Developing an SPC-EPC Unified Framework to Improve Production Disruption in Chemical Industry in Kuwait

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Abstract

The quality of products in the industry can be improved by monitoring the manufacturing process and adjusting/optimizing the process input variables based on the output deviation from the target. EPC stands for Engineering Process Control, and it is concerned with adjusting systems inputs to keep the system output on target using different types of controllers such as Integral Controllers and PID controllers. SPC stands for Statistical Process Control and is used to monitor processes in order to identify any assignable causes of variation. Combining EPC and SPC as a unified framework proved to be effective in reducing production disruption in manufacturing industries. The main aim of this project is to redesign the production and quality control system in XYZ Chemical Company by developing an Engineering Process Controller in order to adjust the chemical process inputs to keep the output chemical concentration on best optimized target while monitoring the system using the sensitive Time Weighted Control chart to identify and eliminate the process assignable causes of variation, improve system elements life, and reduce overall system wide costs.

Keywords

Production Disruptions, Engineering Process Control (EPC), Integral Controller, Statistical Process Control (SPC), Time Weighted Control Chart

1. Introduction

Engineering process control (EPC) & Statistical process control (SPC) are two very different approaches to improve the process efficiency by reducing the process disturbances or variability and achieving a much better product quality which will lead to customer satisfaction and increase in sales (Mastrangelo, 1998). SPC works by monitoring the process by utilizing different types of control charts and tries to identify any points located outside the control limits (Montgomery, 2013) (Page, 1954). Points located outside the control limits are commonly referred as assignable causes which means there's a specific cause that caused the point to be out of the control limits (Roberts , 1959). It is sometimes difficult to differentiate between common cause and assignable cause, furthermore just because the points are within the control limits does not mean the process is under control (Bernard , 1959). The points sometimes generate a suspicious pattern which will indicate there's something wrong in the process and must be fixed. Now for the EPC it's a continuous process of manipulating the process input controls in order to keep the output on target (Ogata, 2010). EPC utilizes different types of controllers that work by feedback adjustment such as the integral controller and the PID controller (Ogata, 2010) (Montgomery, 2013). These controllers will work in conjunction with a certain type of control chart where if a point falls outside the control limits then it will automatically trigger the controller to take corrective actions to bring the process back in control. The SPC & EPC unified framework has been proven to be very effective at significantly reducing the process variation and drastically improving the product quality. According to Karim Al Jebory & Mohammed Al Shebeb (Aljebory & Mohammed Al shebeb, 2014) they implemented the SPC & EPC unified framework in a chlorine manufacturing company and they managed to reduce the process variation by 30%. The findings of the case study (Aljebory & Mohammed Al shebeb, 2014) has shown us how effective it is to combine both techniques and that is why it is called SPC & EPC unified framework. As we previously mentioned there are many types of Shawhart control charts, however there are two types of control charts that are very good at detecting small shifts in the mean and they are the Cumulative Sum control chart (CUSUM) and the Exponentially Weighted Moving Average control chart (EWMA). These control charts can be generated by inputting the necessary data needed into Minitab. In order to construct a controller, we must first mathematically model the process by knowing the inputs, outputs, flow rates…etc. and then we can translate them into programming code and input it into MATLAB.

2. Background and literature review

2.1 Statistical Process Control

Statistical process control (SPC) is a useful quality tool in statistical quality control developed by Shewhart, where it is used to monitor the process and identify any assignable causes (Montgomery, 2013). The tools used in SPC are the control charts and each control chart can satisfy a different need. There are three main types of control charts, which are the variable control charts, the attribute control charts, and the time weighted control charts. The variable control charts are used to estimate the amount of variation that is within a certain process where the measured values are variables (e.g. dimensions, weight, concentration) (Zhang , 1998). The attribute control charts are used to monitor and evaluate the process where the data plotted are attributes (i.e. counts data). The time weighted controls are used to detect small shifts in the process mean where they gather information about the current and previous process observations in order to make the control chart more sensitive. There are three types of time weighted control charts and they are the exponentially weighted moving average control chart, cumulative sum control chart and the moving average control chart. All control charts have the same basic format where they all have a center line, an upper control limit, and a lower control limit. Using these tools will make it easier for the process engineer to identify any assignable cause by simply adopting SPC and implementing it into a manufacturing process, where it would drastically reduce the nonconforming (defective) and nonconformities (defect) (Montgomery, 2013). As a result, it would meet the specification requirements and will end up with an overall a more efficient process. SPC can be implemented to any process where the conforming product can be measured. This paper will be using the EWMA control chart in section 5, the EWMA control chart is explained in section 2.1.1.

