Implementing a Compressed Air Leak Preventive and Repair Program

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Abstract *— In recent years the energy cost in Puerto Rico has been constantly increasing. The reasons vary from more expensive fuel costs, new environmental regulations requirements and inefficiencies in the system. The major efficiency opportunities can be found in the plant systems, but frequently these opportunities are overlooked due to unawareness of the cost of the inefficiencies. One of the major system inefficiencies is the compressed air system. The problem in the compressed air system is the air leaks that result in higher production costs. Air leaks can be a significant source of wasted energy in an industrial compressed air system. To reduce these losses, the project will develop a strategy to reduce the air leakage. To reach this goal the Lean Six Sigma DMAIC methodology will be used. This methodology will go from defining a problem through implementing solutions and establishing best practices to make sure the solutions stay in place.*

Key Terms *— Compressed Air System, DMAIC, Lean Six Sigma, Cost of Inefficiencies.*

PROJECT STATEMENT

According to system audits of the U.S. Department of Energy, the average leakage rate of a compressed air system is 25 % [1]. In some systems leakage rate can be as high as 80 %. These compressed air system leaks are considered a source of wasted energy. The compressed air leaks can be found at any part of the system. The most common place for the leak is the point of use. Through the year's compressed air specialists have emphasized in the last 30 feet of piping to the point of use [2].

By implementing a Compressed Air Leak Program, the average leakage rate can be maintained at less than 10% resulting in high savings for the facility. Another benefit of the program is a reduction in repairing costs because of less workload for the compressors, improve the compressed air system reliability, increase productivity and reduce unscheduled downtime.

Research Description

The focus of this project is on the current state of a Compressed Air System in an electric utility steam power plant in Puerto Rico. The electric utility doesn't have a compressed air leak prevention program in place. This project will analyze and evaluate the Compressed Air System of the electric utility to point the cost and savings opportunities related with air leaks. The facility has five compressors and thousands feet of pipe, thus increasing the areas of leakage.

Research Objectives

The objectives for this project are:

- Evaluate and analyze current state in terms of cost of leakage;
- Find the most common areas of leakage;
- Develop a guide to implement a Compressed Air Leak Prevention Program in an electric utility steam power plant

Research Contributions

The main contribution of implementing a Compressed Air Leak Preventive Program in an electric utility steam power plant is cost reduction. The preventive program will increase the compressed air system efficiency by reducing maintenance requirements and unscheduled downtime. This preventive leak program then can be a pioneer preventive program and with some changes adapted to use it in other types of leaks like water and steam leaks.

LITERATURE REVIEW

Compressed air systems are very important in the electric utility steam power plant industry. The compressed air system in power plant is one of those critical systems of the plant which is necessary for day to day routine operations in the plants. Many of the instruments that monitor flow, level, pressures, and temperatures incorporate instrument air quality compressed air to transfer information [3]. Flow and level control is accomplished by the throttling operation of air operated valves. Most of the operation instruments, valves and electrical breakers in the plant require instrument air for operation whereas service air is used to operate many pneumatic equipments and air operated tools. Non-availability of air supply may lead to shutting down of whole unit. For that reason the Compressed Air System is very important to the operation of a steam electric power plant. One of the most common problems with the compressed air system is the air leakage.

Air leaks can be a significant source of wasted energy in an industrial compressed air system, sometimes wasting 25 to 30 percent of a compressor's output. A typical plant that has not been well maintained will likely have a leak rate equal to 25 percent of total compressed air production capacity . On the other hand, proactive leak detection and repair can reduce leaks to less than 10 percent of compressor output. This system represents big potential for energy savings from a small effort [4]. Air leaks can also contribute to other operating losses like a drop in system pressure, which can make air tools function less efficiently, adversely affecting production. In addition, by forcing the equipment to run longer, leaks shorten the life of almost all system equipment. Increased running time can lead to additional maintenance requirements and increased unscheduled downtime.

