Mayo, S. M., R. R. Rhinehart, and S. V. Madihally, on www.controlglobal.com/assets/Capital-Assessment-of-APC-Projects.pdf. (Introduction is an editorial "Plan Ahead for APC Maintenance", Other Voices Series in CONTROL magazine, Vol. 23, No. 6, June, 2020, pp 12-14.)

Advanced Process Control Capital Decisions Must Include Operations Planning for APC Maintenance

Stephen M. Mayo, R. Russell Rhinehart, Sundararajan V. Madihally
School of Chemical Engineering, Oklahoma State University,
420 Engineering North, Stillwater, OK 74078
2020-05-05

Keywords: Advanced Process Control; Maintenance; Scheduling; Optimization; Experience

MESSAGE

1. APC Projects have a high economic return, and could have a long life, classifying them as capital projects, competing against other capital projects for funding.
2. But often, APC life is only a year or two, because the process drifts. And when the initial models become marginally valid, control degrades, the benefits drop, and the APC is placed off-line.
3. Recalibration of the models can restore benefit, and an optimum recalibration interval can be predicted.
4. These two aspects (the benefit declines over time, and benefit can be restored with recalibration) need to be included in both the capital project evaluation and the operating budget. For several reasons:
    a. It properly represents what management can expect.
    b. Extending project life enhances APC reputation.
    c. It permits plant budgeting of both expenses and human resource allocation, needed to extend project life.
    d. Operations supervisors will be aware of, not surprised by the recalibration need and schedule.
5. This monograph shows how.

ABSTRACT

APC installations are often considered to be capital projects, relatively expensive, but with a high rate of return (pay-back time of a year or less) that makes them attractive; however, the high decline rate of performance relative to other capital equipment installations requires frequent maintenance. If this maintenance is not performed, the typical APC functionality will decline and be turned off in 2-3 years. Typical economic profitability evaluations of capital projects (Net Present Value, Internal Rate of Return, etc.) presumes that long-term functionality. Accordingly, the costs and scheduling of maintenance must be planned-in when the project is installed for the APC project to have a life approximating the life of the process. This article indicates procedures to estimate the initial capital investment, recalibration costs at an optimum frequency, and long-term return. Contained within the capital estimates are the calculations to estimate the optimum maintenance frequency for the APC project. This article presents how the economic profitability analysis of a capital project should be modified to include these aspects. The

concept of continuous improvement is introduced to indicate how periodic maintenance raises profitability above the original project returns. And, the need for continuing performance monitoring of APC is encouraged.

1. Introduction

Advanced process control (APC) programs are investments which improve process profitability. There are two basic budget discretions through which financing APC projects could be considered: Operating Expense Budget (OPEX) and the Capital Expense budget (CAPEX). Most companies treat the APCs as capital expenditure projects. However, although APC projects in the process industries have very high returns, they frequently have a short life, contradicting the basis for a capital project analysis. Payouts can be 4 months to 2 years; however, greater than 65% of APC installations reach zero performance after 18-24 months [1, 2]. This short life can be attributed in large part to not completing the required maintenance to keep the APC projects in good working order.

The frequently encountered short life has a deleterious impact on APC reputation, which can be barrier to management accepting it. However, this could be cured with periodic model recalibration. This would both extend the APC lifetime benefit and change the reputation, and this maintenance aspect needs to be included in the CAPEX analysis.

It may be possible to estimate how much improving that 65% failure rate for APC is worth, globally, to the process industries. One possible way is to look at the overall chemical sales and then estimate how much value could be added by applying APC. The American Chemistry Council estimated in 2018 that the global shipments of chemical products were around $4 trillion/yr [3]. Assuming that about 35% of the capacity could benefit from APC, but either does not have APC or did but the APC benefit has failed to effectively zero, and assuming about 4% improvement in production for that percentage of capacity, this estimate for the value of correcting this APC maintenance problem would be about $56 billion/yr for the global CPI. These figures do not include sectors such as petroleum refining, liquefied natural gas, electrical power generation, pulp and paper manufacturing, minerals processing, computer chip manufacturing, etc. Even if this estimate is an overstatement of the true situation, the amount of value that could be created by correcting this opportunity gap is large, and worth the effort.