2.1.1 Exponential Weighted Moving average

The Exponentially Weighted Moving Average control chart is a time weighted control chart which uses the weighted average Z_i , as the chart statistic rather than the sample number i. The weighted average can be calculated by using the following equation (Montgomery, 2013) (Shawhart , 1931):

$$EWMA_i = Z_i = \lambda X_i + (1 - \lambda)Z_{i-1} \tag{1}$$

The EWMA control chart control limits can be calculated by using the following equation:

$$UCL = \mu_0 + L_{\sigma}\sqrt{\frac{\lambda}{(2-\lambda)}(1 - (1 - \lambda)^{2i})} \tag{2}$$

CL=μ0

$$UCL = \mu_0 + L_{\sigma}\sqrt{\frac{\lambda}{(2-\lambda)}(1 - (1 - \lambda)^{2i})} \tag{3}$$

The factor L, that is shown in equation 2 and 3, is called the width of the control limit and the λ is called the weighting factor. The common values of λ ranges from $0.05 \leq \lambda \leq 0.25$ (Montgomery, 2013). Generally, using a smaller weight would be better at detecting small shifts in the process mean. The boundary value L is usually determined from an engineering decision based on the costs of being off target and the costs of making the adjustment (Aljebory & Mohammed Al shebeb, 2014). Montgomery proposed the following equation (4) to estimate $\sigma^{\wedge}EWMA$ (Montgomery, 2013) (Shawhart , 1931).

$$\sigma^{\wedge}EWMA = \sqrt{\frac{\lambda}{2-\lambda}}\sigma^{\wedge} \tag{4}$$

2.2 Engineering Process Control

Engineering process control (EPC) focuses on adjusting the process controls based on the current deviation from the target. EPC will use feedback adjustment to remove any assignable cause that the SPC approach failed to remove (Montgomery, 2013). The Integral control approach works by adjusting the process input variables based on the error that started to accumulate over a certain period of time. Usually, integral controls are used in conjunction with a proportional controller which is responsible for making corrective adjustments to the proportion of error in the input, so it can adjust faster and more accurate (Ogata, 2010). The combination of the integral controller and proportional controller is referred as the PI controller where they use feedback adjustment to reduce the deviation from the target (Montgomery, 2013).

2.2.1 Process control by feedback adjustment: Integral control

The main objective in feedback adjustment is to make the output as close to the desired target as possible. Let's say the process at period time t has an output of y_t and a singular input process variable of x, so changing x will affect the output y. $y_{t+1} - T = gx_t$, where T is the desired target and g is a constant called the process gain. The process gain is basically relating to the magnitude of change in x_t to the magnitude of change in y_t. It basically acts like a regression coefficient (Ogata, 2010) (Montgomery, 2013). In any process, there will most likely be some disturbances, we will denote the disturbance in the process with N, so $y_{t+1} - T = N_{t+1} + gx_t$ .This equation shows that at period t+1, the output deviation $y_{t+1} - T$ will depend on the disturbance in period t+1 plus the input variable x_t which is our chosen set point. By forecasting the disturbance, we would know the optimal set point to cancel out the disturbance.

$$x_t = \sum_{j=1}^{t}(x_j + x_{j-1}) = -\frac{\lambda}{g}\sum_{j=1}^{t} e_j \quad \textbf{(5)}$$

The actual set point for variable x_t at the end period t is the sum of all adjustments through time t, where λ the weight and *e* is are the predicted error (Montgomery, 2013). This type of process adjustment scheme is called the integral control, where it uses feedback control to manipulate the variable input x_t, to reduce the process deviation from the target.

2.2.2 Process control by feedback adjustment: Proportional integral derivative controller (PID)

A PID controller has the optimum control dynamics as it has zero steady state error and would eliminate the overshoot and oscillations of the output (Ogata, 2010). Moreover, it has a quicker response time compared to the integral controller or the proportional integral controller. Choosing the manipulative variable for a PID controller is calculated as shown below:

$$x_t = k_p e_t + k_i \sum_{i=1}^{t} e_i + k_D(e_t - e_{t-1}) \quad \textbf{(6)}$$

Where the k and c are constants that are chosen based on the tuning of the controller (Ogata, 2010).

2.3 Integration of SPC/EPC Methods

The SPC & EPC are two techniques that complete each other as they both work together to reduce the process disturbances and improve the product quality. There is a relationship between the EWMA predictor and the integral controller, where they both work hand in hand in order to make predictions (Hunter, 1986). Using EWMA control charts in conjunction with I controllers are frequently used because of their simplicity and efficiency. According to (Jiang & Farr, 2007), they proposed four different categories of the application of the two different quality control approaches, which are going to be illustrated:

1. The EPC scheme is not needed if the data is not correlated. The SPC will be used to monitor the process and identify any assignable causes
2. The EPC control scheme should be examined if the data is correlated. The SPC control charts should be brought up to monitor the autocorrelation if no possible EPC control scheme exists.
3. Even though the EPC control scheme can compensate some auto correlation disturbances, however a single EPC control scheme will not be able to compensate all the different kind of variations
4. The diagnostic process of the SPC will be used in conjunction with the feedback adjustment of the EPC control scheme, where the SPC will detect any sudden shift in the process mean & the EPC will take corrective actions based on the deviation from the target

