Using Key Process Indicators in Prioritizing Control Loop Maintenance Activities

Alireza Haji-Valizadeh
Technology Development Manager
ControlSoft Inc.
Cleveland, OH 44143

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ABSTRACT

In many processing units, Key Performance Indicators (KPI) are defined, measured (or calculated), and used as economical metrics for the process. These KPI are measures for the efficiency of the underlying production unit's operations. Engineering economy in today's competitive market requires optimizing the KPI. Many factors affect the process KPI, such as: 1. Underlying technology used in the production; 2. Operating conditions designed for the production; and, 3. Regulation of the production unit at assigned operating conditions. Thus, we could view loop regulatory control – which tries to maintain the process variables at their respective setpoint – as an effort to optimize process KPI.

In this paper we suggest guidelines for defining maintenance KPI for the process. Based on the contribution of each loop's performance to the maintenance KPI, one can determine if a loop needs maintenance and what should be the precedence of maintaining the loop. This method is also based on expressing a given maintenance KPI in terms of a set of predefined process-independent control loop performance indices. The contribution of each loop's performance on the overall maintenance KPI can then be evaluated and used as the criteria for prioritizing maintenance activity. We also provide an example to demonstrate the application of the suggested methods. Such prioritization is a crucial step in predictive maintenance, and could be used to maximize maintenance – and in turn process – KPI for a given level of maintenance resource.

I. INTRODUCTION

A *predictive maintenance* policy uses process diagnostics and performance analysis tools to focus maintenance resources mainly on *problematic* loops and components offering the greatest return on investment. Surveys reported in [LD] have shown that there is considerable room for improvement in plant operations if an effective loop maintenance policy is adopted. This multi-industry loop audit survey has reported that only 32% of loops have acceptable or excellent performance. According to a survey reported in [PH], many industries now are adopting some form of Condition Based Maintenance (CBM) method as a predictive maintenance policy.

The objective of predictive maintenance is twofold. First, it aims to address under-performing and problematic loops before they become intolerably faulty where chances for occurrence of costly unscheduled shutdowns are high. The second objective is to better the cost effectiveness of the maintenance effort. This second objective necessitates prioritizing the maintenance of the various loops.

Various policies could be utilized in prioritizing maintenance of loops on a plant-wide scale. In this paper we focus on two economically oriented methods as the following:

1. Prioritizing based on contribution to Unit Fluctuations Cost Model (UFCM);
2. Prioritizing based on the contribution to Pseudo Fluctuations Cost Model (PFCM).

In the following sections we describe each method of prioritization in more detail.

II. PRIORITIZING MAINTENANCE BASED ON CONTRIBUTION TO UNIT FLUCTUATION COST MODEL (UFCM)

Having key indicators to measure the effectiveness of maintenance activities has long been a common practice in industry. One commonly used indicator is the ratio of unscheduled process shutdowns to the sum of scheduled and unscheduled process shutdowns. An effective maintenance policy should drive this ratio to lower values over time. Other maintenance indictors may take into consideration the cost of maintenance in a budgetary period to evaluate the efficiency of the maintenance in addition to its effectiveness. However, maintenance indicators of this sort, which are designed to provide information to managers, present few shortcomings when they are viewed in the framework of predictive maintenance. For example: The above indicator cannot be used to determine if a specific controller of a process needs maintenance. It also cannot be used in prioritizing the maintenance effort. In modern predictive maintenance, the traditional key indictors should be used in conjunction with newly defined methods and measures to render improved maintenance practices.

Costs incurred because of fluctuations in the process variable or control output is the main factor for efficiency loss and a loop's poor performance. Quality degradation of the product, loss of energy resources, waste of production, loss of production time, and shortened life time for process components are side effects of a fluctuating process. Industry vendors and academic researchers have suggested many indicators for measuring process fluctuation. Examples are Integral Absolute Error (`IAE`), Standard Deviation of Error (`StdDevE`), Process Variability (`PVar`), and the like [KA, AV1]. Current practice in industry is to measure and calculate indices of this kind online preferably by using moving time windowed analysis then compare them against their historical optimum baseline values to determine if the corresponding loop needs maintenance. This practice is enhanced when we incorporate the financial or monetary implications of the fluctuations in determining the need and the priority for maintaining a loop.

