Evaluating reliability of diesel generator peakers using Six Sigma methodologies

Salma Shaik, Scott M. Sampson and
Matthew J. Franchetti*

Department of Mechanical, Industrial and Manufacturing Engineering,
The University of Toledo,
Toledo, OH 43606, USA
Email: salma.shaik@utoledo.edu
Email: scott.sampson@rockets.utoledo.edu
Email: matthew.franchetti@utoledo.edu
*Corresponding author

Abstract: This case study demonstrates the application of DMAIC process improvement methodology to improve the reliability of diesel generator peaker units when called into activation. Although the application of Six Sigma methodologies is commonplace in manufacturing industries, they lack the same level of adaptability in non-manufacturing processes and service industries especially in power generation sector. The main objective of the present case study is to address this gap by developing a thorough analytical framework that can be adapted to improve the reliability of peaker units in any business sector based on Six Sigma methodologies. Failure in control systems, temperature extremes, incorrect flagging of the unit as available were some of the major causes identified for the failure of peaker units.

Keywords: peakers; diesel generators; reliability; Six Sigma; process improvement; design-measure-analyse-improve-control; DMAIC; continuous improvement; case study.

Reference to this paper should be made as follows: Shaik, S., Sampson, S.M. and Franchetti, M.J. (2021) 'Evaluating reliability of diesel generator peakers using Six Sigma methodologies', *Int. J. Six Sigma and Competitive Advantage*, Vol. 13, No. 4, pp.456–476.

Biographical notes: Salma Shaik is a PhD candidate in Industrial Engineering at University of Toledo. Her research interests span the applications of data analytics and machine learning to gain valuable insights and to develop predictive models in diverse fields such as criminal justice and sustainability. She has over eight years of work experience in corporate and academic sectors.

Scott M. Sampson is a practicing Mechanical Engineer in Northwest Ohio. He earned his BS in Mechanical Engineering in 2018 and his MS in Mechanical Engineering in 2020 from University of Toledo.

Matthew J. Franchetti is a Professor in the Mechanical, Industrial and Manufacturing Engineering and the Associate Dean of Undergraduate Studies at the University of Toledo, USA. He has worked as an Industrial Engineer and Technical Manager for the US Postal Service. He received his PhD (2003) in Industrial Engineering and MBA (2000) from the University of Toledo, USA. He is certified Six-Sigma black belt from the American Society of Quality (ASQ).

1 Introduction

Electricity is a necessity for modern world and has propelled the development of societies and growth of economy. Improvements in living conditions across the world, rising household incomes, advent of electric vehicles and increasing usage of electrical and electronic equipment, contribute to the ever-increasing demand for electricity. According to the International Energy Agency (IEA, 2019), developing economies are emerging as the major players for increased electricity demand contributing to nearly 90% of global electricity demand growth by 2040 (IEA, 2019). IEA further reports that the largest share of electricity consumption is by industrial sector which is projected to increase by almost 30% between 2018 and 2050. One of the major contributors to the growth in electricity demand is the growth of Information and Communication Technology (ICT) sector. As mentioned by Smil (2000) and Mills (2013), an increasing portion of our economy in this 'instantaneously interconnected global civilisation' is powered by electricity. Based on Andrae's work (Andrae et al., 2015), Jones (2018) discusses that the electricity demand of ICT sector is projected to constitute more than 20% of the electricity demand by 2030.

Though almost 13% (around 940 million people) of the world's population still lack access to electricity, it is certainly hoped that everybody in any part of the world will get access to electricity in the future. Even in developed countries, power outages or discrepancies in power supply would create havoc as most of the appliances are electric and majority of daily tasks such as cooking, cleaning, lighting, HVAC, communication, etc. are dependent on electricity. As the world is racing towards to being a truly global village interconnected by telecommunications, the demand for electricity is only going to go up. In order to meet this increasing demand, hundreds of MW of additional peaking power will be required (Gravity Power, 2017). Baseload generation of electricity is sufficient under normal circumstances when the power required by the electrical grid is fairly constant during various times of the day. But during a special event or an extreme temperature scenario, high demand occurs which contributes to peak loading and higher prices (Sino Voltaics, 2015; ESA, 2020). As such, electricity providers should develop optimised processes and set up systems in place that help them to cater to the fluctuating demands while maintaining efficiency and profitability.

To serve businesses and general public with reliable and uninterrupted supply of electricity, as a public utility, electrical providers receive funding from state and local governments based on the amount of MW that they can generate and supply to their customers. In addition to the main power plants, many of them also operate fleets of peaking power plants which generally sit on standby and only run when demand for electricity is at its peak. Hence, it is very important to ensure that a peaker is reliable and that it will start up properly, when called into activation. Because funding is directly tied to the ability of a unit to successfully provide power, even small increases in reliability can ensure that funding remains secure. Also, units that remain in service for longer periods of time provide a larger degree of return on investment for their owners. This makes reliability a top priority for engineers that are responsible for peaker units.

The current paper discusses a case study which utilised Six Sigma DMAIC methodology to analyse the performance of diesel peaker units operating during peak demand hours at a public utility company. To retain funding and customer base, it was essential for the company to thoroughly evaluate the performance of its peaker units. This study helped the company in identifying the potential causes affecting the reliability of peaker units and provided recommendations to improve their performance and reliability.

2 Literature review

The concept of Six Sigma, a quality improvement and business strategy, was originally introduced by Motorola Corporation in 1987 which set a goal of producing only 3.4 defects or problems per million opportunities (Barney, 2002; Folaron, 2003). Another widely popular success story is that of General Electric which implemented Six Sigma in their operations under the supervision of Jack Welch, the then CEO of GE. This ensured excellent quality of GE products which ultimately resulted in a $12 billion savings for GE (6Sigma, 2017). In order to achieve such success, rigorous implementation of Six Sigma methodologies such as design-measure-analyse-improve-control (DMAIC) is warranted. Based on the report by Dusharme (2001) for Quality Digest's Six Sigma Survey, Bane (2002) identified that around 47% of the responders were applying Six Sigma in areas such as customer service, purchasing, etc. Further, Akpolat (2004) discussed how Six Sigma started to gain wide acceptance in non-manufacturing, service, and business process industries from the late 1990s to help improve processes, achieve high operational efficiency, reduce waste and minimise costs. The comprehensive literature review on Lean Six Sigma for services by Sunder (2018) provides evidence that, in spite of certain shortcomings, both Lean and Six Sigma have great advantages in the service sector applications. Recent studies have discussed relevant Six Sigma methodologies for use in industry applications (Ahmed et al., 2020; Sánchez-Rebull et al., 2020; Tsarouhas, 2020; Francisco et al., 2020).

