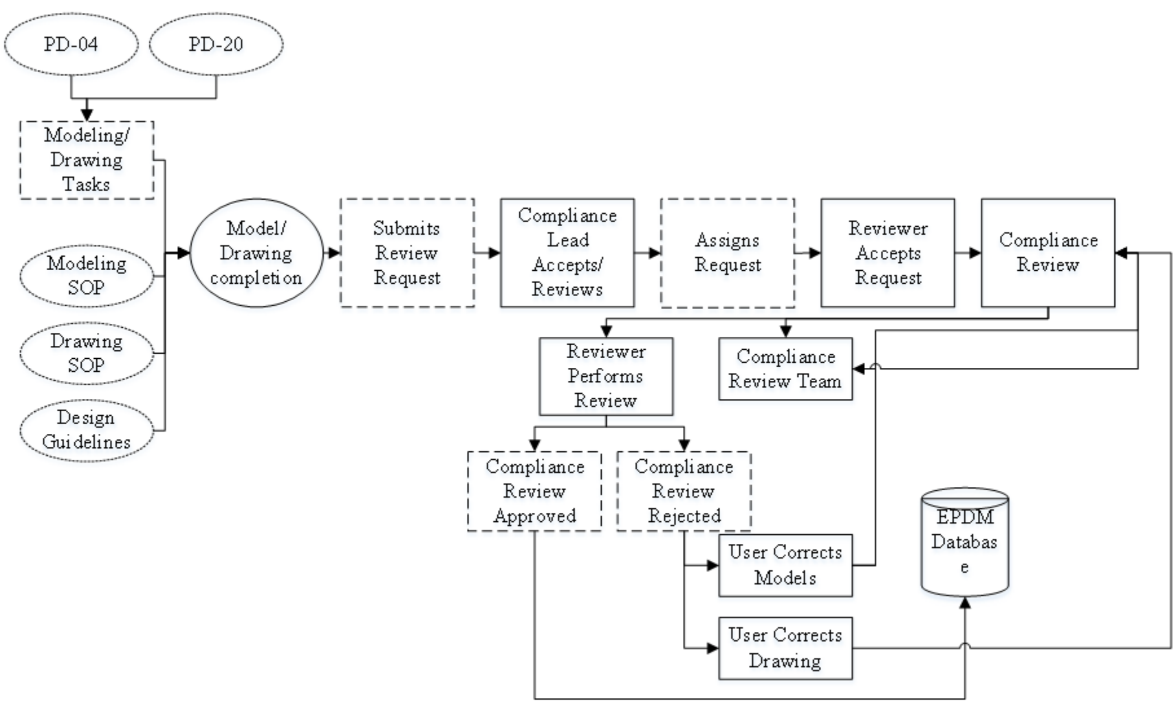

Figure 12: Value stream map for the improved process

6.5 Control

This phase employed the use of Standard Operating Procedures (SOP), training plans, communication, implementation and modelling support to sustain the improvement and CAD reviews by the Compliance Team. The following measures were taken:

SOP: All necessary steps of the process were documented in detail. All existing SOP are revised to contain stringent measures to avoid chances of noncompliance and rework. The 5S were also introduced and converted to CAD housekeeping: Set in Order – Establish base features and components to do the heavy lifting, Shine – Focus on layers and design intent, Standardize – Reference the SOP for feature creation and assembly dependencies, Sustain – Organized parametric models will be more flexible and allow other users to manage them, and Sort – Model Tree management will organize features in a logical, cascading and robust manner.

Training Plan: Two half-day introduction sessions to the revised SOP are conducted.
Communication: Email notifications, Webex rollout (Virtual meeting) for two half-hour sessions, and biweekly informational training sessions are being carried out.
Implementation: All relevant documents and SOPs are kept accessible to necessary employees.
Modelling support team: A full-time appointed team is employed to help designers create error-free models

CAD compliance review was also a critical step in the corrective action of non-compliant models. A sampling of the population was reviewed by the team and non-compliance was identified and corrected. The use of automated Model-Check provided a great deal of scripting and a manual process covered the missing compliance steps.

7. Results

Post-implementation of the improvement tools of the DMAIC approach, proportion of non-compliant parts, assemblies and installations non-compliant were collected and analyzed for validation of improvement. It had been noticed that the number of non-compliances post improvement were substantially reduced. The non-compliances in parts were found to be 2 out of a sample size of 758, and the non-compliances of assemblies and installations were nil. Therefore, improvement was measured only for non-compliances in parts through a. Control chart, b. Pareto analysis and c. Hypothesis testing.

Figure 13 shows the P control chart for the non-compliant parts post improvement. It can be seen that the variation of proportion non-compliant is in control, with average non-compliant proportion at 0.0026 (the center line) and UCL and LCL at 0.1115 and 0 respectively. Most of the points lie at LCL, while 2 points lie within control limits.