Compressed Air system leaks can be estimated. Air leaks can translate to large amounts of energy and money being wasted on a daily basis. An example of the cost of leaks can be estimated with the Equation (1):

$$\text{Annual cost of a leak} = \text{Leakage rate (cfm)} \times \frac{\text{kW}}{\text{cfm}} \times \frac{\$}{kWh} \qquad (1)$$

Assuming a typical compressor efficiency of 22.4kW/ 100cfm (.224kW/cfm), an electric rate of $0.15 per kWh, 1/16" leak with 100 psig and nearly continuous operation the annual cost of a leak using Equation (1) is $1,747 per year.

After knowing the problem of compressed air leaks in the steam electric power plant a structured problem solving methodology is needed. To meet the objectives of this project the lean six sigma methodology will be used. The lean six sigma methodologies is a fact based, data driven philosophy of quality improvement that values defect prevention over defect detection. It drives customer satisfaction and bottom line results by reducing variation and waste, promoting a competitive advantage [5]. It applies anywhere variation and waste exist, and every employee should be involved. This view of Six Sigma uses the approach known as DMAIC (define, measure, analyze, improve and control). DMAIC starts with identifying the problem and ends with the implementation of long lasting solutions.

METHODOLOGY

The methodology used in this project will be DMAIC. DMAIC is a structured problem solving methodology that composes the five phases of Six Sigma improvement. The letters of DMAIC means Define- Measure- Analyze- Improve- Control. This methodology will go from defining a problem through implementing solutions and establishing best practices to make sure the solutions stay in place [6].

- **Define**: In this phase the problem is defined as clearly as possible and includes the scope of the project, objectives, the plan and goals of the project. It delivers a confirmed project charter and set the objectives and forms the project team.
- **Measure**: Team characterizes process to measure baseline performance and collect data and document surrounding factors. It delivers

performance metrics describing inputs, outputs and their known or potential relationships, Process flow diagram at detailed level, Cause-effect analysis and diagrams (FMEA), Data collection and sampling plans and confirmed or modified project goals.

- **Analyze**: Hypothesis testing of potential causes with statistical tools and other techniques based on collected or experimental data to investigate and verify cause and effect relationships.
- **Improve**: Quantify cause-effect relationships through experiments or simulations and compare alternate solutions. Identify the opportunities to eliminate the root causes to fix the problem.
- **Control**: The future state of the process. Design, document and distribute necessary controls to hold gains. In this phase a control plan is created to monitor the improvements made. Some components are documentation, visual programs, training plan, production boards and periodic reviews and audits to monitor success

RESULTS AND DISCUSSION

This section presents the problem analysis and improvement results using the Lean Six Sigma Methodology and DMAIC tool.

Define Phase

The costs of energy production using a steam electric power plant in Puerto Rico are increasing due to high price of the fuel needed to produce energy and the new environmental regulations. Every process in the energy production should be improved to reduce production costs. One of the processes that should be improved is the compressed air system. The average leakage rate of a compressed air system is 25 % according to audits of the U.S. Department of Energy and in some systems leakage rate can be as high as 80 %. Although everyone knows there is a problem, the compressed air system leaks problems are often neglected because they are not quantify in dollars. A more efficient compressed air system will result in less energy production costs for the company and subsequently to the customer.

The project goal is to reduce the compressed air system leaks to less than 10% of the compressed air generated in an electric utility steam power plant in Puerto Rico by implementing the Compressed Air Leak Preventive Program. The project scope includes the facility five air compressors; all control pneumatic valves and all piping of the Units 6, 5, 3 and 4.

The team members will be the shift engineer, the auxiliary operators and the instrumentation technicians. The roles of the shift engineer and an auxiliary operator is to discuss the problems of air leaks, follow the guidelines of this project and collect the data necessary to reduce the compressed air system leaks.

The business impact is that the reduced compressed air leaks will translate in less energy production costs or cost avoidance. One of the major benefits of this project implementation is that it can be adapted to other types of leaks that are in the plant like water and steam leaks.