Though there are few studies investigating the applications of Six Sigma methodology in power sector, they are still lacking and relatively scarce. Prabhakar and Dinesh (2009) and Sudhakar (2015) implemented Six Sigma DMAIC methodology in thermal power plant to achieve improved performance. But their main focus was on providing recommendations for reducing de-mineralise water consumption in power plant. Further, Singh and Bakshi (2014) conducted a case study utilising Six Sigma to optimise the backup power systems in India with the goal of reducing running cost through parametric optimisations. Sony (2019) reviewed the possibility of transforming the ailing power sector organisation in India using LSS and based on the findings, emphasised that efficiencies, profits and customer satisfaction in generation, transmission and distribution of electricity can be achieved using LSS tools. But the study may not be immediately generalisable beyond Indian markets and there was no particular attention on peaker units.

Since peaker units are used when the demand for electricity is maximum and crucial, it is of paramount importance to ensure that peaker units are reliable and function well when activated so that the businesses are not affected, and life isn't disrupted. Al-Shaalan (2019) emphasises the need for evaluating reliability of power systems as a vital component in planning, designing, and operation of power systems. Ericson and Olis (2019) outline that power outages lead to losses in productivity, revenue and customers for businesses. Grid reliability becomes especially important to ensure the resilience of power infrastructure during extreme weather conditions such as hurricanes, heat waves, wildfires, storms and deep freezes (King, 2019). Interest in the generators as a source of reliable backup power has been steadily growing to avoid costly power outages due to the severe weather events. Decision makers should have a good understanding of the cost and reliability associated with backup generators or peaker units (Ericson and Olis, 2019).

As evident from the literature, there is a need for research to find solutions for improving the reliability of peaker units to deliver reliable service, sustain revenues and government funding. Studies in power generation sector are lacking and to our knowledge a comprehensive study that incorporates Six Sigma methodologies to evaluate the reliability of peaker plants has not been carried out so far. Since the consequences of unreliable peaker units are devastating, it is important to carefully analyse the reliability of peaker plants and take corrective measures to make sure they are efficient with 6 sigma process capabilities. To address this gap in research and the growing need for electricity providers to stay afloat in a competitive and challenging market, the current paper conducts a detailed analysis of peaker units by adopting various Six Sigma concepts. Main contributions of this novel research study are to provide a

1 framework for evaluating the reliability of the startup operation of a diesel generator using Six Sigma (DMAIC) methodology

2 recommendations and guidelines for process improvement that can be used to improve the reliability of a Six Sigma process

3 foundational work for future research.

Table 1 DMAIC methodology overview

Step	*Functionality*
Define	Describe the problem
	Identify and validate the opportunity for improvement
	Identify and map related processes
	Create team charter to implement the improvements
Measure	Identify how the process currently performs and the magnitude of the problem
	Develop the methods by which data will be collected to evaluate success
	Gather and analyse current state data
Analyse	Understand the true root causes of process issues
	Verify hypotheses before implementing solutions
	Develop a plan for improvement
Improve	Generate and discuss solution ideas
	Implement solutions to resolve the root causes
	Collect data to confirm there is measurable improvement
Control	Develop a monitoring plan to track the success of the updated process
	Craft a response plan in case there is a dip in performance
	Document the improved process

Source: Swan (2017), Corley (2019), SSD (2014) and Rastogi (2018)

3 Methodology

Six Sigma DMAIC methodology has been adapted for the study since it is one of the popular process improvement and quality control methodologies as epitomised by various success stories and literature presented above. DMAIC continuous improvement model provides a structured way of improving a process and is an integral part of any Six Sigma initiative (Kumar, 2018; EPM, 2020). Table 1 provides a brief overview of each phase of the traditional DMAIC model (Swan, 2017; Corley, 2019; SSD, 2014; Rastogi, 2018).

As a general hypothesis, this Six Sigma improvement plan was intended to yield a startup process for peaker units that will be far below the standard necessary to be considered a high performing Six Sigma process. The Six Sigma DMAIC methodology as explained in Table 1 was applied to a case study involving a public utility company to evaluate the reliability of a group of diesel generator peaker units with the goal of identifying potential solutions to address and improve reliability.

Table 2 Modified DMAIC methodology

Step	*Functionality*
Define	Pre-research information gathering
	Defining reliability
	Identifying needs for improvement
	Defining the problem
	Parameters and constraints for the project
	Defining the factors to be measured, analysed, improved and controlled
	Defining stakeholders
Measure	Data collection
	Data categorisation
Analyse	Analysing the current reliability of DG peaker units
	Identifying the potential root causes
	Characterising failure in control systems during the startup operation
	Characterising extreme fluctuations in temperature
	Analysis of operational errors
Improve	Review of failure in control systems during the startup operation
	Review of extreme temperatures
	Review of operational errors
	Review of mechanical component failure
Control	Control of Failure in control systems during the startup operation
	Control of operational errors
	Control of mechanical component failure
	Control of extreme temperatures
	Update of process procedures

3.1 Adaptation of the DMAIC process to the diesel generator peaker units

The DMAIC methodology for this project was modified based on the goal of the study, constraints, and key stakeholder feedback. The modified methodology is displayed in Table 2.

3.2 Study site background

The company with which this case study was performed is a public utility company, providing electricity to a variety of residential, corporate, and government customers. Company strives to provide uninterrupted and reliable power to all its customers by adopting best practices in its operations and continually monitoring and improving its power generation processes. The company receives funding from the state and local government to ensure that its power generation is able to meet the demand for power from their customers, even during peak hours. If the company promises a certain number of MW to be generated on a given day and then fails to generate that amount due to an unexpected outage, the company is at risk of losing funding. Hence, it is important that their generators are reliable, so that there are no lapses in service, and it is in the best interest of the company to maximise the number of MW of electricity that they output. Since the units don't run all the time, they have to be continually monitored and repaired to ensure that they are ready to run when called upon.