There are various ways we could incorporate the economical implications of process fluctuations in predictive maintenance. A common theme in all methods is based on relating process fluctuations to quality loss, resource waste, energy waste, and production loss and then to quantify the cost of these fluctuations. To this end, we could use material and energy balance laws that govern the underlying production, process dynamics, laws governing heat transfer and mass flow, properties of process materials, and the like in order to express the cost of fluctuations in the process variables and controllers' output. Knowing the financial model for the unit fluctuations we could then calculate the percentile of contribution of each loop to the total cost of unit fluctuations in an online fashion. By ordering loops based on their contribution to the cost of fluctuations, and, setting up threshold levels for each loop's cost, we could determine the priority, and respectively, the need for maintaining the loop.

Among the advantages of the aforementioned method, we have the following:

1. It is production unit oriented;
2. It provides monetary measure for the underlying production unit's fluctuations;
3. It provides criteria for both determining the need as well as the priority of maintenance;
4. It incorporates different types of controllers (or loops) in the same maintenance scheme.

One serious disadvantage for this method, that could prohibit its practical application in a plant-wide scale, is the need for developing a monetary cost model for process fluctuation which can be an expensive and cumbersome task requiring statistical analysis of process and financial data for the underlying unit. This requires time and extensive expertise and thus is itself a costly undertaking.

As an example, consider a simplified version of a real world batch process that consists of a cooking vessel depicted in Figure (1). First, raw material is fed into the vessel in liquid form. Then the temperature of the material is brought up to a desired level. After the food is cooked at a certain temperature for a preset length of time it is discharged. A food-processing site has a number of these vessels working in cascade and parallel configurations to cook the foods for various recipes. A maintenance regime for this site should determine when unit controllers need maintenance and how to prioritize maintenance among various loops.

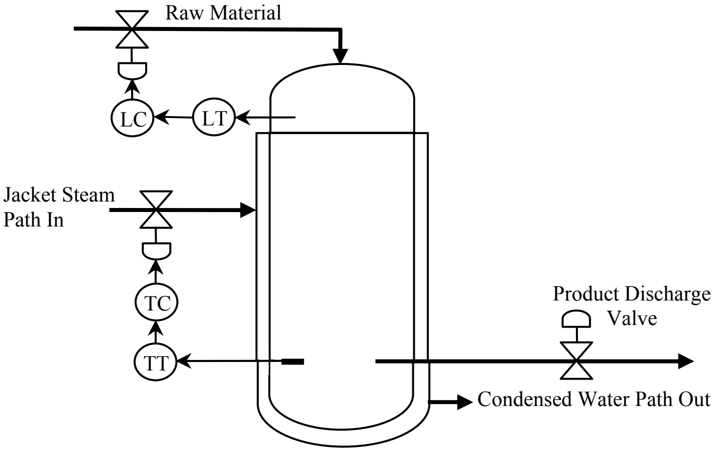


FIGURE 1 – FOOD COOKING VESSEL

The performance of the temperature controller directly affects the efficiency of the process. To increase the output of the process, we want to raise the temperature to its setpoint as fast as possible and then to maintain the temperature at its setpoint for a preset length of time. There are, however, two common fault modes for this process:

1. The controller behaves too slowly which results in a loss of production time.
2. The controller behaves too aggressively causing the temperature to overshoot its setpoint.

This second fault mode results in a build up of a layer of burned food on the inside wall of the vessel. This heat insulating layer changes the dynamics of the heat exchange process by increasing the time constant of heat exchange process and consequently forcing the controller to saturate CO more easily, and, cause the waste of heating energy. Despite CO saturation the process temperature may take a long time to rise to its setpoint which results in a loss of production time. Through this trend of behavior, the process suffers from loss of energy and production time. Gradually, process operation degrades to an intolerable level until the operation is stopped. As a corrective action the vessel is flushed with fresh water to remove the layer of burned food from the inside walls of the vessel. The flushing process results in further loss of production time and introduces extra cost for the operations. Although flushing could not be avoided completely, good maintenance of the process controller decreases the frequency of flushing.

One way to monitor the performance of the temperature controllers of the vessels is to measure the Integral Absolute Error (`IAE`) of the corresponding controllers. When `IAE` exceeds a preset threshold level then a maintenance work order is issued. To prioritize maintenance activity, the precedence could be given to maintaining the controller with the higher `IAE`. Two shortcomings of this method are these: 1. It does not suggest what should be the preset threshold level; and, 2. Among vessels that cook various recipes, which controller should be maintained first. Note that a vessel that is cooking a highly priced product whose controller's `IAE` may not even trigger the issuance of a maintenance work order in the above scheme, could be wasting more money than the maintenance-demanding vessels.