By using the EWMA control chart in conjunction with the integral controller is a very effective way for reducing the process variation (Vander Wiel, Tucker, Faltin, & Doganaksoy, 1992). Using the EWMA with the integral controller comes with many advantages (Jiang & Farr, 2007), first of all the EWMA control chart is able to predict the next error which is essential in control engineering (Hunter, 1986). Secondly using the EWMA control chart in conjunction with the integral controller would drastically reduce the process variation and also would transform the current system into an automated system where the integral control would automatically calculate the exact adjustment needed to keep the process on target. The SPC & EPC unified framework will look for the best chance for quality improvement and will take it. By combining the strengths of SPC control charts and the strengths of the EPC control scheme, we will be able to significantly reduce the process variation (Shawhart , 1931). These two different quality control techniques can be implemented in a manufacturing company where they can drastically improve their product quality and achieve customer satisfaction.

There are three integration methods that can be used to integrate statistical process control (SPC) and Engineering process control (EPC) (Sachs, Hu, & Ingolfsson, 1995). The first one is the algorithmic statistical process control (ASPC) method which used to reduce the predictable variation. ASPC basically means to use EPC before the SPC (Wardell, Moskowitz, & Plante, 1994). So, the system would adjust the controllable variables before monitoring the process, instead of monitoring then adjusting the variables. The second method of integrating SPC and EPC is the active statistical process control which means to monitor the process and adjusting it at the same time. The third method is the run-to-run (RTR) method which is used to reduce the variability of the process. The Run-to-run process method uses SPC and EPC as batches. For example, adjusting the controllable variables for a certain process between runs every hour then start again. The PID controller is one of the most common EPC tools used in industries rather than other tools like MMSE (Tsung & Shi, 1998). The main goal of PID controller is to reduce the process variability as much as possible and to minimize the quality loss of their process (Mean-Squared-Error). To monitor the performance of the PID controller, SPC tools can be used. Furthermore, to evaluate the performance of the PID controller and SPC charts they used the relative efficiency (RE), absolute efficiency (AE) and ARL (Average Run Length) (Tsung & Shi, 1998). Relative efficiency measures the improvement that the PID controller achieves over the state of control (Tsung & Shi, 1998). Absolute efficiency (AE) measures the ratio of the MMSE over the PID. Average Run Length (ARL) is a measure performance of SPC charts. It measures how many in-control points on average plotted until the first out of control point. The Bonferroni approach which means to monitor the input and the output at the same time; this will help to improve the quality of monitoring. However, this approach is not sensitive and is not capable of detecting small shifts in the process mean (Tsung & Shi, 1998). So, by using the EWMA control chart would be more effective at detecting small shifts in the process mean and would drastically reduce the process variation (Shawhart , 1931).

3. Case study

Company XYZ is a locally based Hloro-Alkali Company that was listed in Kuwait Stock Exchange Market in 2002 and is focused on continual growth and optimization. Company XYZ complies with many international standards such as ISO 9001: 2008 quality management systems, ISO 14001: 2004 environmental management systems and OHSAS 18001: Occupational health and safety management. The company XYZ has a total equity of $106,019,515 dollars and produces and exports many kinds of salt-based products such as sodium chloride, sodium hypochlorite, sodium hydroxide, hydrogen and chlorine. These products have many uses in industrial sectors as they play an important role in the chemical manufacturing industry and the oil and gas industry. Company XYZ suffers from ***production disruptions*** and is unable to keep the feed brine concentration on target. The production disruptions are causing the cell membranes lifecycle to decrease due to the high variability in the feed brine concentration. The cell membranes main function is to prevent any unwanted reaction to occur in the electrolysis chamber. Company XYZ has a total of 120 cell membranes with a total cost of $594,060 dollars. By integrating the SPC & EPC unified framework into Company XYZ manufacturing line, it would drastically reduce the variation in the feed brine concentration and as a result would increase the cell membranes lifecycle.

To regulate the salt levels of the process, the current control practice in company XYZ uses sensors such as the hydrometer to measure the acidity and the concentration of the prepared feed brine solution and inputs them into a regression model in order to predict the proper feed brine concentration. The values of the feed brine concentration are plotted on IMR- control chart as seen in Figure 1 to monitor the process. If there is an out of control point then an alarm will sound in the Control Room and the Control Engineer will then manually manipulate the salt levels to bring the process back in control.

Now the current control system has many problems. First, the company uses IMR-control charts which has low sensitivity and is unable to detect small shifts in the process mean. Second, the IMR-control chart lacks the ability to predict the next error, which is a big problem since predicting error is essential in control engineering. The third problem is that the adjustments are done manually by the control engineers in the control room. Now manually adjusting the process comes with many drawbacks. First, the control engineers may not input the exact adjustment. Secondly the control engineer must always be present and alert at all times, and that would cause cognitive fatigue whereby human error is more likely to occur.

