The Integration of Statistical Process Control and Engineering Process Control in Reactor System

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***Abstract*—Integration of Statistical Process Control (SPC) and Engineering Process Control (EPC) in the system for the purposed to monitoring and adjusting the disturbance and fault that cause variation to the system or process. Batch reactor have a bigger issue in controlling the temperature also lack of on-line monitoring and controlling worst the problem. The main goal of this research paper is to present the integration of SPC and EPC in the batch reactor. The EPC adjustment have been applied apart from assignable cause and fault detection using SPC. The SPC mechanism act as trigger to EPC have been approached in control scheme. The different type of SPC tools: Shewhart chart, Exponential Moving Average (EMWA) chart and Cumulative Sum (CUSUM) chart have been approach to monitor the process. The CUSUM and EMWA chart is more effective than Shewhart because can quickly detecting mean shift that are small relative to measurement system.**

Keywords— Engineering Process Control, Statistical Process Control, Shewhart, CUSUM, EMWA, Batch Process, PID Controller

I. Introduction

Statistical Process Control (SPC) is being used along with feedback control system also known as Engineering Process Control (EPC) in improve the product quality in industrial process. In basic, SPC focus on to determine whether assignable causes exits in manufacturing process through the analyzing the quality characteristics data from process output. In the contrary, EPC is adjust the process variable in order to keep the output on set point or target. The integration of SPC and EPC will produce efficient tool for process variation reduction and improve the final product quality by creating necessary condition. In most literature, researches more focus on integrated of SPC and EPC into continuous process. A little attention in integrated SPC and EPC in batch system process especially in batch reactor. The main problem of batch reactor system is temperature and it is very difficult to control [1]. Moreover, the lack of online monitoring (real time data) on the monitoring and controlling of the batch reactor system.

There are two different type of approach to improve product quality in industry which are Statistical Process Control (SPC) and Engineering Process Control (EPC)[2]. This approach have different function in process control. SPC is monitoring procedure to reduce the output variability by detecting and eliminating the disturbance causes of variation. While EPC focus on adjusted the manipulated variable in order to keep the output on target[3]. Until recently, the reasons why these two have been keep separately because are different view each of them in industrial processes.

Product quality is very important aspect in all in industries. The product with high quality become high demand in market. Therefore, various industries have their own strategies to make sure their product always in good quality. This issue become critical objective because of increasing of raw materials and energy consume of the process. Therefore, in order to monitor the process, there are technique that have been used or approached for improving the quality of product, at the same time will reduce the cost of operation. The technique that had been approached was integration of Statistical Process Control (SPC) and Engineering Process Control (EPC). SPC is monitoring scheme to reduce the process output variability in the system that is very effective by detecting and eliminating the disturbance that causes of variation. Meanwhile, EPC is used to minimize and adjust the output process variable by making online adjustment of one or more process input to keep the output on set point or target [4].

There are numerous studies that related with integration of SPC and EPC in production and manufacturing industries. The combination of SPC and EPC technique in monitoring the output and input of the process result in detection of assignable cause in all causes.This is enhance the capability of the integration of SPC and EPC under different working condition [5]. The integration of SPC and EPC can also act as decision making tool for engineer if the production is affected by certain disorders that effect the satisfactory and product quality of manufacturing. Hachicha and Moussa (2012) had proposed integrated SPC and EPC for batch process using two type of integration which are active SPC and Run to Run (RTR). This integration is performed in two successive phase. Xuihong proposed the compositive method of Neural Network to monitor the process output and Exponentially Weighted Moving Average (EMWA) and Shewhart to detect the process input in integrated SPC and EPC scheme [6]. Matos and Requeijo proposed a methodology and framework integration of EPC and SPC that could be tested and applied to real case study. The final product performance can represent a breakthrough of integration of SPC and EPC by creating necessary condition to reduce the process variability of quality characteristics both short and long term.

Reactor are very important equipment in many industry such as in the production of polymer, food, pharmaceutical and fine chemical. Reactor are sort out into continuous reactor and batch reactor based on production capacities, different material accession mode and product output. Batch reactor are used extensively in the manufacture of relatively small scale production with superior selectivity such as in industry polymer, dyes, inks, pharmaceutical and food industry. Achieving a stable operating condition in batch reactor is very important to achieve yield, product quality and cycle time that met the commercial need.