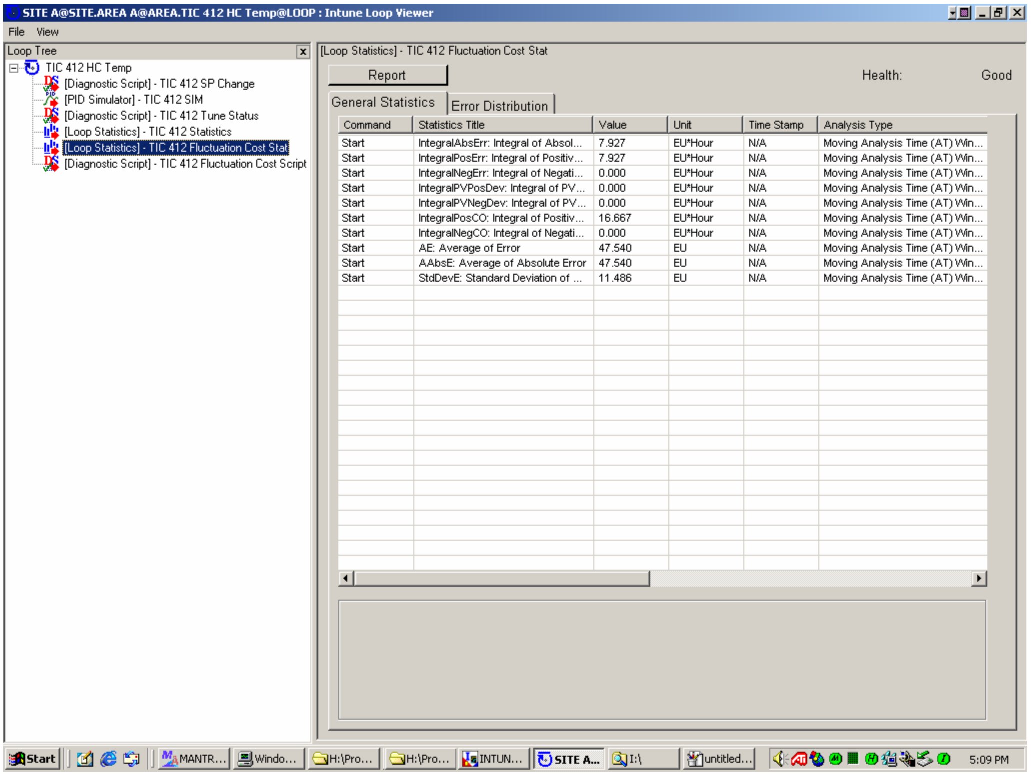
An improved maintenance method incorporates the cost associated with the fault modes in the decision making process. To this end, we can model the cost of fluctuations as follows:

$$\mathit{NumberOfFlushes} = f(\texttt{IntegralPVPosDev}) \quad (1)$$
$$\mathit{ProductionTimeLossCost} = \mathit{NumberOfFlushes} * \mathit{CostOfEachFlush} + g(\texttt{IntegralPosErr}) \quad (2)$$
$$\mathit{EnergyCost} = h(\texttt{IntegralNegErr}) + k(\texttt{IntegralPosCO}) \quad (3)$$
$$\mathit{FluctuationCost} = \mathit{ProductionTimeLossCost} + \mathit{EnergyCost} \quad (4)$$

In equations (1) through (4), relationships *f(.), g(.), h(.),* and *k(.)* are nonlinear. These might be approximated by first-order linear functions by applying a least square curve fitting method to historical data. In the above equations, `IntegralPVPosDev` is the integral of positive deviation of PV from a pre-known level at which the product starts to burn. As `IntegralPVPosDev` increases the number of necessary flushes also increases. Build up of temperature insulating layer inside the cooking vessel causes loss of the production time, captured in (2), through two mechanisms: 1. Increase of number of water flushes, and 2. Increase of system time constant which in turn results in higher values of *g(*`IntegralPosErr`*)*, where `Err=(SP-PV)`. Energy is wasted in the system through two mechanisms: 1. Overheating the process that is captured by *h(*`IntegralPosErr`*),* and 2. Increasing the time constant and thus causing CO to push harder to achieve the same objective. This second energy cost is captured in *k(*`IntegralCOPos`*)*. The total cost of fluctuations can now be obtained as in equation (4).