Measure Phase

In the measure phase the team will find the compressed air system leaks of an Electric Utility steam power plant in Puerto Rico and estimate the cost of air leaks. The Equation (1) mentioned above is used to calculate the cost of compressed air leaks.

For this formula the team will assume a compressor efficiency of the five compressors of an electric utility steam power plant in Puerto Rico of 22.4kW/ 100cfm (.224kW/cfm). This efficiency is given in the Atlas COPCO compressors equipment manual. For calculation purpose the electric rate will be of $0.15 per kWh. That is the cost of energy production in the electric utility steam power plant that this project was made. The leakage rate (cfm) will vary depending on the air pressure and the size of the orifice. Table 1 shows a table for leakage rates for different supply pressures and equivalent orifice sizes. For well rounded orifices, multiple tables values by 0.97, and for sharp edges multiple tables values by 0.61.

Table 1
Leakage Rates

Pressure		Diameter of orifice (")										
psi	bar	0.016	0.031	0.063	0.125	0.25	0.375	0.5	0.63	0.75	0.875	1
		Discharge in cfm										
1	0.07	0.028	0.112	0.45	1.8	7.18	16.2	28.7	45	64.7	88.1	115
2	0.14	0.04	0.158	0.633	2.53	10.1	22.8	40.5	63.3	91.2	124	162
3	0.21	0.048	0.194	0.775	3.1	12.4	27.8	49.5	77.5	111	152	198
4	0.28	0.056	0.223	0.892	3.56	14.3	32.1	57	89.2	128	175	228
5	0.34	0.062	0.248	0.993	3.97	15.9	35.7	63.5	99.3	143	195	254
6	0.41	0.068	0.272	1.09	4.34	17.4	39.1	69.5	109	156	213	278
7	0.48	0.073	0.293	1.17	4.68	18.7	42.2	75	117	168	230	300
9	0.62	0.083	0.331	1.32	5.3	21.2	47.7	84.7	132	191	260	339
12	0.83	0.095	0.379	1.52	6.07	24.3	54.6	97	152	218	297	388
15	1.03	0.105	0.42	1.68	6.72	26.9	60.5	108	168	242	329	430
20	1.38	0.123	0.491	1.96	7.86	31.4	70.7	126	196	283	385	503
25	1.72	0.14	0.562	2.25	8.98	35.9	80.9	144	225	323	440	575
30	2.1	0.158	0.633	2.53	10.1	40.5	91.1	162	253	365	496	648
35	2.4	0.176	0.703	2.81	11.3	45	101	180	281	405	551	720
40	2.8	0.194	0.774	3.1	12.4	49.6	112	198	310	446	607	793
45	3.1	0.211	0.845	3.38	13.5	54.1	122	216	338	487	662	865
50	3.4	0.229	0.916	3.66	14.7	58.6	132	235	366	528	718	938
60	4.1	0.264	1.06	4.23	16.7	67.6	152	271	423	609	828	1082
70	4.8	0.3	1.2	4.79	19.2	76.7	173	307	479	690	939	1227
80	5.5	0.335	1.34	5.36	21.4	85.7	193	343	536	771	1050	1371
90	6.2	0.37	1.48	5.92	23.7	94.8	213	379	592	853	1161	1516
100	6.9	0.406	1.62	6.49	26	104	234	415	649	934	1272	1661
110	7.6	0.441	1.76	7.05	28.2	113	254	452	705	1016	1383	1806
120	8.3	0.476	1.91	7.62	30.5	122	274	488	762	1097	1494	1951
125	8.6	0.494	1.98	7.9	31.6	126	284	506	790	1138	1549	2023
150	10.3	0.582	2.37	9.45	37.5	150	338	600	910	1315	1789	2338
200	13.8	0.761	3.1	12.35	49	196	441	784	1225	1764	2401	3136
250	17.2	0.935	3.8	15.18	60.3	241	542	964	1508	2169	2952	3856
300	20.7	0.995	4.88	18.08	71.8	287	646	1148	1795	2583	3515	4592
400	27.6	1.22	5.98	23.81	94.5	378	581	1512	2360	3402	4630	6048
500	34.5	1.519	7.41	29.55	117.3	469	1055	1876	2930	4221	5745	7504
750	51.7	2.24	10.98	43.85	174	696	1566	2784	4350	6264	8525	11136
1000	69.0	2.985	14.6	58.21	231	924	2079	3696	5790	8316	11318	14784