Diesel generators which are used by the company to cater to the electricity demands during peak loads are considered for this analysis. Diesel generators were preferred by the company due to their lower capital costs, lower component costs, ease of operation and maintenance, ability to fully deliver power within seconds to meet electric system interruptions, storage of fuel on-site, ready availability and flexibility for new units to be added to meet changing needs are some of the other advantages (Ericson and Olis, 2019).

Evaluating the reliability of peaker units is an example that demonstrates how engineers across many industries are often faced with analysing and optimising different systems. The main purpose of evaluating reliability is to obtain appropriate measures to gauge the performance, identify potential issues and solutions that can be implemented in order to improve the reliability of the unit. Six Sigma DMAIC methodology was chosen for the study because it can be a powerful tool in analysing the reliability of a given mechanical system as well as setting a standard that can be pursued as part of process improvement activities.

4 Case study

The DMAIC methodology was used for this case study at the public utility company to evaluate the reliability of a group of diesel generator peaker units. The methodology was based on several studies cited in recent literature (Ahmed et al., 2020; Sánchez-Rebull et al., 2020; Tsarouhas, 2020; Francisco et al., 2020). The main objective was to present potential solutions to understand and address reliability issues. A diverse team of subject matter experts, team leaders, engineers and operators identified the need for improved reliability of peaker units and developed an action plan to gather data, apply the DMAIC methodologies and to gain insights. Through data collection, interviews, and data analysis, various factors affecting the reliability of peaker units were identified and potential solutions to mitigate these effects were recommended. Following sections discuss the implementation of Six Sigma DMAIC methodology with respect to the current study.

4.1 Define

During this step, meetings with team administrators and site leaders were performed to help define the problem, scope and goals of the project and to formulate a path forward. Primary focus is on identifying as well as refining the problem in a way that there is an attainable goal with a measure to show quantifiable progress (Raisinghani et al., 2005).

4.1.1 Pre-research information gathering

During the pre-research information gatherings, interviews with various subject matter experts (SMEs) and team administrators were performed to gather information about the problem that could be addressed by the research. During these meetings, it was unanimously agreed and established that high reliability of the peaker units is essential for their operation. This is due to their nature as 'peakers', meaning that they are only called upon during peak operating hours when the grid is under high strain and needs increased electrical output. Outside of these peak hours, the units are held in reserve, or stand by, ready to be called into service remotely on a moment's notice. Because of this, there is little room for failure and high reliability is essential. Consistent failing of the unit to start when called upon or tripping unexpectedly could be signalling that reliability of the unit may be a large problem. These types of red flags can be quickly picked up on by reviewing run reports or speaking with site personnel who are responsible for starting up the unit.

4.1.2 Defining reliability

In the context of this study, reliability is defined as the ability of a unit to successfully start when called upon. Thus, a unit would be considered 100% reliable if it started properly every single time it was called into service. On the other hand, a unit would be considered 0% reliable, or 100% unreliable, if that unit failed to start every single time it was called into service. For reference, to be considered a Six Sigma process, the startup of a single unit would need to be 99.99966% reliable or be able to start successfully 99.99966% of the time to meet the Six Sigma criteria (Raisinghani et al., 2005).

4.1.3 Identifying needs for improvement

Majority of the energy provided by the peaker group of the company comes from a group of combustion turbine generators, or CTGs, which are the newest units and have few issues with reliability. However, the peaker group originally generated majority of its power from a large fleet of diesel generators or DG, units, which are large Pratt and Whitney aircraft engines running on diesel and have a much lower MW output per unit. Since these units are still operable and capable of contributing power to the grid, they continue to remain in service today by the peaker group to meet energy demands during peak hours. Given that these units are much older, they fail to start more often and are considered much less reliable. Since these units will continue to remain in service and their reliability directly determines their profitability to the company, diesel generators are the focus of this case study.

4.1.4 Defining the problem

Based on the information and inputs gathered during the 'pre-research information gathering' step, it was established that the problem should be defined as follows: DG peaker units are unreliable, failing to start when called upon at an unacceptable level.

4.1.5 Parameters and constraints for the project

At this stage, meetings were held with the group manager as well as the project lead that was tasked with overseeing the DG units to identify time, resource and budget limitations that the project must consider. Both parties expressed that budget would be a major concern for the project. The peaker group budget was allotted yearly into two categories, operations and maintenance (O&M) and capital expenditures (CapEx). Depending on the work that would be performed to address the reliability problem, some of the upgrades would likely fall into CapEx while others would likely fall into O&M. However, due to the previously discussed use of the CTG units as the primary source of power generation for the peaker group, a vast majority of the O&M funding is earmarked for expenditure on them. This meant that whatever solutions would be suggested for increasing reliability would need to be cost-effective and budget conscious.

4.1.6 Defining the factors to be measured, analysed, improved and controlled

During this part of the define step, it was identified that a baseline understanding of the reliability of the DG peaker units would need to be established. In order to do this, run data would need to be gathered during the measure step. Run data should include the number of attempted runs, the number of successful runs and the number of failures to start over the elapsed time period. This could be gathered through the compilation of unit event history logs which include all of the major events that occur for a unit. Once the current reliability was established in terms of a Six Sigma process, it could be compared to the Six Sigma standard of 3.4 defects per million opportunities and will serve as the basis on which improvements are suggested and controlled.

4.1.7 Defining key stakeholders

When developing process improvement plan, it is important to identify the stakeholders who would be involved in the implementation and monitoring of the potential solutions. Additionally, if the DMAIC process is being performed by a team then this time should also be used to delegate responsibilities and assign team members with roles. For the purpose of this case study, the key stakeholder are referred to by title with their role being described in Table 3.

Table 3 Important people to the project

Title	*Role description*
Peaker group manager	Provided the approval to commit time and resources to the project. Also provided clearance to acquire run data records that would be used in the measure and analyse steps.
Project manager	Responsible for budgeting and allotting funds to the project as well as overseeing the timeline of implementing a solution and the personnel that would be assigned to perform the work.
Peaker engineer	Would be responsible for evaluating and overseeing the technical side of implementing a reliability solution. Would provide insight and guidance to technicians that would be physically completing the implementation of the solution.
Purchasing agent	The purchasing agent would be responsible for utilising the allotted budget to purchase tools, parts, and equipment from suppliers that would be used to implement solutions to fix the reliability problem.