Compared to the former method of prioritization, which depends on a single loop assessment index `IAE`, this method depends on `IntegralPVPosDev`, `IntegralNegErr`, `IntegralPosErr`, and `IntegralCOPos` assessment indices. The advantage is that this latter method provides a monetary maintenance KPI, i.e. *FluctuationCost*. Evidently this KPI makes it easier to establish a monetary threshold level for issuance of a maintenance work order for a controller. It is also easier to prioritize maintenance activity among a number of service-demanding controllers.

Figure (2) depicts `IntegralPVPosDev`, `IntegralNegErr`, `IntegralPosErr`, `IntegralCOPos` loop assessment indices being calculated using moving time windowed analysis with the batch-time length. Note that the above-mentioned indices are defined to assess any controller behavior and can be used to develop a fluctuation cost model for various processes. The loop assessment indices are calculated online using a moving-window or an expanding-window depending on the application. Figure (3) depicts implementation of a VBScript to evaluate *FluctuationCost*. Figure (4) depicts a maintenance scheme implemented utilizing the above method.

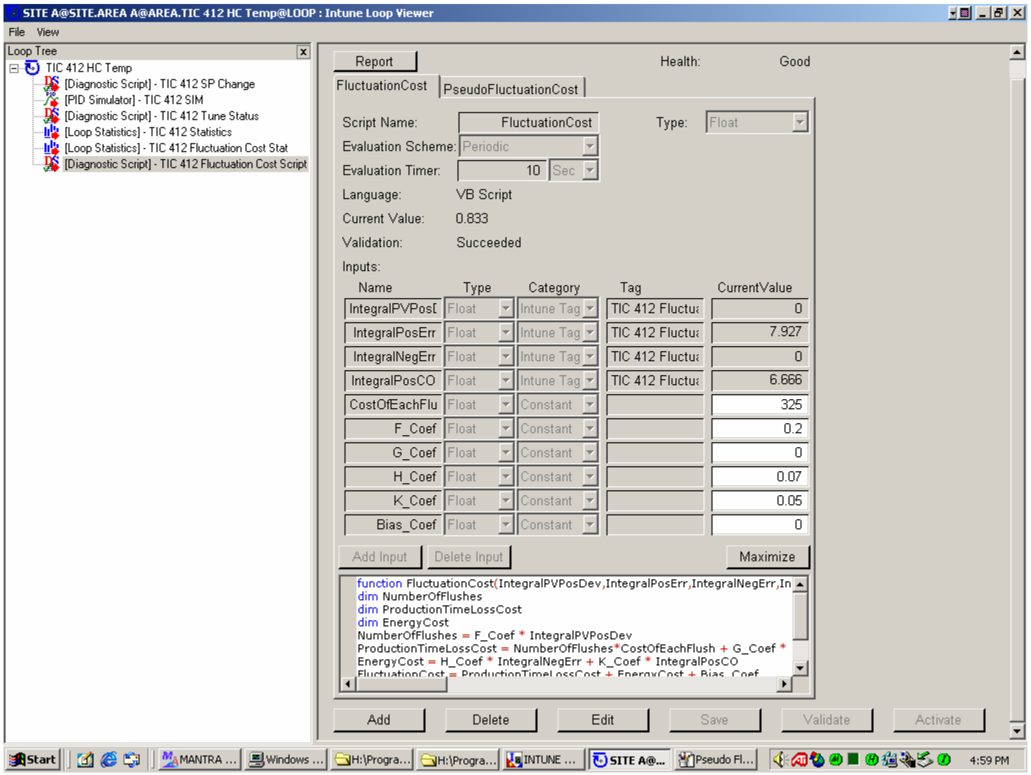


[Loop Statistics] - TIC 412 Fluctuation Cost Stat

Health: Good

Command	Statistics Title	Value	Unit	Time Stamp	Analysis Type
Start	IntegralAbsErr: Integral of Absol...	7.927	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralPosErr: Integral of Positiv...	7.927	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralNegErr: Integral of Negati...	0.000	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralPVPosDev: Integral of PV...	0.000	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralPVNegDev: Integral of PV...	0.000	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralPosCO: Integral of Positiv...	16.667	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	IntegralNegCO: Integral of Negati...	0.000	EU*Hour	N/A	Moving Analysis Time (AT) Win...
Start	AE: Average of Error	47.540	EU	N/A	Moving Analysis Time (AT) Win...
Start	AAbsE: Average of Absolute Error	47.540	EU	N/A	Moving Analysis Time (AT) Win...
Start	StdDevE: Standard Deviation of ...	11.486	EU	N/A	Moving Analysis Time (AT) Win...