An example of air leakage cost using an orifice of 1/16”, the leakage rate of 6.5 cfm is given in the Table 1, a compressor efficiency of 0.224 kW/cfm, an electric rate of $0.15 per kWh and 8,000 hours per year and using the Equation (1) showed above, the air leakage cost can be estimated. Using these parameters the total annual cost of air leakage for these conditions is $1,747 per year.

At the time the team realized this project, the plant has not yet purchased an ultrasonic detector to identify the compressed air system leaks. This equipment represents the most efficient way to identify air leakages in the system. For this reason the team only used the ear and eye method and the soapy water method to detect air leaks in all the compressed air system. The team was able to identify many air leaks in steam plant Unit 6, 5, 4 and 3. Table 2 to Table 5 shows the current state of compressed air leakage of an electric utility steam power plant in Puerto Rico and an estimated cost of compressed air leaks. The leaks are grouped by steam plant unit number.

Table 2
Compressed Air Leaks Detected in Unit 6

Unit	Leak Descripcion	$Lost/Month	$Lost/Year
	Unit 6		
6	Faulty valve diaphragm in Noth Side of 11th Boiler floor	$ 5,887	$ 70,641
6	Faulty Valve in North Side of 2nd Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in East Side of 2nd Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in East Side of 3rd Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in North Side of 4th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in South Side of 4th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in South Side of 6th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in Wesr Side of 7th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in East Side of 7th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in South Side of 8th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in North Side of 8th Boiler Floor	$ 4,415	$ 52,980
6	Faulty Valve in West Side of 10th Boiler Floor	$ 4,415	$ 52,980
6	Non Return Valve Heater #7	$ 1,472	$ 17,660
6	Non Return Valve Heater #5	$ 1,472	$ 17,660
6	Non Return Valve Heater #4	$ 1,472	$ 17,660
6	Solenoid of Condensate Recirculation valve	$ 147	$ 1,766
6	Solenoid in BFP Recircultion 6-1	$ 123	$ 1,472
6	Faulty Valve South Side Last Boiler Floor	$ 98	$ 1,177
6	Faulty pneumatech filter joint U#6	$ 98	$ 1,177
6	Heater Control System #7	$ 98	$ 1,177
6	Heater Test Valve #4	$ 74	$ 883
6	Heater Control System #4	$ 74	$ 883
6	Control System pump 6-1	$ 49	$ 589
6	Fitting Heater # 7 HI-HI valve	$ 49	$ 589
	Total	$ 59,676.62	$ 716,119.49

Table 3
Compressed Air Leaks Detected in Unit 5

Unit	Leak Descripcion	$Lost/Month	$Lost/Year
	Unit 5		
5	Faulty Valve in North Side of 2nd Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in South Side of 2nd Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in West Side of 2nd Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in West Side of 4th Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in East Side of 4th Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in North Side of 6th Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in South Side of 6th Boiler Floor	$ 4,415	$ 52,980
5	Faulty Valve in West Side of 6th Boiler Floor	$ 4,415	$ 52,980
5	Non Return Valve Heater #4	$ 1,472	$ 17,660
5	Non Return Valve Heater #6	$ 1,472	$ 17,660
5	Non Return Valve Heater #4	$ 147	$ 1,766
5	Solenoid in BFP Recircultion 5-1	$ 123	$ 1,472
5	Solenoid in BFP Recircultion 5-2	$ 123	$ 1,472
	Total	$ 38,656.13	$ 463,873.54