Batch reactor is closed system process, where once the reactant is enter into reactor, the product will come out only after the completion of the reaction. No material is added or removed during the process. The majority problem of batch reactor is involve with temperature control via heating and cooling system. Moreover, many chemical reaction are very sensitive to temperature for formation of desired product and reaction rate highly dependent on temperature. Therefore batch temperature is typically control by using jacket around the reactor by circulate the hot and cold fluid. The temperature is control by manipulating the heat content from the jacket to the reactor.

There are many studies and literature related with temperature control of chemical batch reactor. Author focus on to developed or proposed new strategy to control temperature in batch reactor. The temperature control of batch reactor can be control by approach the new model free adaptive control that is based in expert system, fuzzy control and neural network [7]. Another technique can be applied in batch reactor system to control temperature by installation of a predictive fuctional control (PFC). [8]. In the system that have been proposed by Bouhenchir and Cabassud they implemented cascade control stucture in the batch reactor system.

Sampath and Palanki proposed design of robust controller for the temperature tracking problem in jacketed batch reactor [9]. In this design the controller has a multi-loop feedback configuration which are inner loop for approximation input-output linearization of nominal plat and outer loop for stability and robust performance by utilizing result from structured singular values. Huzmezan and Gough state that advanced controller has the ability to model and control marginally stable processes with long time delays and long time constant that found in the batch reactor temperature control [10].

This research is conducted to study in detail the integration of Statistical Process Control (SPC) and Engineering Process Control (EPC) by approach SPC mechanisms act as a trigger of EPC control scheme. This study also to determine whether EPC adjustment should be applied apart from assignable causes and fault detection using SPC. The different type of SPC tool control charts have been approached to determine the more effective control chart for batch reactor system.

This research is focus on batch esterification reactor system. Esterification is an important reaction in chemical industry. Enzymatic esterification is used in the reactor to increase the reaction rate and conversion of the reactant but it very sensitive to reactor temperature.Thus, it is very important to determine and control the optimal temperature of the reactor. Figure 1 show the schematic diagram of the the batch reactor.

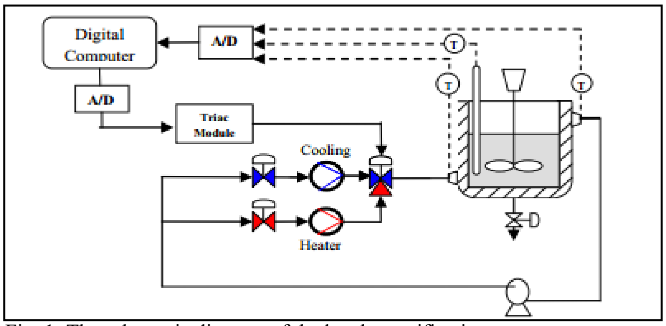


Fig. 1: The schematic diagram of the batch esterification reactor system.

2. Statistical Process Control (SPC)

SPC is achieved by plotting and comparing statistical measure of the variable with some user defined control limit. The process is considered out of control, if the process exceed the control limits. Then the corrective action is applied by identify and eliminate the disturbance that causes the variation of the process. To control a process using variable data is achieved by the aid of control chart. It is help to monitor the current state of accuracy and precision data. There are several type of charts used such as Shewhart, Exponential Moving Average (EMWA) and Cumulative Sum (CUSUM).

Shewhart chart is developed by Walter A.Shewhart. This principle also known as Shewhart control chart. The Shewhart chart is the common use in SPC. Shewhart control chart is use detect larger shift of process [11]. This is general model for the control chart as expressed below:

$$\begin{aligned} UCL &= \mu_w + L\sigma_w \\ CL &= \mu_w \\ LCL &= \mu_w - L\sigma_w \end{aligned} \qquad (2)$$

2.1 The Cumulative Sum Control Chart (CUSUM)

The CUSUM chart is more effective for relatively small magnitude of the shift compare to Shewhart chart[12]. Furthermore, CUSUM control chart particularly effective with sample of size $n = 1$. This is make CUSUM is suitable to use in chemical and process industries where rational subgroups are frequently of size 1. CUSUM chart was proposed by Page (1954). The tabular CUSUM control chart works by accumulating derivations from μ_o that are the above target with one statistic C^+ and accumulating derivations from μ_o that below target with another statistic C^- . The statistic C^+ and C^- are called one-sided upper and lower CUSUM.They are computed as follows:

$$\begin{aligned} C_i^+ &= \max[0, x_i - (\mu_o + K) + C_{i-1}^+ \\ C_i^- &= \max[0, (\mu_o - K) - x_i + C_{i-1}^- \end{aligned} \qquad (3)$$