FIGURE 2 – STATISTICS PLUGIN EVALUATING BASIC LOOP ASSESSMENT INDICES IN ONLINE FASHION



Health: Good

Script Name: FluctuationCost

Type: Float

Evaluation Scheme: Periodic

Evaluation Timer: 10 Sec

Language: VB Script

Current Value: 0.833

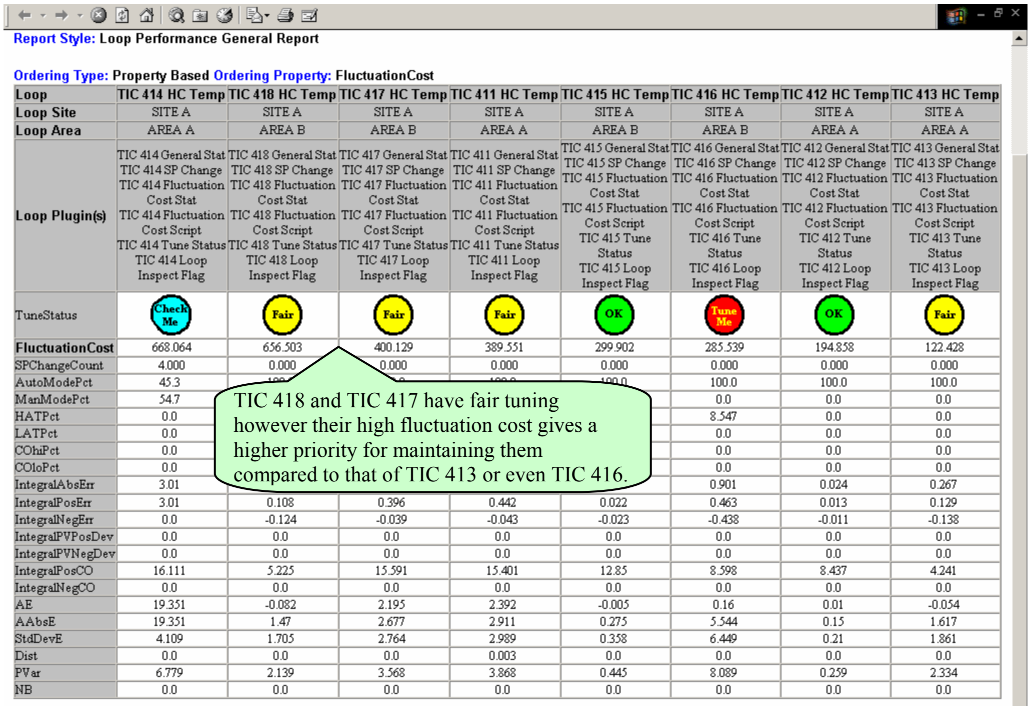
Validation: Succeeded

Inputs:

Name	Type	Category	Tag	CurrentValue
IntegralPVPosI	Float	Intune Tag	TIC 412 Fluctu	0
IntegralPosErr	Float	Intune Tag	TIC 412 Fluctu	7.927
IntegralNegErr	Float	Intune Tag	TIC 412 Fluctu	0
IntegralPosCO	Float	Intune Tag	TIC 412 Fluctu	6.666
CostOfEachFlu	Float	Constant		325
F_Coef	Float	Constant		0.2
G_Coef	Float	Constant		0
H_Coef	Float	Constant		0.07
K_Coef	Float	Constant		0.05
Bias_Coef	Float	Constant		0

```
function FluctuationCost(IntegralPVPosDev,IntegralPosErr,IntegralNegErr,In
dim NumberOfFlushes
dim ProductionTimeLossCost
dim EnergyCost
NumberOfFlushes = F_Coef * IntegralPVPosDev
ProductionTimeLossCost = NumberOfFlushes*CostOfEachFlush + G_Coef *
EnergyCost = H_Coef * IntegralNegErr + K_Coef * IntegralPosCO
FluctuationCost = ProductionTimeLossCost + EnergyCost + Bias_Coef
```