Table 4
Compressed Air Leaks Detected in Unit 4

Unit	Leak Descripcion	$Lost/Month	$Lost/Year
Unit 4			
4	Non Return Valve Heater #7	$ 1,472	$ 17,660
4	Air valve between Air Heater and boiler	$ 1,226	$ 14,717
4	Deaerator Help Regulator	$ 491	$ 5,887
4	Separator Tank Trap Compressor #5-1	$ 368	$ 4,415
4	PinHole BFP 4-2 Recirculation valve diaphragm	$ 294	$ 3,532
4	BFP Suction Temperarure Controller	$ 245	$ 2,943
4	Burner Controller B Boiler Corner	$ 245	$ 2,943
4	Piston Burner Controller	$ 245	$ 2,943
4	Boiler Level	$ 123	$ 1,472
4	Boiler Regulator	$ 123	$ 1,472
4	Tubing front boiler 4	$ 74	$ 883
4	Control of BC Regulator Valve	$ 74	$ 883
Total		$ 4,979.18	$ 59,750.21

Table 5
Compressed Air Leaks Detected in Unit 3

Unit	Leak Descripcion	$Lost/Month	$Lost/Year
Unit 3			
3	Non Return Valve Heater #7	$ 1,472	$ 17,660
3	Faulty tubing B boiler corner	$ 736	$ 8,830
3	Valve Boiler Corner A, front of chemical tanks	$ 245	$ 2,943
3	Deaerator Help Regulator	$ 245	$ 2,943
3	Burner Controller A Boiler Corner	$ 245	$ 2,943
3	Burner Controller D Boiler Corner	$ 245	$ 2,943
3	Control System D Boiler Corner	$ 245	$ 2,943
3	Sootblowing Regulator Control	$ 245	$ 2,943
3	Tubing front boiler 3	$ 147	$ 1,766
3	Solenoid Seal Regulator Valve	$ 123	$ 1,472
3	Filter Reduction Pressure Feewater Valve 2	$ 123	$ 1,472
3	Filter Reduction Pressure Feewater Valve 1	$ 123	$ 1,472
Total		$ 4,194.29	$ 50,331.46

Table 6
Total Losses from Compressed Air Leaks

Unit	$Lost/Month	$Lost/Year
6	$ 59,676.62	$ 716,119.49
5	$ 38,656.13	$ 463,873.54
4	$ 4,979.18	$ 59,750.21
3	$ 4,194.29	$ 50,331.46
Total	$ 107,506.22	$ 1,290,074.70

In Unit 6 the team found 24 compressed air leaks using the eye and ear method and the soapy water method. The most common air leaks found in Unit 6 was the faulty air valves in the boiler. The estimated losses of compressed air leak in Unit 6 are $59,676.62 per month and $716,119.49 per year. In Unit 5 the team found 13 compressed air leaks using the same method on leak detection used in Unit 6. The estimated losses of compressed air leak are $38,656.13 per month and $463,873.54 per year. In Unit 4 the team found 12 compressed air leaks and the estimated losses are $4,979.18 per month and $59,750.21 per year. In Unit 3 the team found 12 compressed air leaks and the estimate losses are $4,194.29 per month and $50,331.46 per year. In total the team documented 51 compressed air leaks in an electric utility steam power plant in Puerto Rico. The estimated losses due to compressed air leaks are summarized in Table 6. The losses due air leaks are $107,506.22 per month and $1,290,074.70 per year.

Analyzed Phase

In this phase the team will analyze and try to find opportunities for the improvements in the compressed air system in an electric utility steam power plant in Puerto Rico. The team will analyze the data collected in the measure phase. After analyzing the current state of a compressed air system of an electric utility steam power plant in Puerto Rico, the team will implement a program to reduce the losses of the compressed air system.