Where the starting value are $C_o^+ = C_o^- = 0$
In the equation, K is called reference value and it often chosen about halfway between the target μ_o and the out of control of the mean μ_1 that are interested in detecting quickly. Shift is expressed in the standard deviation units as $\mu_1 = \mu_o + \delta\sigma$, then K is one-half the magnitude of the shift expressed as:

$$K = \frac{\delta}{2}\sigma = \frac{|\mu_1 - \mu_o|}{2} \qquad (4)$$

Note that C_i^+ and C_i^- accumulates deviations from the target value μ_o that are greater than K, with both quantities reset to zero on becoming negative. If either C_i^+ or C_i^- exceed the decision interval H , the process is considered out of control [13].

2.2 Exponential Moving Average Chart (EMWA)

The EMWA chart is introduced by Robert (1959). It is widely used in order to monitor the process mean, since it weigh the average of all the past and present observation. The exponential moving average is defined as:

$$z_t = \lambda x_t + (1 - \lambda) z_{t-1} \qquad (5)$$

Where $0 < \lambda \le 1$ is a constant and the starting value required for the first sample at $t = 1$ is the process target, so that

$$z_o = \mu_o$$

The EMWA chart would be constructed by plotted z_i versus the sample number or time. The center line and control limits for the EMWA control chart are as follow:

$$UCL = \mu_o + L\sigma\sqrt{\frac{\lambda}{2-\lambda}[1-(1-\lambda)^{2i}]}$$
$$CL = \mu_o \qquad (6)$$
$$LCL = \mu_o - L\sigma\sqrt{\frac{\lambda}{2-\lambda}[1-(1-\lambda)^{2i}]}$$

The EMWA control chart is very effective in detecting mean shifts that are small relative to the measurement system[14]. The parameter used in EMWA chart are the multiple of sigma used in the control limits (L) and the value of λ . There many theoretical studies of the average run length properties of EMWA control charts for example Lucca and Saccucci (1990) and Razmy and Peiris (2013). This studies provide average run length tables and graph values of λ and L .

3.0 Integration of SPC and EPC Methods

The integration of SPC and EPC in the system can both secure the optimization and improvement of the process system. There are four categories of ongoing research and application of quality approaches[15]:

I. The traditional SPC control chart can be used if the process is not correlated without employ the EPC schemes.
II. If process correlated, the possibility of implement EPC scheme should be examined. SPC control charts are applied to monitor auto correlated processes if no feasible EPC controller exist.
III. EPC control can be implement to compensate the autocorrelated disturbance if appropriate controller is available. However, no single EPC can compensate all kinds of variations.
IV. Feedback control must be use to identify and understand the cause of process changes, while using the diagnostic capability of SPC to detect sudden shift disturbance to the process.

The need of combining the SPC and EPC have been stated by [16] in his study. These are the following reasons integration of EPC and SPC is necessary to studied and applied in practical process domains:

1) Although the EPC allows to make regular adjustments to manipulative variable process within a certain range in order to keep output near the target, EPC competence is limited to the presence of common cause variation
2) Some of the transient response of the uncertainty disturbance still can make the process out of control. SPC is able to eliminate the assignable cause, which will be ignored if the EPC took over and keep the process stability.

II. METHODOLOGY

$$g_c = 0.00016(1+\frac{1}{13.17s}+0.328\ s) \qquad (1)$$

$$g = \frac{15540}{1+11.1s}e^{-6.573s} \qquad (2)$$

The proposed SPC and EPC integration approach is conducted in three phase process selection, simulation phase, and integrating SPC and EPC phase as shown in Figure 2.

Process selection phase

In this phase, the process was selected and narrow to batch reactor system. After that, the process analysis was conducted to understand the entire process including the critical relation between quality requirement and the the performance of input and output condition. The manipulated variable, set point and disturbance variable was identified for the system. In this case study, temperature of the reactor is the key to the production of ester because of sensitivity of enzymatic behavior to the reactor temperature. To maintain the temperature of the reactor at the desired set point which is at 310K, the inflow of cooling water must be control. The manipulated variable to maintain the temperature of the reactor is inlet flowrate of coolant and jacket temperature of the reactor act as disturbance in this system.