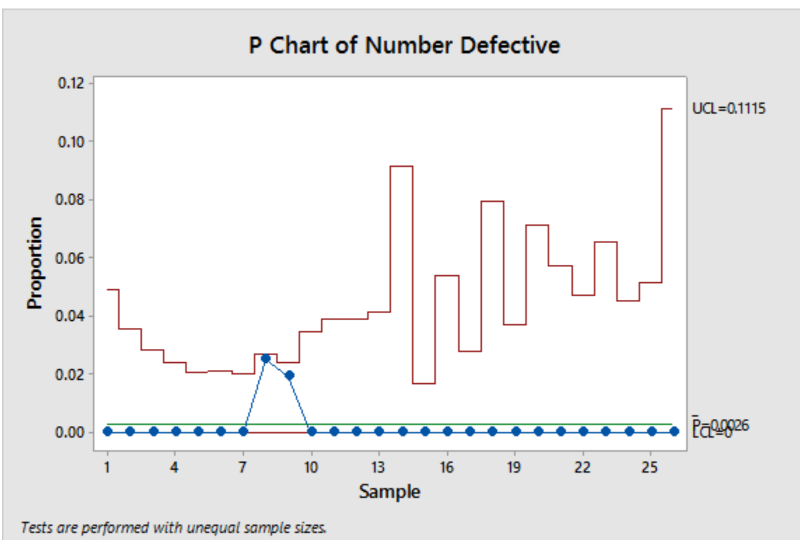

Figure 13: P-chart of rejected parts post improvement

Figure 14 illustrates the Pareto analysis of rejected parts. There is only one root cause resulting in the 2 defects, which is layers. It is noticed that the rest of the root causes are eliminated post improvement and no resultant defects are found.

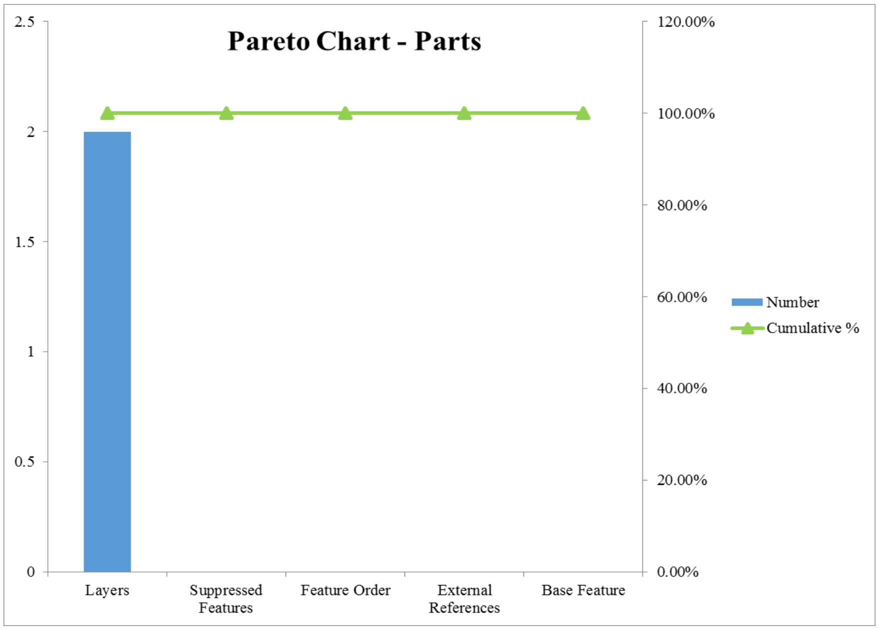

Figure 14: Pareto Analysis of rejected parts

Another validation technique used to measure the improvement is hypothesis testing. For this scenario, proportion hypothesis testing method was used. Test was conducted to observe if the proportion of defects had improved. Since it is conducted on the same number of samples, proportion testing is conducted to show the statistical significance.

$H_0: P <= 0.2$
$H_a: P > 0.2$
$x = 2, n = 758$
Since $x < np_0$ i.e. 2 < 758*0.3 = 151.6

$$Z_0 = \frac{(x + 0.5) - np_0}{\sqrt{np_0(1 - p_0)}} = \frac{2.5 - 151.6}{\sqrt{151.6 * 0.8}} = -13.53$$

$$P(Z > -13.53) = 1 - P\ (Z < 13.53) \cong 1 = pvalue$$

Assuming $\alpha = 0.05$

Since $pvalue > \alpha$, we do not have evidence to reject the null hypothesis. Hence, the new proportion or the number of defects are lesser than the previous number of defects.

8. Conclusion

This project successfully applies the concept of DMAIC to a real situation and effectively helps to mitigate the problem. Various six sigma tools were discussed and understood in detail in the course of this project. Although the DMAIC processes were implemented, the true tool of success was communication.

Upon developing an SOP and supporting Guidelines for various modeling techniques that were posted in the company's intranet, it was the physical SOP introduction sessions that brought awareness and understanding of the need to improve modeling quality. The directive was also supported by upper management in companywide webinars.

It was also recognized that the formal documentation that would govern compliance be processed as official company documents and additional training be available. The SOP's would also become mandatory on-boarding material for all direct hires and contractors that would be model generators.

The Compliance Team was a necessary action to act as a go-no-go gage. In the initial stages the reviews were manual with the assistance of Model Check, but future efforts would be coordinated with the Information Technology (IT) for automated processing and retention. It is important that critical metrics be identified and made available for progress review and future training for items that continue to be non-compliant.

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