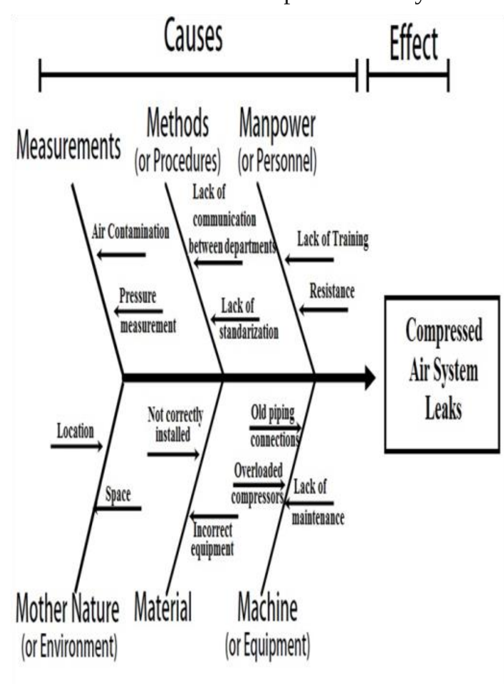

Figure 1
Fishbone Diagram of the Compressed Air Leaks

Using a cause and effect diagrams are used to explore all the potential or real causes or inputs that result in a single effect or output. The fishbone diagram helps to analyze and relate some of the interactions among the factors affecting a particular process or effect. These effects were determined as the greatest offenders in the measure phase. Figure 1 shows a fishbone diagram of the compressed air system leaks in an electric utility steam power plant in Puerto Rico.

The fishbone diagram was drawn by the project team trying to understand the causes of the compressed air system leaks. In manpower the team selects the lack of training of the workers to detect the compressed air system leaks. In addition to the lack of training there also a resistance of the workforce to make something that for them they are not supposed to do. In the electric utility steam power plant in Puerto Rico the workers are divided in two groups: management and workers union. The workers union has always a resistance to make things that are not in their charter of duties. Some workers may identify a compressed air leak but because of their charter of duties they may or not may report the problem. In the methods cause the major offender is the lack of communication between the operation and the instrumentation department. If the auxiliary operator identifies an air leak he then notifies to the shift engineer. The shift engineer has to make a work order to the instrumentation department in order for the instrumentation technician to repair the air leak. Sometimes the order is made and the instrumentation department closes the order because they didn't find the leak. A solid communication between both departments is needed. The lack of standardization in the process of identifying an air leak is a problem. For this reason, a compressed air leak preventive and repair program will be implemented. This will standardize the way the compressed air leaks are detected and corrected. The material causes the biggest problem is that incorrect equipment are installed in the compressed air system. The installed part may fit but it will not work. An example is the hose fittings. Some hose fittings may look the same but do not work acceptably on all systems. If the instrumentation technician installs a water hose fitting on compressed air systems, this installation will lead to leaks. The other problem in equipment is that the majority of the compressed air system piping is old. The team not identified major leaks in the piping and fittings because the ultrasonic air leak detector was not available for the project realization.

Through the year's compressed air specialist have emphasized in the last 30 feet of piping to the point of use and given the old condition of the piping and valves, the team would have identified more air leaks. The last 30 feet of piping to the point of use is the part that gets the most vibration and stress from the point of use. Using the ultrasonic air leak detector will lead to find more air leaks in the point of use, flanges, shut-off valves, packings, couplings, fittings and pipe joints, filters, hoses, condensate traps and valves.

The team made a benefit effort matrix using the causes analyzed in the fishbone diagram. Figure 2 shows the benefit-effort matrix.