3.1. Simulation phase

In the phase, the set point tracking and disturbance rejection must be done to make sure that the on-line and simulation of the controller response in a good agreement. The simulation of process model is simulated in Matlab software. Then, the data of process will be extracted from the Matlab to calculate the control limit. The control chart is plot using Minitab software. From this resut, the fault detection and diagnosis will conducted based on SPC and EPC rules. The SPC control chart will monitor the process system within the SPC limits. If the process exceed the control limit, the integration of SPC and EPC will be conducted in the system. However, if the system is in control, the process will proceed because no disturbance is detected.

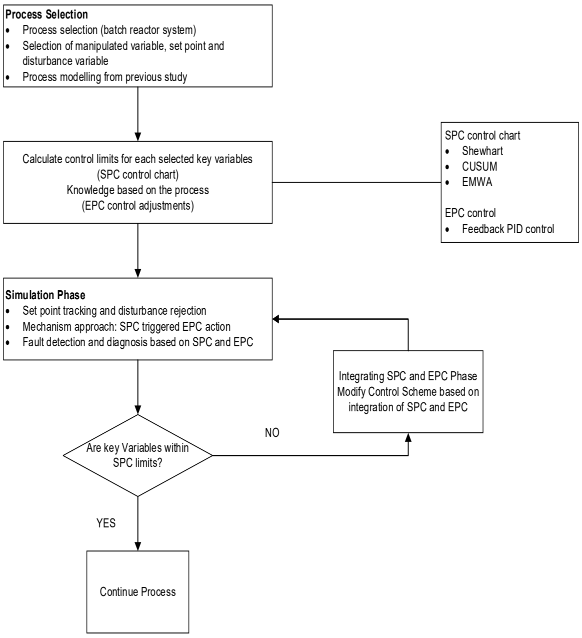


Fig. 2: The flowchart of integration of SPC and EPC.

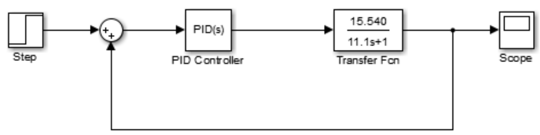


Fig. 3: Matlab Simulink of the reactor system

The batch reactor system that have been selected, is simulated in Matlab simulink as shown in Figure 2. The PID controller and process control parameter of the system is adopted from [17]

III. RESULTS AND DISCUSSION

The system in reactor use feedback PID controller to adjusting the variable in order to stabilize the system. The system is simulated in three condition:

1) Without PID controller and disturbance
2) With PID controller but without disturbance

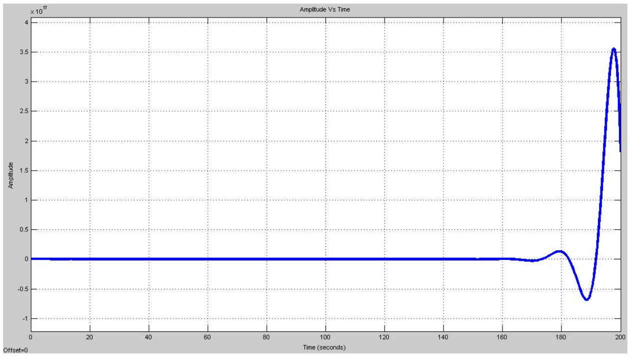


Fig 4: The reactor system without PID controller and disturbance

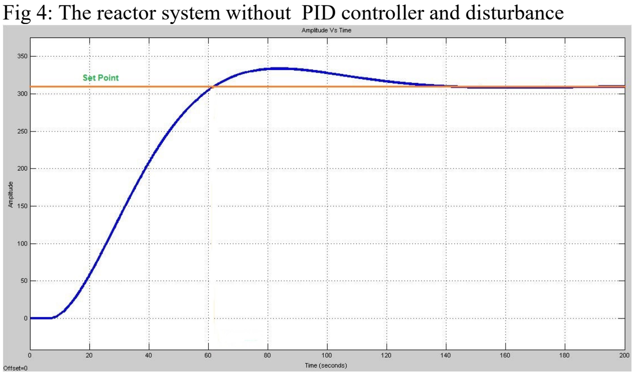


Fig 5: The reactor system with PID controller and disturbance

As can be seen in Figure 4, the system show that the the instability of the process occur when the system is run without PID controller. The integral absolute error (IAE) for the system is about 2.334×10^{18}. Meanwhile, the simulation process of system is more stable when PID controller is installed in the system as shown in Figure 5. The plot show the process response undergo overshoot about 8.152% before reach set point at 310 approximately at 140s. The integral absolute error for this system is 1.146×10^{4}.