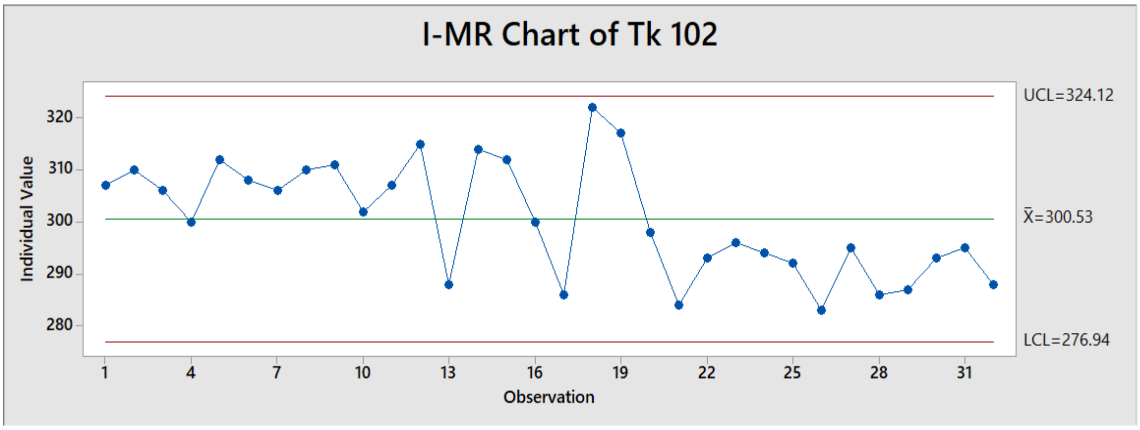

Figure 1: IMR-Control Chart, Brine Concentrations

4. Integrated SPC & EPC unified framework

The integration of SPC & EPC will be done in three phases which are the offline monitoring phase, the online measuring & detecting phase, and the integrated SPC & EPC phase. The offline monitoring phase focuses on analyzing the process flowchart, identifying key input variables, identifying critical to quality, collecting historical data and checking them for normality and autocorrelation. The online measuring & detecting phases focuses on generating control charts ensure all points are within the limits and there's no pattern present in the data. Also, the analysis of the current control system happens in this phase. The integrated SPC & EPC phase focuses on the implementation of the concept.

Beginning with the offline monitoring phase, we will analyze the process flowchart shown in Figure 2, identify the key process variables and identify the critical to quality. The process starts by pumping in sea water as it then undergoes many multiple filtration steps to remove varies types of impurities that may be present due to sea pollution. The sea water will eventually be evaporated away until only purified salt will be left behind and it will be stored into super purified salt storage tanks. The salt will be mixed with purified water in the Ferric Treatment Tank shown in Figure 3 and undergoes further filtration and re-saturation until we get super purified brine (pure salt dissolved in water). The purified brine then enters the Electrolysis Chamber shown in Figure 4, where the solution will breakdown into its elements to make hydrogen, chlorine and sodium hydroxide. These chemicals will then undergo further processing until they get their final product which is hydrochloric acid, sodium hypochlorite and sodium hydroxide. Finally, some of the feed brine will be recycled back into the treatment tank for re-saturation

Varies things happens in the Electrolysis Chamber. First, when the feed brine enters the Electrolizer, then the NaCl (salt) and the water, H_2O, will breakdown into their elements where chlorine ions will go to the positive electrode (anode) and sodium ions and hydroxide ions will go to the negative electrode, cathode, and hydrogen gas will also be formed. Both electrodes are separated by a Cell Membrane where it helps with ion exchange and also prevents any unwanted reaction to occur in the Electrolizer.

The main purpose of the ferric treatment tank is to re-saturate the brine solution to the optimum concentration to make sure it does not affect the cell membrane located in the Electrolizer. The treatment tank begins with the input tank Tk102 then brine goes through varies filtration steps until it reaches the refiner R101 where caustic soda and soda ash is added to the brine solution to remove impurities such as calcium and magnesium. The brine will then keep going through varies filtration stages in the treatment tank until it reaches the final tank which is Tk151 which is where the super purified feed brine is stored with a target concentration of 306 gpl. The feed brine will then exit the treatment tank and enter the Electrolizer.