FIGURE 3 – SCRIPT PLUGIN EVALUATING FLUCTUATION COST USING LOOP ASSESSMENT INDICES



Report Style: Loop Performance General Report

Ordering Type: Property Based **Ordering Property:** FluctuationCost

Loop	**TIC 414 HC Temp**	**TIC 418 HC Temp**	**TIC 417 HC Temp**	**TIC 411 HC Temp**	**TIC 415 HC Temp**	**TIC 416 HC Temp**	**TIC 412 HC Temp**	**TIC 413 HC Temp**
Loop Site	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A
Loop Area	AREA A	AREA B	AREA B	AREA A	AREA B	AREA B	AREA A	AREA A
Loop Plugin(s)	TIC 414 General Stat TIC 414 SP Change TIC 414 Fluctuation Cost Stat TIC 414 Fluctuation Cost Script TIC 414 Tune Status TIC 414 Loop Inspect Flag	TIC 418 General Stat TIC 418 SP Change TIC 418 Fluctuation Cost Stat TIC 418 Fluctuation Cost Script TIC 418 Tune Status TIC 418 Loop Inspect Flag	TIC 417 General Stat TIC 417 SP Change TIC 417 Fluctuation Cost Stat TIC 417 Fluctuation Cost Script TIC 417 Tune Status TIC 417 Loop Inspect Flag	TIC 411 General Stat TIC 411 SP Change TIC 411 Fluctuation Cost Stat TIC 411 Fluctuation Cost Script TIC 411 Tune Status TIC 411 Loop Inspect Flag	TIC 415 General Stat TIC 415 SP Change TIC 415 Fluctuation Cost Stat TIC 415 Fluctuation Cost Script TIC 415 Tune Status TIC 415 Loop Inspect Flag	TIC 416 General Stat TIC 416 SP Change TIC 416 Fluctuation Cost Stat TIC 416 Fluctuation Cost Script TIC 416 Tune Status TIC 416 Loop Inspect Flag	TIC 412 General Stat TIC 412 SP Change TIC 412 Fluctuation Cost Stat TIC 412 Fluctuation Cost Script TIC 412 Tune Status TIC 412 Loop Inspect Flag	TIC 413 General Stat TIC 413 SP Change TIC 413 Fluctuation Cost Stat TIC 413 Fluctuation Cost Script TIC 413 Tune Status TIC 413 Loop Inspect Flag
TuneStatus	Check Me	Fair	Fair	Fair	OK	Tune Me	OK	Fair
FluctuationCost	668.064	656.503	400.129	389.551	299.902	285.539	194.858	122.428
SPChangeCount	4.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AutoModePct	45.3	[illegible]	[illegible]	[illegible]	100.0	100.0	100.0	100.0
ManModePct	54.7	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0
HATPct	0.0	[illegible]	[illegible]	[illegible]	[illegible]	8.547	0.0	0.0
LATPct	0.0	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0
COhiPct	0.0	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0
COloPct	0.0	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0
IntegralAbsErr	3.01	[illegible]	[illegible]	[illegible]	[illegible]	0.901	0.024	0.267
IntegralPosErr	3.01	0.108	0.396	0.442	0.022	0.463	0.013	0.129
IntegralNegErr	0.0	-0.124	-0.039	-0.043	-0.023	-0.438	-0.011	-0.138
IntegralPVPosDev	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IntegralPVNegDev	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IntegralPosCO	16.111	5.225	15.591	15.401	12.85	8.598	8.437	4.241
IntegralNegCO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AE	19.351	-0.082	2.195	2.392	-0.005	0.16	0.01	-0.054
AAbsE	19.351	1.47	2.677	2.911	0.275	5.544	0.15	1.617
StdDevE	4.109	1.705	2.764	2.989	0.358	6.449	0.21	1.861
Dist	0.0	0.0	0.0	0.003	0.0	0.0	0.0	0.0
PVar	6.779	2.139	3.568	3.868	0.445	8.089	0.259	2.334
NB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TIC 418 and TIC 417 have fair tuning however their high fluctuation cost gives a higher priority for maintaining them compared to that of TIC 413 or even TIC 416.