Since the return period is short, there is a case for funding to come out of OPEX, not CAPEX. The OPEX funding procedure typically analyzes the additional investment on APC as if it is going to be returned over and above the initial investment. Site management usually has more discretion over spending money in this category of funds than for the CAPEX budget, which would more easily permit the inclusion of periodic maintenance. The OPEX/CAPEX choice will follow practices around the ethical treatment of the funds, tax regulations, etc. In any case include plant budgeting and resource allocation to APC model recalibration.

This report intends to provide an overall procedure for CAPEX funding of APCs. The calculations are explored as well as the impact of uncertainty on the basis values. This article gives guidance on how to estimate the optimum maintenance cycles for APC projects. It also demonstrates how to estimate the overall cost for APC projects and calculate the returns. Both net present value and internal rate of return are presented as ways these projects can be compared with other competing projects for the funding. The focus of this article is that the owner/operator will have expectations for maintaining the overall APC going into the project. Additionally, the concept of continuous improvement is introduced so that a plan can be established and budgeted.

The improved control from an APC project reduces process variability, which translates to any number of benefits – higher throughputs, reduced waste, etc. Many articles have focused on how one can estimate the initial benefits of an APC; and usually in a CAPEX analysis, the benefits are presumed to be permanent, misrepresenting reality. This article is not about how to estimate the financial benefit of installing APC. This is about including the necessary recalibration in 1) the Economic Evaluation that would justify the APC project, and 2) the plant budgeting and scheduling.

2. Capital Expenditure (CAPEX) Analysis

The CAPEX analysis usually involves a limited budget of funds. Hence, analysis needs to identify the one-time funds that are expended to implement the project, the funds that will be returned from the resulting program and the continuing costs that are needed to maintain the improvement in cash flow from the investment.

2.1. Scaling Capital Costs

Much of the expenses and the one-time expenditure are scaled by the size of the APC project. There is some data on the overall sizes of APCs in terms of the variables that they process. One of the studies performed in Japan detailed the size distribution of their process industries [4].

In general, APC variables are grouped into three classes: Manipulated Variables (MV) are the controller outputs, and Disturbance Variables (DV) and Controlled Variables (CV) are inputs to the APC. From **Figure 1**, one could infer an average of about 7.6 MVs, 5.4 CVs, and 5.4 DVs for an APC. This distribution may not be the same as a worldwide implementation of APC. In general, the primary variables in the overall cost of an APC are the MVs, the APC outputs that cause change in the process. In some cases, the number of MVs is much higher, for example, 20-40 in a process for the crude unit with another tower [5, 6] and 24 for a hydrotreater [7].