Data collection of the Process

Based on the analysis from the previous study, one key variable were selected as critical to monitor the process and one final output. This variable that being monitor was jacket temperature and the final output is reactor temperature. This critical variable is selected from fifty successful random value that have been simulate in Matlab. The final output of reactor temperature were presented in Table 1.

Fault Detection and Diagnosis

The standard deviation of the system is estimated from sample size of process. In this process, the standard deviation is estimated from Minitab in probability capability report of sample. The standard deviation of this system is 23.19.

In this process, the sample size of the process monitoring is $n=1$. There are many type of control chart in Shewhart chart such as x, R and s chart. In a situation that the sample size used for process monitoring is $n=1$ that consists of individual unit, the control chart for individual units is useful Montgomery (2008). Therefore, In order to monitor the process variability, the Shewhart chart for individual measurement is selected. The individual control chart and moving range chart are used for this process. Individual and moving range control chart shown in Figure 4.6 indicating that the lack of statistical stability in the process.

From the result, there are three point that are out of control from the individual chart which are at 1,12 and 43. Meanwhile,in the moving range chart that is only one point that out of control at point 43. The value that out of control limit indicate that the value of x is large that lead to the large value of moving range for that sample. As the Figure 4.6 makes clear, an upward shift in temperature has occurred around observation 43 and downward shift at 1 and 12, since there is an obvious shift process control level pattern on the chart for individual chart. The moving range also reacts to this level shift with large point at 43. This point on the moving range is helpful in determine exactly where the process shift in the mean has occurred. Clearly possible assignable causes must be look or check around 43. Possible causes maybe from jacket temperature that have been injected in the system.

Table 1: Measurement of final output temperature for fifty successful processes

Exp	Reactor Temperature
1	222.2
2	285.0
3	353.7
4	318.0
5	316.9
6	330.1
7	381.5
8	313.3
9	311.6
10	310.6
11	310.2
12	238.8
13	297.1
14	362.8
15	315.9
16	310.5
17	325.0
18	315.5
19	312.9
20	311.3
21	310.5
22	256.6
23	311.3
24	310.1
25	331.7
26	356.6
27	321.7
28	312.5
29	311.1
30	310.4
31	320.3
32	311.9
33	256.6
34	319.2
35	314.3
36	312.2
37	310.9
38	310.3
39	330.3
40	272.4
41	313.6
42	317.6
43	407.0
44	343.0
45	320.0
46	336.3
47	310.3
48	314.8
49	310.7
50	313.7

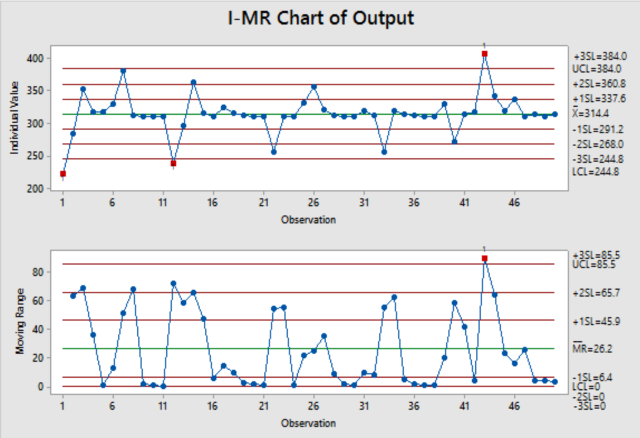


Fig 6: Individual and moving range chart.