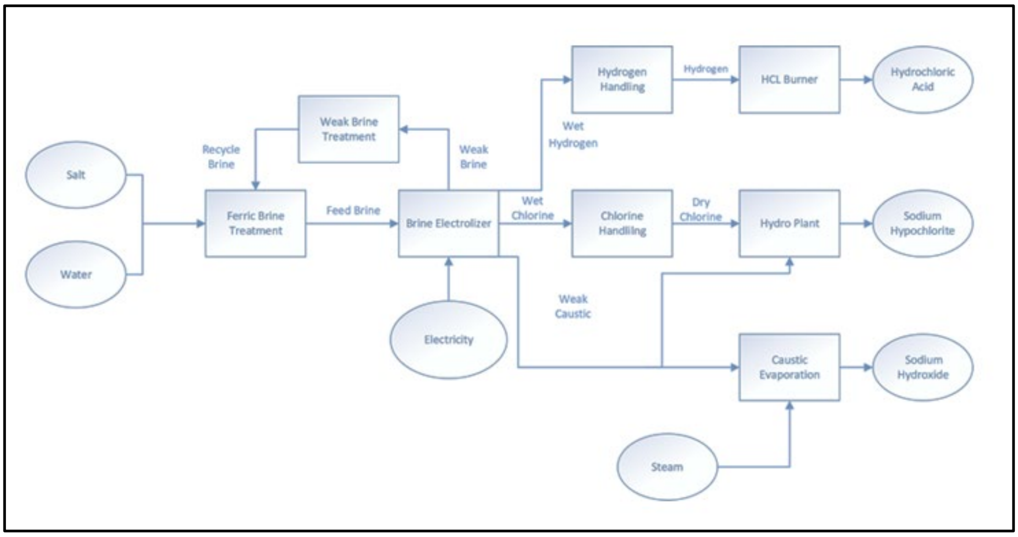

Figure 2: Process Flowchart

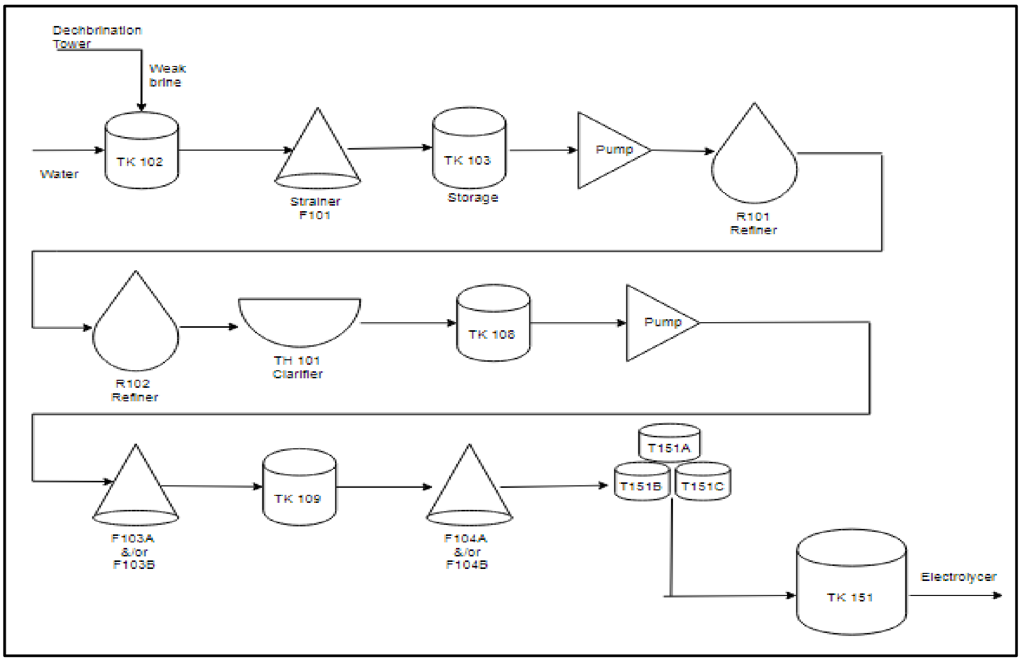

Figure 3: Ferric Treatment Tank

It has been found out that the cell membrane located in the Electrolizer is very sensitive to the feed brine concentration and needs to be replaced every three to four years. The cell membrane has a current Lifecycle of 3-4 years, each cell membrane costs $4,950 dollars and the company have 120 membranes with a total cost of $594,060 dollars. Our objective is to increase the Cell Membranes life cycle to 6-8 years by reducing the variation in the feed brine concentration.