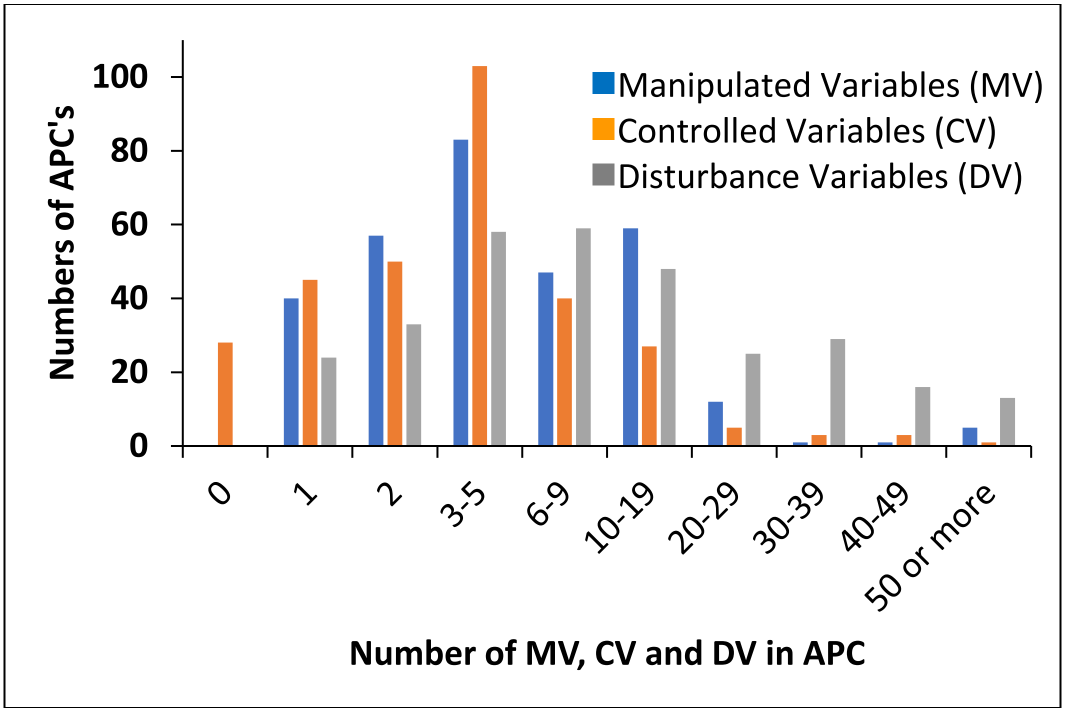

Figure 1 Data from "The State of the Art in Advanced Chemical Process Control in Japan" [4]

In addition to these variables, there are special controlled variables that require significant attention. These are referred to as inferred variables, alternately inferential variables. Some refer to these as "soft sensors" [6]. Inferential variables are those that are not directly measured but are inferred from more easily measured process variables. Models for inferential variable values can be created using laboratory data as the dependent variable and other, easily measured, process variables as the independent variables. This is process dependent and the regressions to develop these relationships are specific to the equipment, the site, and the laboratory from which the streams are analyzed. There is typically extended work necessary to create the correlations. These correlations could be created and used outside of the APC project; however, these variables are typically created during a project to ensure that the APC works correctly. In **Table 1**, some of the inferred variables that have been used in regulatory control or conjunction with an APC are listed.

Table 1. Examples for Inferred Variables

Stream/Product	Inferred Variable	Reference
Diesel	Initial Boiling Point	[6]
Diesel	End Point	[6]
Diesel	Vaporization up to 360°C	[6]
Jet	95% Distillation Point	[5]
Kerosene	End Point	[6]
Kerosene	Cloud Point	[6]
Kerosene	95% Distillation Point	[5]
Kerosene	Flash Point	[8]
Naphtha	95% Distillation Point	[8]
Residuum	Kinematic Viscosity	[6]

Vacuum Gas Oil	Initial Boiling Point	[6]
Vacuum Gas Oil	End Point	[6]
Vacuum Naphtha	95% Distillation Point	[5]
Reactor Effluent	Ethylene Selectivity	[9]
Stabilizer Bottom	Sulfur Content	[7]

These inferential variables need to represent what the laboratory readings would reveal, but they are calculated from alternate process data. In some cases new instrumentation, such as near-infrared spectrum (NIR) analyzers, can be added to improve the soft-sensor prediction [10, 11]. Typically, an analyzer with a NIR is placed on the process and used instead of alternate correlated process variables. Such a real-time measured value of the NIR correlation helps in decreasing the errors near the limits of the correlation. However, real-time monitoring using NIR analysis requires additional field instrumentation (the NIR sensors) and the correlation work to create the inferred variables. When NIR equipment is used, the additional equipment cost needs to be justified. Possible justifications for the NIR correlation and control are improved accuracy, (or reduction in error) breadth of items analyzed, and more rapid response. Adequate accuracy may be possible through the use of available process variables. One negative aspect is that putting in the analysis by NIR can take one year of work [11].