4.2 Measure

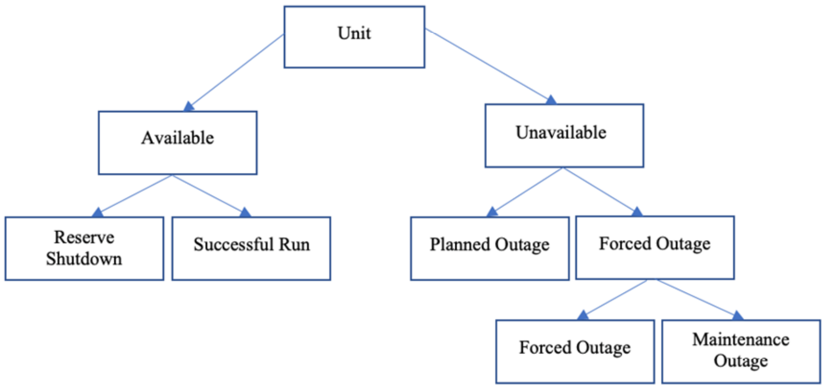
After defining the important factors that need to be measured, required data is gathered and compiled during the measure step to help describe the problem and to uncover clues about the root causes of the issues. In addition, inputs, outputs, and processes will be identified and categorised. Event history logs were processed to denote successful runs and failures of peaker units. It was ensured that any information on the circumstances under which a failure to start occurred was recorded so that it can help in root cause analysis later. In this case, failures to start were separated into two groups: maintenance outages and unplanned outages which are further discussed in the next section.

4.2.1 Data collection

During this part of the measure step, event history logs for each unit were accessed and data was gathered based on the parameters set in the define phase such as sample size and timespan. The logs included a listing of each event that occurred for an individual unit over a predetermined time period and consisted of each DG unit with at least one attempted run in 2019. Data collected mainly consisted of run data including, but not limited to, successful unit runs, failures to start and run history events such as planned maintenance activities. These events are separated into different categories such as successful starts, failures to start and events insignificant to reliability for later use during the analysis step.

Based on the gathered data, successful runs will be considered successful starts and will contribute positively toward reliability because when called upon, the unit was able to successfully perform a start-up cycle and contribute power to the grid. Alternatively, forced outages and maintenance outages will be considered failures and will contribute negatively to reliability. In contrast, a planned outage is a period of time where the unit is unavailable to be called upon due to testing, scheduled maintenance, or a similar phenomenon. Since planned outages prevent the unit from being called upon in the first place, they are insignificant to measuring the reliability of the unit. Based on the events from peaker unit run logs, the different possible states of a peaker are depicted in Figure 1.

Figure 1 Possible states of a peaker unit (see online version for colours)



A brief summary of each state is presented in Table 4.

Table 4 Summary of events from peaker unit run log

Unit event name	*Description*
Reserve shutdown	• A standby mode in which a peaker unit is marked as available and is hypothetically ready to be called upon to activate and begin contributing power to the grid. • This state is insignificant when determining reliability since a start-up cycle of the unit is not involved.
Successful run	• The unit was able to successfully complete a start-up cycle and begin contributing power to the grid. • This run could have occurred as part of testing or just because the power was needed by the grid at the time.
Planned outage	• An outage that has been planned and pre-approved by administration during which the unit will be unable to be activated and/or to contribute power to the grid. • These outages occur during scheduled maintenance, environmental inspections, testing, and upgrades.
Forced outage	• An outage that is unplanned due to a failure of the unit to activate correctly when called into service. • This is usually due to a failure of a specific part or component within the unit. • Due to this outage, the unit fails to contribute power to the grid when requested.
Maintenance outage	• Maintenance outages occur when a unit attempts a start-up cycle as part of an inspection or planned test but fails to successfully activate and contribute power to the grid. • The unit is then put into an outage to diagnose and repair the problem, generally without any disruption of providing power to the grid. • While maintenance outages don't result in lapse of service for customers, they should still be counted as a failure when evaluating reliability.

4.2.2 Data categorisation

Table 5 shows the categorisation of inputs, outputs, and processes considered for this case study.

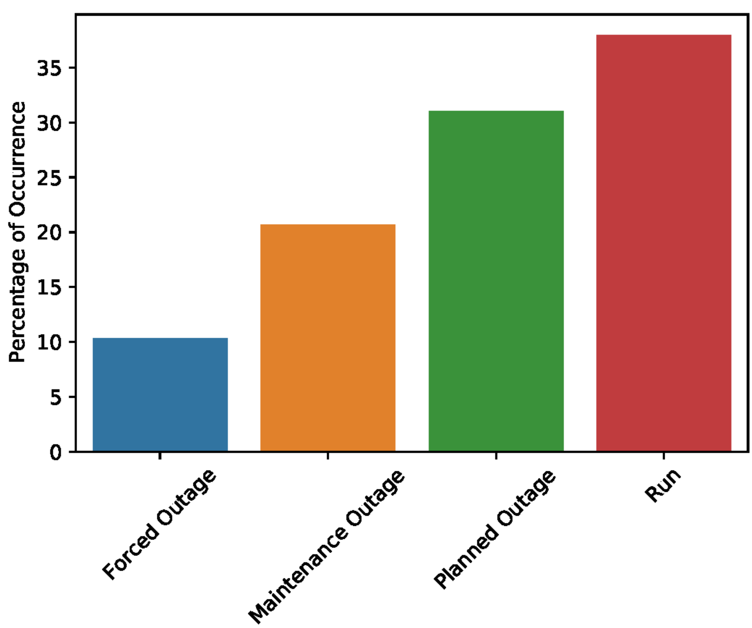
Table 5 Categories of measurable items for peaker reliability

Inputs	*Processes*	*Outputs*
An activation request from a controller for a peaker unit to begin a start-up cycle	A start-up cycle is performed	The start-up cycle fails The unit successfully starts

4.3 Analyse

During the analyse step, the data gathered during the measurement phase is processed. Based on the results of the processed data, conclusions are drawn about the root causes affecting the reliability of peaker units. After analysing the data recorded in the event history logs for all units for the year 2019, it was observed that the units ran successfully only 37% of the time as shown in Figure 2 (data available upon request). Reserve shutdown was not considered in this analysis since it is irrelevant in determining the reliability of the unit.