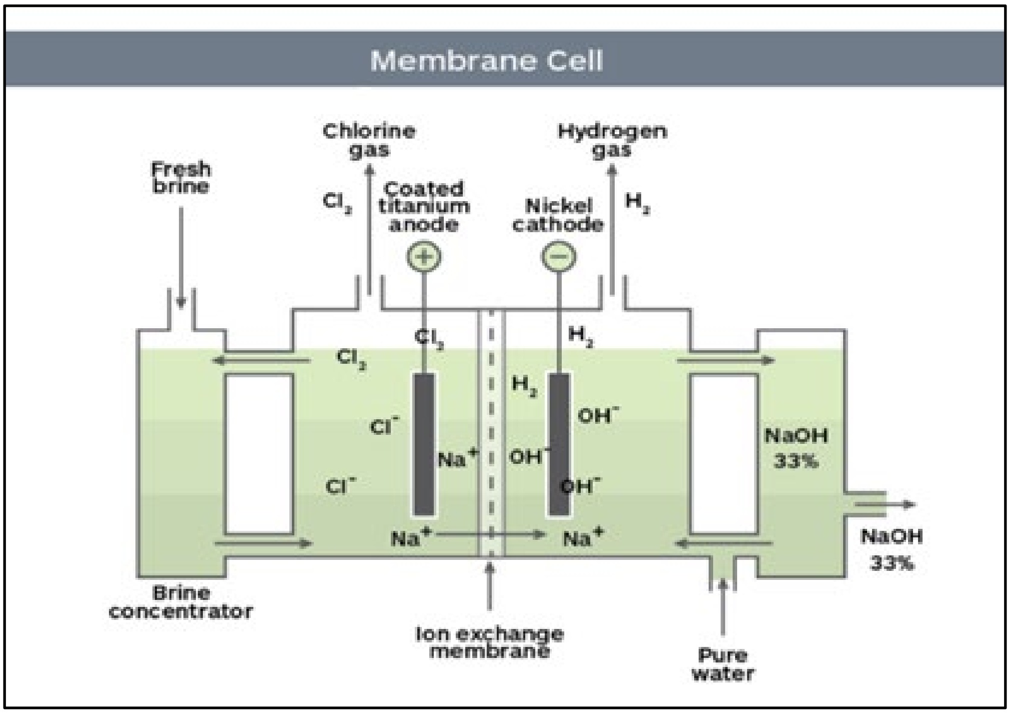

Figure 4: Electrolysis Chamber - Electrolizer and Cell Membrane

5. Framework Demonstration

Our research ***Concept*** is proposing the use of the sensitive EWMA control chart in conjunction with the Integral Controller where we will have two Arrays, one is the EWMA points and the other is the process observation. The integral controller will continue checking the EWMA points and once it exceeds the boundary limits then the integral controller would formulate an adjustment and send it to the process. Figure 5 is a visual representation of our Concept, where Array 1 is the weighted averages and Array 2 is the actual measured process values.

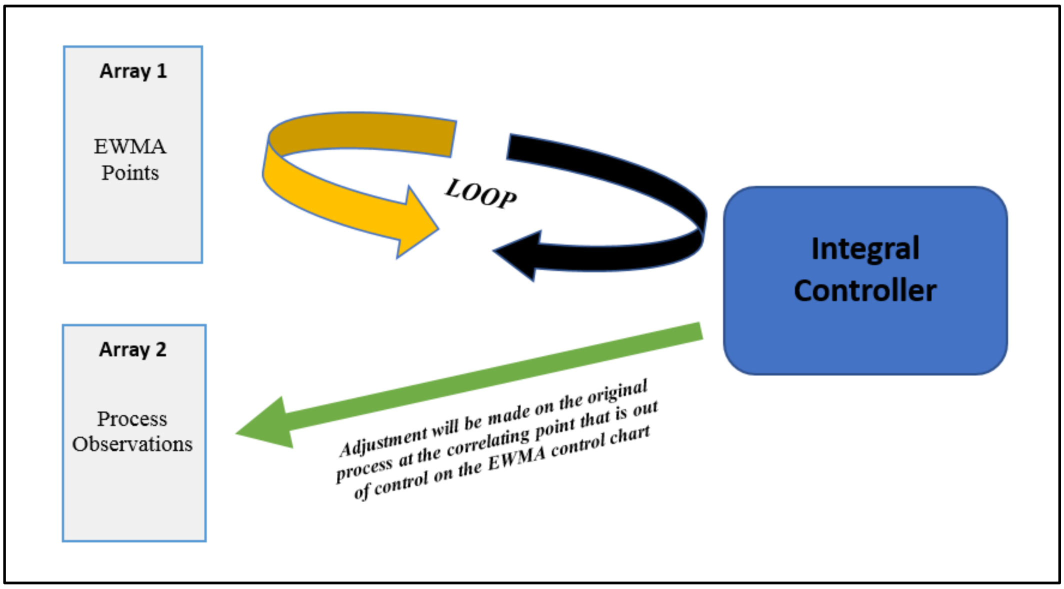

Figure 5: Research Concept

The boundary limit is an engineering decision that can be calculated based on Equation 4. By using MATLAB, we have created a program that will continually check the EWMA values in array 1 using a "For loop" and when the point exceeds the upper or lower boundary the integral controller will calculate the required adjustment using Equation 5 to keep the process on target and send the adjustment to the actual process. The upper boundary (UB) is equal to 311.78 gpl and the lower boundary (LB) is equal to 300.22 gpl. We used $\lambda = 0.3$ which resulted in a process gain of 0.9795. Figure 6 shows a fitted line plot between the brine concentration levels in the output tank (Tk151) and the input tank (Tk102).