Inferential variables (IV) require about 80 hours each to create. For chemical processing plants, this is not a significant factor; however, for refining sites dealing with a multitude of components, arcane group quality parameters are developed through laboratory testing (ASTM D86, ASTM D1160, etc.) See section 2.3. **Table 1** lists a few of these arcane group parameters. Inferential variables can be a significant cost component when present. IVs are not always present. If there are on-stream analyzers, this is preferable. There are some end-point analyzers; however, these are extremely high maintenance. IVs are easier to maintain

2.2. Workflow

Based on the literature review on the APC project workflow, various steps involved in the process are detailed in **Table 2**. These are written from the beginning of the work to the end of the APC project.

Table 2. APC Project Workflow Steps

<table>
<tr><th rowspan="2">Workflow Step</th><th colspan="4">References</th></tr>
<tr><th>[12]</th><th>[13]</th><th>[14]</th><th>[15]</th></tr>
<tr><td>1</td><td>Economic Benefit Analysis</td><td></td><td></td><td>Benefits and scoping</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">MPC Controller Design</td><td>Preliminary tests to improve the instrumentation and regulatory controls</td><td rowspan="3">Pre-Test and preliminary design</td><td rowspan="2">Functional Design</td></tr>
<tr><td>Application design to define the MV, CV objectives and constraints</td></tr>
<tr><td>3</td><td>Plant Pretest</td><td>Plant testing to develop a dynamic model of the plant</td><td>Engineering and programming – development of</td></tr>
</table>

Table 2. APC Project Workflow Steps

Workflow Step	References			
	[12]	[13]	[14]	[15]
				the dynamic model.
4	Plant Step Test	Plant testing to generate the data required to develop a dynamic model of the process	Plant Testing	Designing the real-time database – Includes step testing
5	APC Controller Development	Model identification to develop a dynamic model using plant test data.	Model and Controller development	Designing the real-time database / Model-based control
6	APC Commissioning	Commissioning to install and tune the closed-loop application.	Commissioning and Training	Commissioning and maintenance – Training is noted to be included.
7	Operator Training and Post Implementation Review	Training operators, engineers, supervisors, etc.		
		Creating documentation		
8		Ongoing maintenance and sustained performance		

To understand the typical workflow steps from both the vendor and customer perspectives, representatives from both were informally consulted to establish the needed process steps and estimate the cost of implementing each step. In general, the steps above contain only labor to develop each one of the production steps. In these procedures, some also include the possibility of additional hardware (field instrumentation and final control elements).

A composite workflow was developed through the interaction with some vendors and customers. The flow chart in **Figure 2** depicts the different items that need to be considered in CAPEX. Some projects include engineering work to prepare the economic benefit analysis/cash flow as described earlier. There is a wide range for this value depending on the difficulty; however, the industry rules of thumb (3-5% throughput or 50% reduction in performance function standard deviation) usually are adequate.

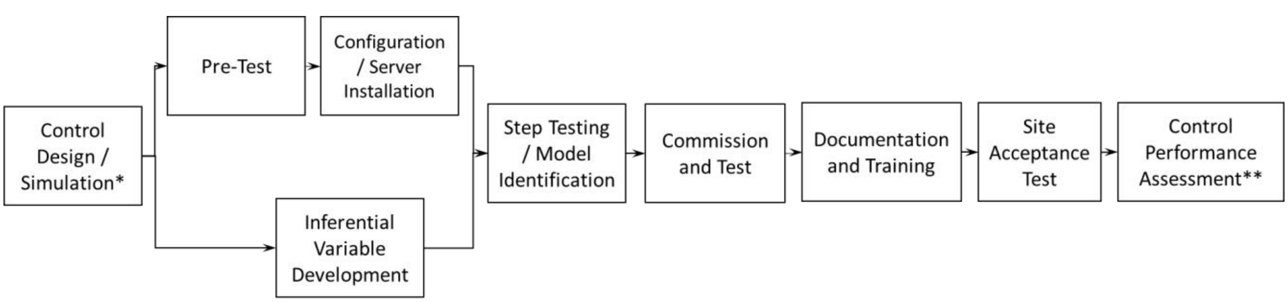

Figure 2 **APC Development Workflow Chart.** *This step could include Hardware Upgrades. Also, the need for inferential variables. ** This step is optional but recommended