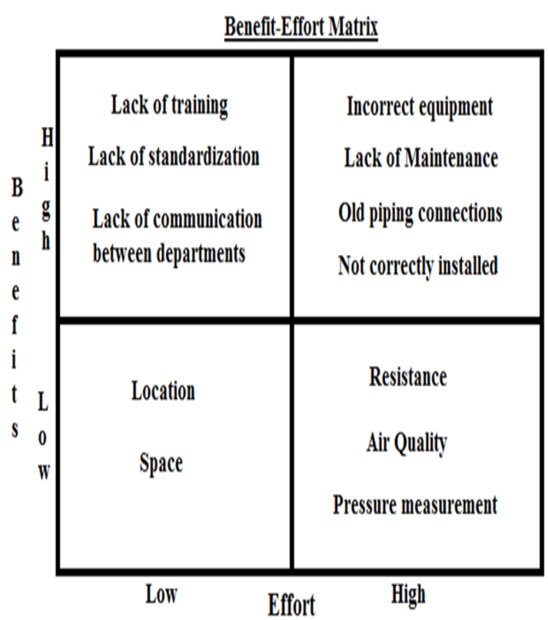

Figure 2
Benefit-Effort Matrix

After analyzing the benefit effort matrix the team select the lack of training, lack of standardization and lack of communication departments as the first things that the project will focus. These causes can be fixed quickly without spending much money and will result in fewer losses due to compressed air leaks. With the training of compressed air leak detection, the workers can quickly indentified the leaks and inform it for quick repair. With establishing the compressed air leak preventive and repair program, the plant will standardize how the compressed air leak detection and reporting is made. Also with high reward but also with high effort is the fixing of lack of maintenance, the incorrect equipment installed, the not correctly installed and the old condition of the air piping system.

As stated in the measure phase, the team found 51 compressed air leaks in an Electric Utility steam power plant in Puerto Rico. The estimated losses due to compressed air leaks are $107,506.22 per month and $1,290,074.70 per year. The team detected the compressor air system leaks using the eye and ear method and the soapy water method. When an ultrasonic air leak detector becomes available the estimated losses will continue to increase. For that reason a compressed air leak preventive and repair program must be put in place.

Improvement Phase

Implementing a compressed air leak preventive and repair program in the electric utility steam power plant in Puerto Rico is needed. This project will include a guide to implement the program.

Implementing a compressed air leak prevention and repair program:

- Train all your employees and show them the benefits of implementing the compressed air leak prevention and repair program. The team has to be trained in the three air leak detection methods: eye and ear, soapy water and ultrasonic detector [7].
- Establish the company goals for the project. For this project the goal was to reduce the compressed air system leaks to less than 10% of the compressed air generated in an Electric Utility steam power plant in Puerto Rico. Other goals should be increasing the life of the compressors, decrease energy waste, reduce repair costs, reduced unscheduled downtime, improved system reliability and increased productivity.
- Print out the goals of the project and publish them in a place when all people involved in the project can constantly review it and make recommendations.
- Create a standard system procedure. Publish a procedure for all three air leak detection method.
    - Shift Engineer: Use ultrasonic air leak detector to find leaks. Use the corresponding tags. Document the leaks using Table 7 and report the problem by making a work request to the corresponding workshop. Start over again. Table 8 represents the legend of the compressed air leaks documentation.

Table 7
Compressed System Air Leak Documentation

Date	Department	Description (Location)	Line Pressure	Orifice Size	Tag Color	Leak Size or dBµV	Estimate Cost($)

    - Auxiliary Operator: Use the eye and ear air leak detection method and the soapy water method to find air leaks. Put a tag on the air leak depending of the size and prioritization. Then inform the shift engineer.

- Instrumentation Technician and other departments- After receive the work order by the shift engineer, repair the air leak following the safety and repairing procedures of their workshop.

- Decide the frequency of the prevention program. In this project the shift engineer and the auxiliary operator will verify the most common air leak areas one time per shift. The shift engineer will verify the system one time per shift. In the control phase the preventive maintenance running inspections will be discussed.
- Find the compressed air leaks. Tag the air leaks detected and inform to the corresponding department for correction.
- Document repairs. The team will document the repairs to find the most reoccurring areas of air leaks. This will help to determine the frequency and the location of the daily verification. Table 8 represents the legend.