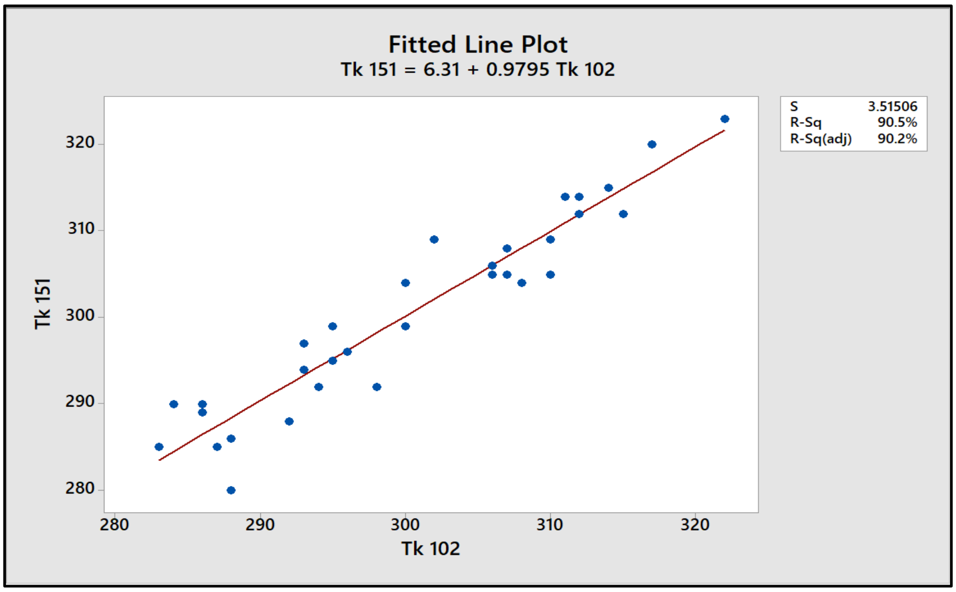

Figure 6: Fitted Line Plot of Tk102 & Tk151

Table 1 shows the unadjusted and adjusted values for brine concentration in Tk102. The first adjustment was made at observation 22 which exceeds the lower boundary and the integral controller calculated the required adjustment of 3.98 to bring the process back on target and reduce the deviation of the output from the target. The control scheme will continue this way where the integral controller will continually calculate the required adjustments to bring back the process and keep it within the boundaries. The third column in Table 2 is called set-points and it's the cumulative adjustments done to the process.

Table 1: Process data before and after adjusting

	Tk 102	Adjusted Tk 102	EWMA	Adjustments	Setpoints
1	307	307.00	306.60	0	0
2	310	310.00	306.12	0	0
3	306	306.00	306.08	0	0
4	300	300.00	303.96	0	0
5	312	312.00	306.37	0	0
6	308	308.00	305.66	0	0
7	306	306.00	305.46	0	0
20	298	298.00	305.74	0	0
21	284	284.00	301.02	0	0
22	293	293.00	299.81	3.98	3.98

6. Results and Findings

After integrating the EWMA control chart in conjunction with the integral controller in the ferric treatment tank, the framework managed to reduce the process variation by 32.8% and also reduced the standard deviation by 18% which is a dramatic improvement. By reducing the process variation and standard deviation, we have successfully achieved our objective of increasing the cell membranes lifecycle. We have tried different values of λ in order to find the optimum one that will give us the least variation, and that is $\lambda = 0.3$ as shown in Table 2.

Table 2: Comparison of λ

Process	Target g/lit	Variance	St Dev
Before Adjustment	300.30	119.16	10.92
Adjustment λ=0.1	302.12	95.91	9.79
Adjustment λ=0.2	303.02	90.97	9.54
Adjustment λ=0.3	304.10	80.07	8.95

This project shows the significance of the EWMA control charts when compared to the individual control charts. With EWMA control charts, we were able to detect out of control points that individual control chart may have missed. In Figure 4 the brine was plotted on individual control charts and all the points were under control, the same points were plotted using the EWMA control charts as shown in Figure 7 and we were ableto detected three out of control points that the individual control chart failed to detect.