FIGURE 4 – PRIORITIZING MAINTENANCE BASED ON CONTRIBUTION TO UNIT FLUCTUATIONS COST MODEL (UFCM)

III. PRIORITIZING MAINTENANCE BASED ON CONTRIBUTION TO A PSEUDO FLUCTUATION COST MODEL (PFCM)

As mentioned in the previous section, obtaining a monetary cost model for the fluctuations of a unit in the UFCM method is, in general, an expensive undertaking. This may prove to be a prohibitive factor in applying this method on a plant-wide scale. However, an alternative method that is rather easily implemented on a large scale is based on only three steps: 1. Developing a pseudo fluctuation cost model for the controllers; 2. Categorizing the loops based on their type; and, 3. Prioritizing the maintenance of controllers belonging to each type independently.

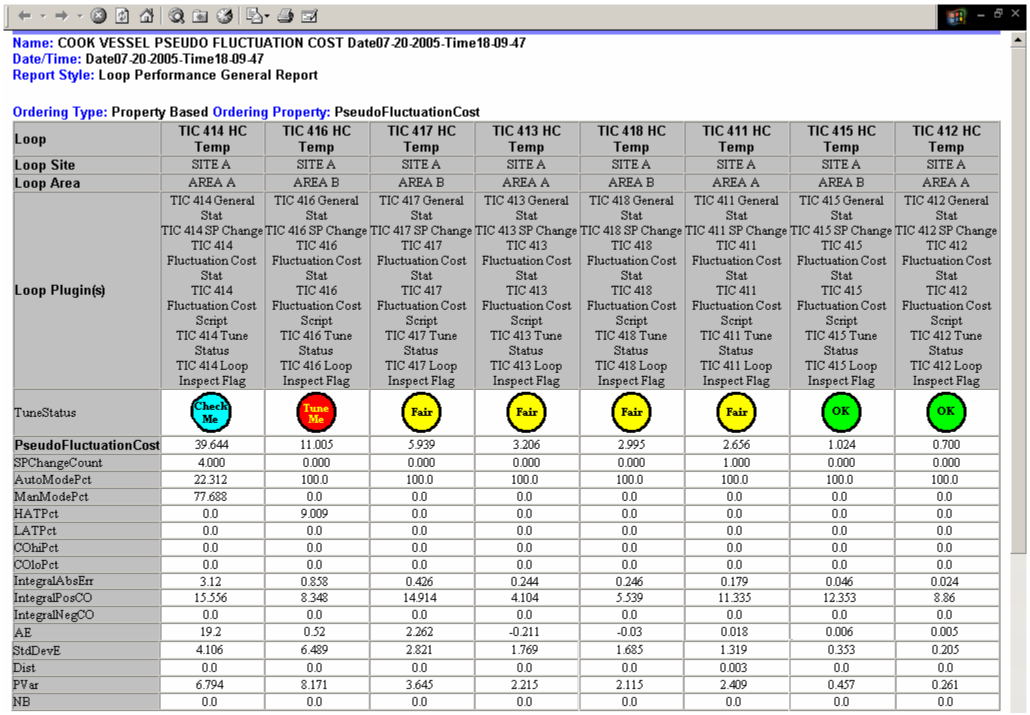
An appropriate pseudo fluctuation cost model is one that is: 1. Monetary; 2. Reflects roughly the cost that is associated with having poor performing controllers; and, 3. It is easily developed. As an example consider the following model that provides a pseudo fluctuation cost per one unit of time:

$$PseudoFluctuationCost = (IAE * ValueOfProcessedProduct) / T \quad (5)$$

The principle used in defining the pseudo fluctuation cost in (5) is that the cost associated with a poorly-performing controller used in producing a valuable product is likely to be higher, and thus its maintenance should be given precedence. In (5), *T* denotes the length of time during which `IAE` and the value of the processed product are evaluated. *T* for a batch process could be the batch time and for a continuous process could be the length of time that it takes the process to reach its steady state, e.g. four times its dominant time constant. In (5) `IAE` captures the amount of fluctuations calculated using percent setpoint error; and the *ValueOfProcessedProduct* denotes the value of processed product in *T*. We could enhance the fluctuation cost function defined in (5) to include pseudo energy cost information. Equation (6) suggests one cost function in this realm.

$$\mathit{PseudoFluctuationCost} = (\texttt{IAE} * \mathit{ValueOfProcessedProduct}) / T + (\texttt{IntegralPosCO} / T) * \mathit{CostOfUnitOfPositiveCO} \quad (6)$$

For certain loop types, energy cost could be easily obtained. For example, for temperature loops where the energy source is electricity or steam, the cost of energy (or power) is well known. For other loop types the energy information may not be readily available, in which case it could be excluded from the cost model. Figure (5) depicts an application of this method.