Following is a description of each stage in **Figure 2**

1. Control Design/Simulation –his first step is capturing plant data for a period to be able to understand the major variables for inputs and perform simulations. At this point, additional hardware may be identified to enable the overall design. Additionally, the need for any inferential variables is determined [12]. Based on these analyses two simultaneous steps are pursued.
2. Inferential Variable (IV) Development – The flow path splits to develop any inferential variables that need to be made. This step can take a considerable amount of the work involved with an APC installation. Developing the correlations to process variables could take 80 work hours to develop each inferred variable from correlations of lab data. If there is an insufficient data space contained in the span of data additional data will need to be created through operation at the edges of the operation.
3. Pre-Test – Also, the base control loops that will be included in the design are pre-testing any of the identified major variable control lists that were identified. In this step, important variables are selected from a collection of the operations and engineering personnel that work with the plant on a day to day operations. Either an initial model is developed from preexisting data to start the model or work is done to create that initial model.
4. Configuration and Server Installation – This step will include the configuration of an existing server or installation of a dedicated server to address the needs of the APC installation and/or any needed communication devices with the distributed control system (DCS). Any inferential variable development, pre-test and configuration work must be complete before the step testing begins. The model development made during step testing relies on these steps being completed.
5. Step Testing and Model Identification – Next is the core part, the Model Predictive Control (MPC) part, of the APC installation. Improved control from the multivariable, constraint-handling MPC will reduce process variability and permit operation closer to constraints which can optimize process performance. The step testing develops the empirical models for the MPC. This step can either be manual or automatic [5, 16]. Generally, automatic step testing is faster and cheaper. The value of manual step testing is that the engineer develops a feel for the process reaction to the changes.
6. Commissioning and Testing – This is the activity of placing the trained model in and seeing how it functions. This step assesses if step testing needs to be redone at this point on certain variables and if the model is well behaved.
7. Documentation and Training – The operators that are going to live with the process need to know how to put the APC in operation, manage it, and how to take it out of operation. There will also need to be instructions for recalibration if that is included in the contract. Ensuring the operators are sufficiently trained is important to keeping the APC functional [17]. Additionally, changes to the procedures are required by the introduction of the APC. For most processes, this requires changing the operating procedures and documentation is required for most of those processes [18].
8. Site Acceptance Test (SAT) – This is an agreed-upon protocol between the APC provider and the owner/operator where the product is accepted. This is the point at which the APC installation is formally accepted by the customer from the provider of the technology [6, 19, 20]. This point has been falling out of favor[21]; however, there needs to be a formal acceptance of the product so the project can formally end. There are examples of site acceptance test protocols. [6]
9. Control performance assessment – This is a procedure where the overall program is assessed in its function and adjusted for the equipment. This is an extended period where the operation of the APC is evaluated, and any additional operating problems dealt with. This is a step that is often avoided but will allow the installers to evaluate the overall function of the APC and take steps to

correct any maloperation. This sometimes has the formal title of a post-audit [6] or economic assessment [22]. If the controls are not working, certainly the economics will not be working. This optional expense for the owner-operator is recommended for the long-term functioning of the APC. This can also be coupled with a post-audit of the project. [6]

The one-time expenditure in funds includes the design and engineering work to put the APC project in place in the process control system. Continuing expenses for the APC include maintenance of the process and program to ensure the flow of cash flows. The difference between the continuing expenses and the benefits from the investment is usually termed the net cash flow.