Figure 2 Percentage of occurrence of various probable states for DG peaker (see online version for colours)



The current reliability of the DG units was calculated both for an individual unit and for all units together in order to establish the current reliability of the process so that it could be compared to the goal of meeting Six Sigma process criteria. Once this baseline is established, potential solutions that will help the DG units approach the goal of Six Sigma reliability were brainstormed.

4.3.1 Analysing the current reliability of DG peaker units

Reliability of the DG peaker unit can be calculated in terms of its sigma value and then compared to a true Six Sigma process, i.e., 3.4 defects per million, using the following equations.

$$DPO = \frac{D}{P * O}. \tag{1}$$

where

DPO Defects per opportunity

D Number of defects

P Number of products produced

O Opportunities for defect

In the preceding calculation, the 'D' refers to the number of failed starts of the DG peaker, 'P' is the number attempted runs made by the DG peaker, and 'O' represents the opportunities for a failure to occur, which is either 0 or 1 indicating either the unit fails to start or successfully starts.

The result of equation (1) is then multiplied by one million, to get the DPMO, or defects per million opportunities using the following formula.

$$DPMO = DPO * 10^6 \tag{2}$$

where

DPMO Defects per million opportunities

DPO Defects per opportunity

The above result can then be utilised in conjunction with a Six Sigma table to find the process sigma. Using the above equations, current reliability of the DG peaker units was calculated and results are presented in Table 6.

Table 6 Current reliability of the DG peaker units

Unit number	*DPO*	*DPMO*	*Sigma value*
1	0.6	600,000.00	~1.25σ
2	0.375	375,000.00	~1.8σ
3	0.429	428,571.00	~1.7σ
Total	0.476	476,191.00	~1.55σ

Generally, 3 or 4 σ is required for a process to be considered as a 'good' process and results show that there is certainly room for improvement in the reliability of the DG peaker units.

Table 7 Failure mode and effect analysis (FMEA)

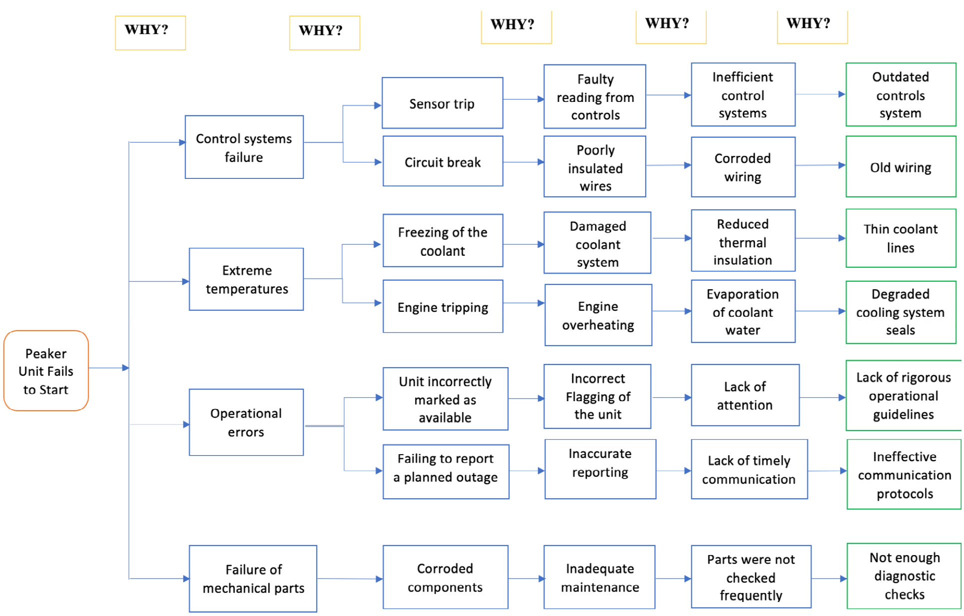
S. no	*Failure mode*	*Potential effects*	*Severity (S)*	*Potential cause*	*Occurrence (O)*	*Current control*	*Detection (D)*	*RPN S*O*D*
1	Trip on a sensor	Failure to start	5	Faulty reading from the unit	4	Troubleshooting	5	100
2	Short-circuit	Failure to start	7	Corroded wires	6	Troubleshooting	5	210
3	Freezing of coolant	Failure to start	9	Coolant freezing due to severe cold temperatures	9	Using glycol with coolant water using a reservoir heater	8	648
4	Engine overheating	Failure to start	9	Evaporation of coolant water due to severe high temperatures	8	Sealing the cooling system	8	576
5	Unit offline	Failure to start	8	Failing to report an outage	5	Dedicated maintenance staff	9	360
6	Unplanned outage	Failure to start	8	Failing to start during an inspection	6	Inspections twice an year	9	432
7	Failure of mechanical components	Failure to start	9	Corrosion of mechanical components	7	Unit diagnostics once a year	5	315

4.3.2 Identifying the potential root causes

Considering the calculations form the analyse step, root causes were identified and investigated to explain the discrepancy between current sigma value of the DG peaker startup process and an idealised Six Sigma process. The project members consisting of site technicians, engineers, and SMEs participated in the brainstorming session in order to draft an extensive list of factors that could reasonably be affecting successful startup of DG peaker units. Failure mode and effect analysis (FMEA) was used to calculate risk priority number (RPN) for all identified potential causes as shown in Table 7.

Even though certain causes have high RPN, team decided to consider all the causes in the subsequent analysis to develop robust recommendations to improve reliability. The five whys process flowchart as shown in Figure 3 was used to further analyse the root causes. During this exercise, the group continually asked 'why?' until analysis moved past the surface level and began to reveal insights about the root causes on which the team can then take action upon.

Figure 3 Five whys analysis for peaker unit startup failure (see online version for colours)



A brief discussion of each failure mode is presented below.

4.3.2.1 Failure in control systems during the startup operation

Analysis of the data gathered during the measure step revealed that it was not uncommon for DG peaker units to go into unplanned outages which often resulted from a trip or fault in the control system. These errors arise from issues with the electronic control systems in the unit and stop the startup of the unit when a sensor gets a bad reading from the unit. More often than not, while troubleshooting the units, the peaker engineers were able to find that the sensor received a faulty reading due to degradation of components. Usually, this degradation is due to old wiring, often more than 50 years old that has lost its insulation over time and started to make an electrical contact with the surrounding metal.