Name: COOK VESSEL PSEUDO FLUCTUATION COST Date07-20-2005-Time18-09-47
Date/Time: Date07-20-2005-Time18-09-47
Report Style: Loop Performance General Report

Ordering Type: Property Based **Ordering Property:** PseudoFluctuationCost

Loop	**TIC 414 HC Temp**	**TIC 416 HC Temp**	**TIC 417 HC Temp**	**TIC 413 HC Temp**	**TIC 418 HC Temp**	**TIC 411 HC Temp**	**TIC 415 HC Temp**	**TIC 412 HC Temp**
Loop Site	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A	SITE A
Loop Area	AREA A	AREA B	AREA B	AREA A	AREA B	AREA A	AREA B	AREA A
Loop Plugin(s)	TIC 414 General Stat TIC 414 SP Change TIC 414 Fluctuation Cost Stat TIC 414 Fluctuation Cost Script TIC 414 Tune Status TIC 414 Loop Inspect Flag	TIC 416 General Stat TIC 416 SP Change TIC 416 Fluctuation Cost Stat TIC 416 Fluctuation Cost Script TIC 416 Tune Status TIC 416 Loop Inspect Flag	TIC 417 General Stat TIC 417 SP Change TIC 417 Fluctuation Cost Stat TIC 417 Fluctuation Cost Script TIC 417 Tune Status TIC 417 Loop Inspect Flag	TIC 413 General Stat TIC 413 SP Change TIC 413 Fluctuation Cost Stat TIC 413 Fluctuation Cost Script TIC 413 Tune Status TIC 413 Loop Inspect Flag	TIC 418 General Stat TIC 418 SP Change TIC 418 Fluctuation Cost Stat TIC 418 Fluctuation Cost Script TIC 418 Tune Status TIC 418 Loop Inspect Flag	TIC 411 General Stat TIC 411 SP Change TIC 411 Fluctuation Cost Stat TIC 411 Fluctuation Cost Script TIC 411 Tune Status TIC 411 Loop Inspect Flag	TIC 415 General Stat TIC 415 SP Change TIC 415 Fluctuation Cost Stat TIC 415 Fluctuation Cost Script TIC 415 Tune Status TIC 415 Loop Inspect Flag	TIC 412 General Stat TIC 412 SP Change TIC 412 Fluctuation Cost Stat TIC 412 Fluctuation Cost Script TIC 412 Tune Status TIC 412 Loop Inspect Flag
TuneStatus	Check Me	Tune Me	Fair	Fair	Fair	Fair	OK	OK
PseudoFluctuationCost	39.644	11.005	5.939	3.206	2.995	2.656	1.024	0.700
SPChangeCount	4.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000
AutoModePct	22.312	100.0	100.0	100.0	100.0	100.0	100.0	100.0
ManModePct	77.688	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HATPct	0.0	9.009	0.0	0.0	0.0	0.0	0.0	0.0
LATPct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COhiPct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COloPct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IntegralAbsErr	3.12	0.858	0.426	0.244	0.246	0.179	0.046	0.024
IntegralPosCO	15.556	8.348	14.914	4.104	5.539	11.335	12.353	8.86
IntegralNegCO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AE	19.2	0.52	2.262	-0.211	-0.03	0.018	0.006	0.005
StdDevE	4.106	6.489	2.821	1.769	1.685	1.319	0.353	0.205
Dist	0.0	0.0	0.0	0.0	0.0	0.003	0.0	0.0
PVar	6.794	8.171	3.645	2.215	2.115	2.409	0.457	0.261
NB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

FIGURE 5 – PRORITIZING LOOP MAINTENACE USING PSEUDO FLUCTUATION COST MODEL (PFCM)

IV. ACKNOWLEDGMENTS

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V. CONCLUSION

Determining if a loop needs maintenance and prioritizing among service-demanding loops are basic steps of any predictive maintenance regime. In this paper, we reviewed two methods UFCM, and PFCM, useful in prioritizing the maintenance of loops. We discussed the strengths and weaknesses of each method. In conclusion, it is worthwhile to note that the above-mentioned methods are not mutually exclusive and different methods could be applied to different loops within the plant.

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