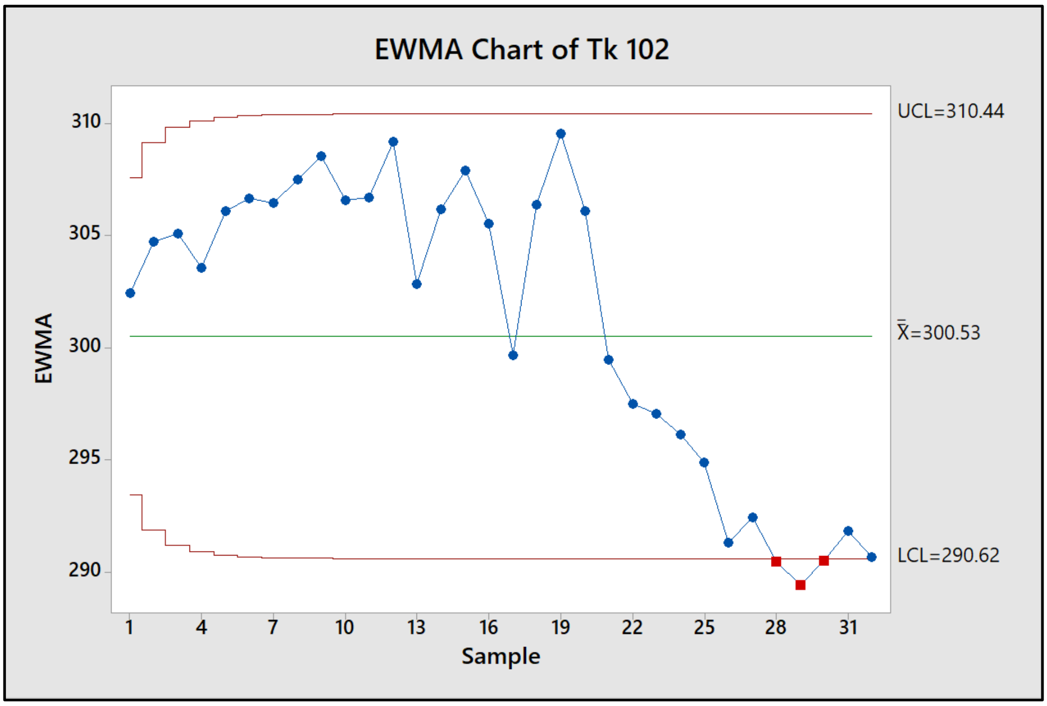

Figure 7: EWMA Control Chart for Tk102

7. Conclusion

In conclusion, the development and application of SPC & EPC unified framework has been proven to be very effective in reducing process variation and improving the product quality. EWMA control charts are very effective at detecting small shifts in the process means thanks to its sensitivity and is also able to forecast the next process error which is essential in control engineering. In this project the objective was to create a concept where we used the EWMA control chart in conjunction with the integral controller in order to keep the feed brine concentration on target in order to increase the cell membranes life cycle. SPC & EPC integration approach was done in three phases; offline monitoring phase, online measuring and detecting phase and finally the integrated SPC/EPC phase. The first phase was about analyzing the process, identifying the CTQ, identifying the key input variables and understating the process flow chart. The second phase involves analyzing the current control system. The third and final phase is where we introduce the concept which is the EWMA control chart in conjunction with the integral controller. After consulting with the process control engineers, they said by keeping the feed brine concentration on target we are able to double cell membrane lifecycle, reduce monthly cost by 50% and reduce process variation. As a whole we firmly believe that our research Concept is able to drastically improve the product quality and reduce cost. The Concept is also very versatile where it is able to easily adapt into different industries such as the oil and gas industry.

Acknowledgements

We would like to acknowledge AUM and the Industrial Engineering department for facilitating this project and for their support throughout the time to make this work come true. Also, we would like to thank Company XYZ for their cooperation and allowing us to practice our engineering knowledge and skills to finalize this work.

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Biographies

Bader Al-Mutawa, Ali Issawy, Osama Ahmad, Abdullah Al-Haj Hasan, and Samer ElKhatib are recently graduated students from the American University of the Middle (AUM) in Kuwait, majoring in Industrial Engineering. During their four years of study they gained several engineering and computational skills. They worked with computer software such as MS Office, AutoCAD, Minitab, MATLAB, Arena, Jack, and Visual Studio. They participated in many AUM academic activities and in addition to their major graduation project presented in this paper, they worked on several course projects in the area of manufacturing processes, safety and ergonomics, operation research, quality control, simulation, and lean six sigma.

Walid Smew is an Assistant Professor in Industrial Engineering at the American University of the Middle East (AUM), Kuwait. He earned B.Sc. and M.Sc. in Industrial and Systems Engineering from Benghazi University, Libya and PhD in Lean Supply Chain Management from the School of Mechanical and Manufacturing Engineering in Dublin City University (DCU), Ireland. Dr. Smew is a Chartered Engineer and member of Libyan Engineers Association, he is also a certified Lean Six Sigma Greenbelt and Product and Process Validation engineer in Ireland. Dr. Smew has published several journal and conference papers and supervised many graduation projects. He has an excellent experience, both theoretically and practically, in machining and metal forming operations and the application of Lean Six Sigma for problem solving and finding optimized solutions through the application of different statistical techniques. Dr. Smew provided technical guidance to assembly processes using work measurement techniques to identify opportunities to improve production performances in terms of time and cost. Dr. Smew has done consulting in the area Supply Chain Management (SCM) and Simulation Modeling along with Dr. John Geraghty from DCU; they developed a comprehensive production and distribution simulation model for Ireland's future oil supply on behalf of Byrne Ó Cléirigh for engineering and management consultancy. Dr. Smew research interest include Quality Control, Lean Six Sigma, SCM, Manufacturing Processes, Simulation and Optimization. Recently Dr. Smew and his research project colleagues won the first place of the Undergraduate Research Competition in IEOM 2018, Bandung-Indonesia, the first place of the Senior Design Poster Competition in IEOM 2018, Paris-France, and the first place of the Lean Six sigma Competition in IEOM 2018, Washington DC-USA.