4.3.2.2 Extreme fluctuations in temperature

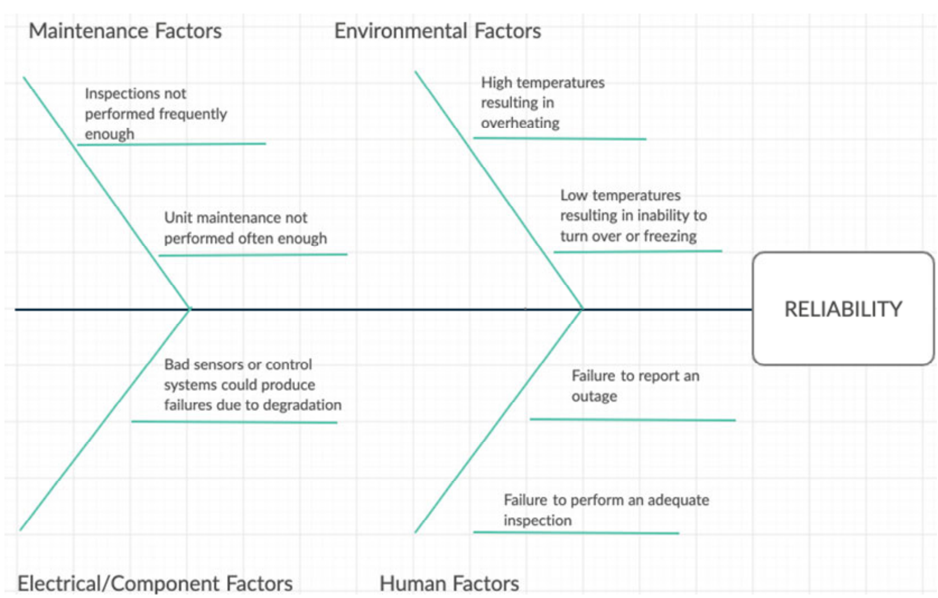
Since the peaker units only run during peak grid usage which is usually on the hottest and coldest days, they most often operate in extreme high and low temperatures.

Extreme cold temperatures cause metal contraction, lower the starting temperature of the fuel making it harder for the diesel engine to complete its startup cycle and can also result in coolant freezing. Freezing mostly occurs in the coolant lines since they are much thinner and less thermally insulated than the main reservoir. High temperatures can cause the units to overheat and trip during startup. This most often occurs when coolant water, responsible for keeping the engine cool during operation, evaporates out of the reservoir due to degradation of the seals in the cooling system. This can occur in the gaskets that are at the attachments of the reservoir to the rest of the system or in the coolant lines, where a small drip at a fastener can turn into a large volume of coolant leakage over time.

4.3.2.3 Operational errors

Most often operational error that contributes to the failure of a peaker unit startup is when a unit is not properly flagged for a planned outage and then an activation order is issued to the unit. This results in a failed start because the unit was accounted for by the internal database as being ready to generate power but failed to activate when called upon. Also, if an engineer or technician failed to report a planned outage and took a unit offline, the unit would fail to start when called upon, hurting the reliability of the unit. A failure to perform an adequate inspection could also be a reason that a unit would be marked as available while unable to perform a proper startup cycle.

Figure 4 Fishbone diagram of potential root causes affecting peaker unit reliability (see online version for colours)



Once an understanding of potential root causes was established, a fishbone diagram shown in Figure 4 was utilised to visualise the root causes and their related issues.

4.4 Improve

During the improve step, the potential solutions to address each of the root causes outlined in the last section are described in greater detail. This information will include the implementation guidelines, benefits as well as drawbacks of each potential solution.

4.4.1 Failure in control systems during the startup operation

Whenever the unit was put into a forced outage rather than a maintenance outage to perform repairs, it was usually due to an issue with the electrical controls such as a trip on a sensor within the unit or a short occurring from a corroded wire. While this is sometimes a simple fix that can be rectified by patching the wire, often times the wire is in such rough condition that technicians experience these older wires crumbling while being worked on. Even more of a predicament, sometimes these shorts occur in places that are inaccessible without removing the wiring entirely for repair which is a costly, time-consuming and error-prone procedure as it could affect many different systems in the unit. Hence, when this type of repair is recommended by an SME or is required to restore the unit to working order, a controls upgrade is performed. This is because a controls' upgrade generally encompasses not only the replacement of the internal wiring of the unit, but also the replacement of vintage dial-based control systems with more user-friendly and accurate electronic systems that feature touch screens and digital readouts.

The site personnel and engineering specialist concurred that control upgrades would minimise errors and failed starts. However, it was estimated that this will be the most expensive and labour-intensive solution for reliability enhancements costing over \$200,000 and requiring 2–3 months to implement. While upgrading the control systems will increase the sigma value of the process and guarantee a higher degree of reliability, it does not address any of the root causes that do not deal with electrical or controls issues.

4.4.2 Extreme temperatures

A potential solution to this root cause is to increase the thermal insulation of the unit as a whole to limit the maximum and minimum temperature extremes that the unit experiences. Though steps are taken to minimise freezing, such as mixing glycol into the coolant water and using a reservoir heater, it can still occur at extremely low temperatures. While this can happen in the reservoir, it is more likely for freezing to occur in the thin, metal coolant lines across the unit. If ambient temperature can be kept from extremes in the engine compartment, it is easier for the unit to avoid failing to start. A proposed way to do this is to augment the housing that the unit is kept in. The DG peakers used in this case study were predominantly housed in utility buildings with rooves and walls made of sheet metal. The introduction of insulation to the unit housing could help to regulate temperature within the unit and prevent temperature failures from occurring in all but the most extreme circumstances. This would increase reliability and the sigma value of the process and its implementation would involve a moderate cost but no changes to process or procedure.

4.4.3 Operational errors

One process that was recommended to address operational errors was designating the responsibility to a single individual. By making a certain, trained individual responsible for cataloguing and processing outages there is a higher degree of scrutiny placed on performing the task correctly. Additionally, when an error does occur, this also makes it easy to design a procedure of who to notify, as there is already a person that can serve as a contact between the multiple business units that would be affected by a failure to start. This solution is the cheapest to implement because usually there is already an employee who this responsibility can be allocated to.