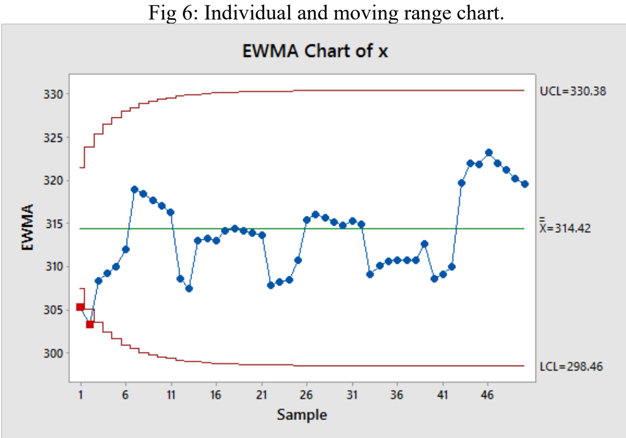


Fig 7: EMWA Chart of Output with $\lambda = 0.1$

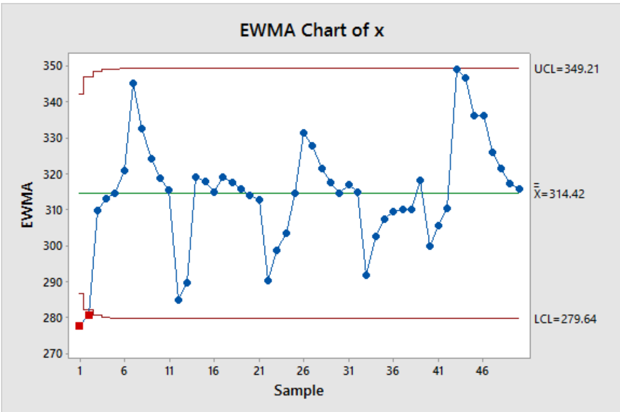
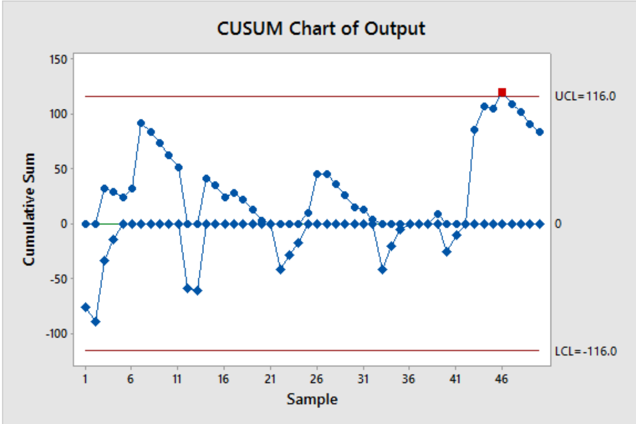


Fig 8: EMWA Chart of Output with $\lambda = 0.4$

An EMWA control chart on the output deviation from target would generally detecting assignable cause more quickly than individual and moving range chart. The EMWA was forecast the disturbance with an EMWA having($\lambda = 0.1$) and ($\lambda = 0.4$).Figure 7 and Figure 8 show the EMWA chart for the process with respective weight, and from the chart the assignable causes at observation ($t = 1$) and ($t = 2$) from both chart. As can be seen in Figure 4.2 and Figure 5, EMWA having $\lambda = 0.1$ more quickly detect smaller shift compare to EMWA $\lambda = 0.4$.

Figure 9 shows the CUSUM chart from Minitab. The control chart show that, at sample = 46 the process is out of control because is above the upper control limit of the system. This control chart also prove that CUSUM control chart quickly detect small shift of process. This is very helpful to monitor the temperature of esterification reactor that very sensitive with temperature.



FFig 9: CUSUM chart of output

Average Run Length (ARL) show in Table 2 is performance measure of the of the control chart to determine the more effective control chart for batch reactor.

Table 2 Average Run Length for performance measure of the EPC/SPC

Magnitude of shift	Shewhart	EMWA λ=0.1	EMWA λ=0.4	CUSUM h=5, k=0.5
0	370.0	500.0	500.0	465.0
0.5	156.3	41.8	71.2	38.0
1.0	43.9	10.3	14.3	10.4
1.5	15.0	6.1	5.9	5.75
2.0	6.3	4.4	3.5	4.01

As can be seen from the Table 2, the best or particularly effective to monitor and control the process of the reactor system is Cumulative Sum (CUSUM) chart. Overall, the EMWA and CUSUM both seem the best option to monitor the process. Moreover, the choice between this two is not critical because of the similarity between them that can quickly detect small shift.

IV. Conclusion

This paper has studied the detail of integration of Statistical Process Control and Engineering Process Control by approach SPC mechanism act as a trigger of EPC control scheme. SPC is focus of process monitoring and fault detection meanwhile, EPC is make adjustment to the process to avoid the process is drifting away from set point . The batch esterification reactor system has approached as case studied. In this batch reactor system, temperature of the reactor is very important to make sure the quality of the product is achieve. Therefore, in this paper the installation of feedback PID control the system help to monitor temperature of the reactor and eliminate the disturbance that causes the process is drift away from set point. The installation of the PID control stabilize the process and help process to run within the control limit.

In this paper, the different type of control charts; Shewhart, EMWA and CUSUM chart was evaluated. The result proved that CUSUM control chart is the best option and particularly effective to monitor the reactor system because it can detect small shift generally detect more quickly assignable causes. EWMA control chart also can be used because of similarity between them both.

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