Table 8
Legend for Documentation

Date	Date the detection was done
Department	What department will repair the air leak. It can be Mechanical, Boiler, Turbine or Instrumentartion workshop
Description (Location)	General Location of the air leak.
Line Pressure	Operating pressure of the line where the air leak was found.
Orifice Size	Diameter of the air leak orifice. Ex. 1/16", 1/8" or ¼".
Tag Color	Level of prioritization. Red tag=high priority,blue tag= medium priority and green tag= low priority
Leak Size or dBµV	Pin hole, fitting, coupling, hoses, packings or decibel measure
Estimated cost ($)	Annual cost of a leak = Leakage rate (cfm) x kW/cfm x operating hours x $/kWh

- Document Savings. To maintain the team highly motivated, everyone must know how much the company has saved. If all the air leaks detected in this project were repaired, the company will save $107,506.22 per month and $1,290,074.70 per year.
- Start to verify all compressed air system again. After each repair verify the area using the ultrasonic air leak detector. And verify continuously the system.

Control Phase

The control phase is the most important step in the Lean Six Sigma methodology. The improvements done in the above steps will be lost if a good control plan is not implemented. When implemented this control phase will show if the project is making progress or if it is having a setback. The ultimate goal in this phase is to sustain the improvements through time.

As stated in the improvement phase, this project will create a preventive maintenance running inspections that the shift engineer has to make. In normal working day the shift engineer has to make many preventive maintenance running inspections. This inspection of the compressed air system will be added to the daily inspections. For this inspection the ultrasonic leak detector will be used. There will be a once a day running inspection that will focus in the most common areas of compressed air leaks determined by the documentation of air leaks. Every six months the team will meet to find the most common areas of compressed air leaks using the air leak documentation. After finding the most common areas the preventive maintenance running inspection will be reviewed. Additionally, a monthly preventive maintenance running inspection will be made to the whole compressed air system. These preventive inspections will be made by the shift engineer.

Another control to be used in order to sustain the gains is the visual program. After the auxiliary operator or the shift engineer detects an air leak, they must write it in the visual aid that will be placed in the shift office. This will help this type of work that there are new personnel every 8 hours. The inclusion of every worker and the reports accessible to anyone, will give the workers a sense of empowerment and safety. A training plan will be implemented to maintain the efficiency and success of this project.

CONCLUSIONS

Using the DMAIC tool, the team was able to use a structured problem solving methodology that composes the five phases of Six Sigma improvement. Using this tool allowed the team to define the problem, evaluate and prioritize the opportunities to improve the current state of a compressed air system in an electric utility steam power plant in Puerto Rico. The project verified the benefits of implementing a compressed air leak preventive and repair program to its plant. The recommendation is to implement the program as soon as possible. In total the team documented 51 compressed air leaks in an electric utility steam power plant in Puerto Rico. It was found in this project that in the current state the plant is losing an estimated quantity of $107,506.22 per month and $1,290,074.70 per year. The compressed air leaks were detected using the eye and ear air leak detection method and the soapy water air leak detection method. The air leak detection methods mentioned above are less efficient than the ultrasonic air leak detector method. The plant should buy the ultrasonic air leak detector for better and more compressed air leaks detections and for more savings. Additionally, the implementation of the program standardize the methods to detect the compressed air leaks and reduces energy consumption by the compressors, reduces repairing costs because of less workload for the compressors, improve the compressed air system reliability, increase productivity and reduce unscheduled downtime.

To sustain the gains after the compressed air leak preventive and repair program implementation, the project establishes a control plan. The control plan includes a preventive maintenance running inspections, a visual program and training in all levels. Some recommendations to the plant that are out of the scope of this project are:

- Adapt the project to other types of leaks like steam and water leaks.
- Stop air supply to equipments out of use and steam plants units that are not in service
- Reduce compressed air system pressure while maintaining operation
- Maintain compressors air filter regularly to prevent unscheduled downtime
- Shutdown air compressors when not needed. Especially on the late and night shifts.

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