4.4.4 Mechanical component failure

Similar to the electrical issues that can result in a failure, sometimes degraded mechanical components can also contribute to the poor performance of peaker units. In order to combat the unexpected failure of mechanical components, the planned solution is to review the process for unit inspections. If necessary, unit inspections will be performed more often and will be designed with more specific checks to ensure that all parts of the unit crucial to operation are functional. Currently, the units are inspected twice a year, with one of these checks being a full diagnostic and the other being an oil change and engine filter replacement. While it might be more expensive to perform full diagnostic twice a year, it would ultimately increase reliability and hence this solution should be actively pursued. Also, as the procedure is already performed once a year, a plan for implementation is already in place, making this option easy to implement. A cheaper and less rigorous option in this same vein would be to perform a multipoint inspection when the semi-annual oil change is being performed. The implementation of this solution would involve designing a process for identifying and inspecting the essential parts of the DG unit needed for operation.

4.5 Control

During the control phase, discussions were carried out to set up a process for monitoring the suggested improvements to tackle the reliability problem of the DG startup units. Also, as part of the control step, it should be expected that the analysis step will need to be performed again at regular intervals to gauge whether the improvements have been successful in increasing the reliability of the DG units. A viable process monitoring plan for the potential solutions proposed to each of the root causes is outlined below.

4.5.1 Failure in control systems during the startup operation

In case of the controls upgrade solution, process monitoring would begin to be performed once the controls upgrade has been successfully completed. After this time, the unit should have its reliability and sigma value calculated on a monthly basis, assuming that it is being called upon to run. If the unit is not being run for the purpose of generating power, the unit could still be tested monthly to ensure that there is a robust group of data to use when performing the measure step at the end of the year. After a year has elapsed, the DMAIC analysis should be performed using the new data gathered in the measure step. Once the new reliability and process sigma values are calculated, they can be compared to the previous year's calculated sigma value in order to identify potential measurable improvement.

4.5.2 Operational errors

When developing a process monitoring plan for the proposed solution to minimise operational errors, it is important that the team works together with management to develop a set of expectations and procedures for the employee tasked with overseeing the successful input of planned outages. This plan should include meetings held with different sectors of the business to ensure that all outages are being conveyed in a timely manner. For example, perhaps a weekly meeting is established where the assigned person sits down with O&M leadership to discuss any planned outages that are expected to be performed in that month. This way, even if there is a breakdown of communication between the peaker group and operations, the assigned person has still logged the planned outages to ensure that any stop work incidents will not result in a DG failure to start. It should also help to establish a schedule for putting in planned outages of units. While it can be a difficult goal to attempt, having the planned outages logged into the system or notifying the proper administrators at least a month in advance would largely eliminate many of the reliability problems associated with the operational error root cause.

4.5.3 Mechanical component failure

As previously mentioned, many of the mechanical failures that result in DG start failures could be prevented through improving inspection procedures. In order to ensure that the new process is being performed and monitored adequately through these inspections, the visual inspection should be performed by a representative from each relevant business unit. By having a technician from operations and a representative of the engineering team present, it is less likely that an issue will go overlooked or improperly inspected. Developing and maintaining rigorous inspection checklists will help to clearly record, identify and dissect the issues as and when they occur. When an issue is encountered during an inspection, a planned outage can then be scheduled to address it and perform required maintenance so that the unit's reliability will not be impacted.

4.5.4 Extreme temperatures

Much like in the controls upgrade solution, the process monitoring for the temperature root cause will involve performing steps again of the DMAIC method. After insulation has been applied to a test unit, or site, occasional testing should be performed during temperature extremes so that a sizable amount of relevant data can be compiled. After a year, another analyse step can be performed to calculate the unit's reliability and process sigma which can then be compared to the original process sigma to show a measurable degree of improvement.

4.5.5 Process update procedures

While performing this case study, a thorough record was kept detailing each step of the DMAIC process and the discussions and suggestions that were produced at each stage. These notes will serve as a guide for evaluating and implementing the solutions proposed to the DG startup reliability issues presented here. If these proposed solutions prove to be successful when applied to the site, they can be successfully implemented fleet wide using the process discussed in this case study.

5 Conclusions

The research and case study presented here sought to implement Six Sigma tools and methodology to evaluate and suggest improvements to increase the reliability of diesel generator units. The need to increase the reliability was quantified and realistic solutions to the problem were evaluated and presented. While the reliability problem stemmed from a wide variety of root causes, each with its own challenges, the DMAIC strategy was able to be used in combination with other Six Sigma tools to present solutions for each of them. While the terminology and evaluation of a Six Sigma process is generally reserved for manufacturing applications, the application of these tools and methodology here presents the idea that Six Sigma also holds great value for improving processes that exist in applications outside of manufacturing. It is through using these tools that it became possible to quantify the baseline reliability, improvements, and ultimate goals for improving diesel generator reliability. Based on the case study and research included in this paper, it is reasonable to assume that the capacity for improvement to the diesel generator reliability is not only possible but can be evaluated and discussed in a way that describes actionable items and areas for improvement.

5.1 Impact

The Six Sigma methodology and improvement processes resulted in an improvement in the reliability of the peakers from 37% to over 99% by identifying and removing root causes. Root cause identification, improvement implementation, and strong process control were the key areas to achieve the reliability improvement.

5.2 Research limitations

While the research and case study present a novel framework for performing a Six Sigma analysis of DG peaker reliability, they are not without limitations. The methodology used to evaluate these DG units was used to evaluate peakers at only one worksite. The data collection was not all encompassing and serves only as a point of reference that can be assumed to be applied on a larger-scale at other locations. Further research could be conducted to focus on evaluating an entire fleet of DG peaker units to draw conclusions as to whether pursuing reliability improvement on a larger-scale would ultimately produce a net financial gain for the company. While the focus of this research was specifically on DG peaker units, it is possible that this same methodology could be applied to perform an analysis of the reliability of CTG units. However, it is likely that many of the solutions and root causes presented here may not be applicable to CTG units and other systems, but they should still serve as a reference on how to identify probable root causes and potential solutions to improve a process.

References

6Sigma (2017) *Six Sigma Case Study: General Electric* [online] https://www.6sigma.us/ge/six-sigma-case-study-general-electric/ (accessed September 2020).

Ahmed, A., Page, J. and Olsen, J. (2020) 'Enhancing Six Sigma methodology using simulation techniques', *International Journal of Lean Six Sigma*, Vol. 11, No. 1, pp.211–232.

Akpolat, H. (2004) 'Six Sigma in non-manufacturing environment', *Asian Journal on Quality*, Vol. 5, pp.17–25, DOI: 10.1108/15982688200400010.

Al-Shaalan, A. (2019) *Reliability Evaluation of Power Systems, Reliability and Maintenance – An Overview of Cases,* Leo Kounis, IntechOpen, DOI: 10.5772/intechopen.85571.

Bane, R. (2002) 'Quality congress', *ASQ's Annual Quality Congress Proceedings*, Milwaukee, pp.245–249.

Barney, M. (2002) 'Motorola's second generation', *Six Sigma Forum Magazine*, Vol. 1, No. 3, pp.13–16.

Corley, C. (2019) *A Step-by-Step Walkthrough of the DMAIC Process* [online] https://blog.kainexus.com/improvement-disciplines/six-sigma/dmaic/a-step-by-step-walkthrough-of-the-dmaic-process (accessed September 2020).

Dusharme, D. (2001) 'Six Sigma survey: breaking through the Six Sigma hype', *Quality Digest*, November, pp.27–32.

EPM (2020) 'The DMAIC model', *Expert Program Management* [online] https://expertprogrammanagement.com/2020/04/the-dmaic-model/ (accessed September 2020)

Ericson, S. and Olis, D. (2019) 'S A Comparison of Fuel Choice for Backup Generators', *National Renewable Energy Laboratory*, NREL/TP-6A50-72509.

ESA (2020) *Energy Storage Association* [online] https://energystorage.org/flexible-peaking-resource/ (accessed August 2020)

Folaron, J. (2003) 'The evolution of Six Sigma', *Six Sigma Forum Magazine*, Vol. 2, No. 4, pp.38–44.

Francisco, M.G., Junior, O.C. and Sant'Anna, Â.M.O. (2020) 'Design for Six Sigma integrated product development reference model through systematic review', *International Journal of Lean Six Sigma*, Vol. 11 , No. 4, pp.767–795.

Gravity Power (2017) [online] http://www.gravitypower.net/markets-and-products/peaking-power-plants/ (accessed August 2020).

IEA (2019) [online] 'World Energy Outlook 2019', *IEA*, Paris [online] https://www.iea.org/reports/world-energy-outlook-2019 (accessed September 2020).

Jones, N. (2018) 'How to stop data centres from gobbling up the world's electricity', *Nature Research* [online] https://www.nature.com/articles/d41586-018-06610-y (accessed September 2020).

King, J.W. (2019) 'Grid reliability in a changing climate', *Energy Policy and Climate* [online] https://datascienceplus.com/six-sigma-dmaic-series-in-r-part-1/ (accessed September 2020).

Kumar, K. (2018) 'Program manager – BI', *Data Analytics & Process Excellence @ HP Six Sigma DMAIC Series in R. Data Science Plus* [online] https://datascienceplus.com/six-sigma-dmaic-series-in-r-part-1/ (accessed September 2020).

Mills, P. (2013) 'The cloud begins with coal', *Digital Power Group* [online] https://www.tech-pundit.com/wp-content/uploads/2013/07/Cloud_Begins_With_Coal.pdf?c761ac (accessed September 2020).

Prabhakar, K. and Dinesh, K. (2009) 'Application of Six Sigma DMAIC methodology in thermal power plants: a case study', *Total Quality Management & Business Excellence*, Vol. 20, No. 2, pp.197–207, DOI: 10.1080/14783360802622995.

Raisinghani, M.S., Ette, H., Pierce, R., Cannon, G. and Daripaly, P. (2005) 'Six Sigma: concepts, tools, and applications', *Industrial Management & Data Systems*, Vol. 1, No. 4, pp.491–505.

Rastogi, A. (2018) *DMAIC – A Six Sigma Process Improvement Methodology* [online] https://www.greycampus.com/blog/quality-management/dmaic-a-six-sigma-process-improvement-methodology (accessed September 2020).

Singh, J.B. and Bakshi, Y. (2014) 'Optimizing backup power systems through Six Sigma: an Indian case study of diesel genset', *International Journal of Lean Six Sigma*, Vol. 5, No. 2, pp.168–192, DOI: https://doi.org/10.1108/IJLSS-09-2012-0008.

Sino Voltaics (2015) [online] https://sinovoltaics.com/learning-center/basics/base-load-peak-load/ (accessed August 2020).

Smil, V. (2000) 'The energy question, again', *Current History*, Vol. 99, No. 641, pp.408–412.

Sony, M. (2019) 'Lean Six Sigma in the power sector: frog into prince', *Benchmarking: An International Journal*, Vol. 26, No. 2, pp.356–370.

SSD (2014) 'Six Sigma fundamentals: what is DMAIC?', *Six Sigma Daily* [online] https://www.sixsigmadaily.com/six-sigma-fundamentals-dmaic/ (accessed September 2020).

Sudhakar, T., Prasad, A.B. and Prahladarao, K. (2015) 'Implementation of Six Sigma for improved performance in power plants', *IOSR Journal of Mechanical and Civil Engineering IOSR-JMCE*, Ver. II, Vol. 12, No. 5, e-ISSN: 2278-1684, p-ISSN: 2320-334X.

Sunder, M.V., Ganesh, L.S. and Marathe, R.R. (2018) 'A morphological analysis of research literature on Lean Six Sigma for services', *International Journal of Operations & Production Management*, DOI: https://doi.org/10.1108/IJOPM-05-2016-0273.

Swan, E. (2017) *DMAIC – The 5 Phases of Lean Six Sigma* [online] https://goleansixsigma.com/dmaic-five-basic-phases-of-lean-six-sigma/ (accessed September 2020).

Tsarouhas, P. (2020) 'Reliability, availability and maintainability analysis of a bag production industry based on the Six Sigma DMAIC approach', *International Journal of Lean Six Sigma* (accessed September 2020)