2.3. Estimation of the One-time Fixed Cost

The one-time expenditure of funds to put an APC in place can include the list of one-time expenses (**Table 3)** that need to be considered. Some of these are fixed. They do not change with the number of input variables with the APC. Additional costs include the creation of additional variables that will be used to mimic the laboratory readings. Sometimes as part of an APC project, capital equipment improvements need to be made to ensure the APC function. These may include sensing equipment or final control element installation or even computer hardware installation. Improvements to the final element may include an endpoint analyzer. Installing the endpoint analyzer will need to be compared closely with an inferential measurement by correlating already installed equipment. The reason to install improved control elements is to achieve better and/or faster control of different items. If this is just replacement in kind, the replacement of a worn-out controller does not qualify as a capital expenditure. When the native control software and the APC software are not the same, there will be an additional expense to ensure they talk with each other. If the software is native to the control system software, the costs are likely included in the licensing of the APC technology. These table values were developed in informal Delphi study on capital projects.

Table 3 Composite Work Estimates Plus Ancillary Items

#	Line Item	Unit	Quantity	Comments
1	Licensing Fee for Controller	$/MV	1500	This is a charge for the software and technology being employed but this depends on the contract. Some quote $1500/MV. Some contracts charge per unit use basis/cloud-sourced.
2	Per Seat License Fee	$/seat	500	This is a charge for each software user and may or may not exist depending on the contract. The users of the software are typically at the console controlling the unit and a control engineer that needs to support the APC.
3	Open Platform Communications (OPC)*	$/License	10000	This is only required If APC software is non-native or it cannot use the historian server.
4	Configuration Costs	Work hr	40	These are engineering costs for determining the overall structure of the APC and the installation of the controller server. These are mostly fixed regardless of the size of the APC.
5	Pretest	Work hr/MV	24	This cost is variable with the size of the MV, and includes per MV plus time to assess other base layer loops within controller scope (LIC, PIC)

#	Line Item	Unit	Quantity	Comments
6	Inferential Variables	Work hr/IV	80	If there are analyzers, such as gas chromatographs, this line item may be zero.
7	Control Design/Simulation	Work hr/MV	20	This work is indexed per MV.
8	Step Testing/Model Identification	Work hr/MV	44	Per MV; scaled for process dynamics the value given for the step testing is manual. There are advancements where this may be reduced significantly with the application of automatic step testing[5, 16]; Automatic step testing may differ.
9	Documentation and Training	Work hr	48	This work is mostly fixed.
10	Commission and Test	Work hr/MV	24	This work is indexed per MV.
11	Site Acceptance Test	Work hr/MV	18	This work is indexed per MV
12	Control Performance Assessment	Work hr	40	This is mostly a fixed quantity of work. This is conducted at SAT + ~6 Months

*OPC license – An OPC is a bit of software that is needed if Brand X is being used for the DCS and Brand Y is being used for the APC software. This is typically not needed if the APC is native to the DCS and presumably talk together well. “OPC is the interoperability standard for the secure and reliable exchange of data in the industrial automation space and other industries. It is platform-independent and ensures the seamless flow of information among devices from multiple vendors. The OPC Foundation is responsible for the development and maintenance of this standard.” [23] Some installations use the OPC installation and licenses for the data historians; however, if a new installation is required this value may range $10-30k.

2.4. Labor Cost Analysis

Now that the apparatus costs in an APC project are described, we need to have a method for considering the labor component of the one-time expense. One of the variables in installation labor costs is the experience of the engineers involved. Typical industrial practice is to recruit someone with five years of experience to lead a project. One has assessed the cost of recruiting such individuals. The labor costs usually start with an analysis of the salaries received by the engineers involved. There are several sources for this information. Generally, the hourly engineering work rate starts with the annual salary and builds up to the cost for that engineer to do the work. Normal salary information can be obtained from several locations. Universities and professional organizations usually are good sources for this salary information. The data presented here came from the American Institute of Chemical Engineers as published in the 2019 salary survey, **Figure 3**. [24]

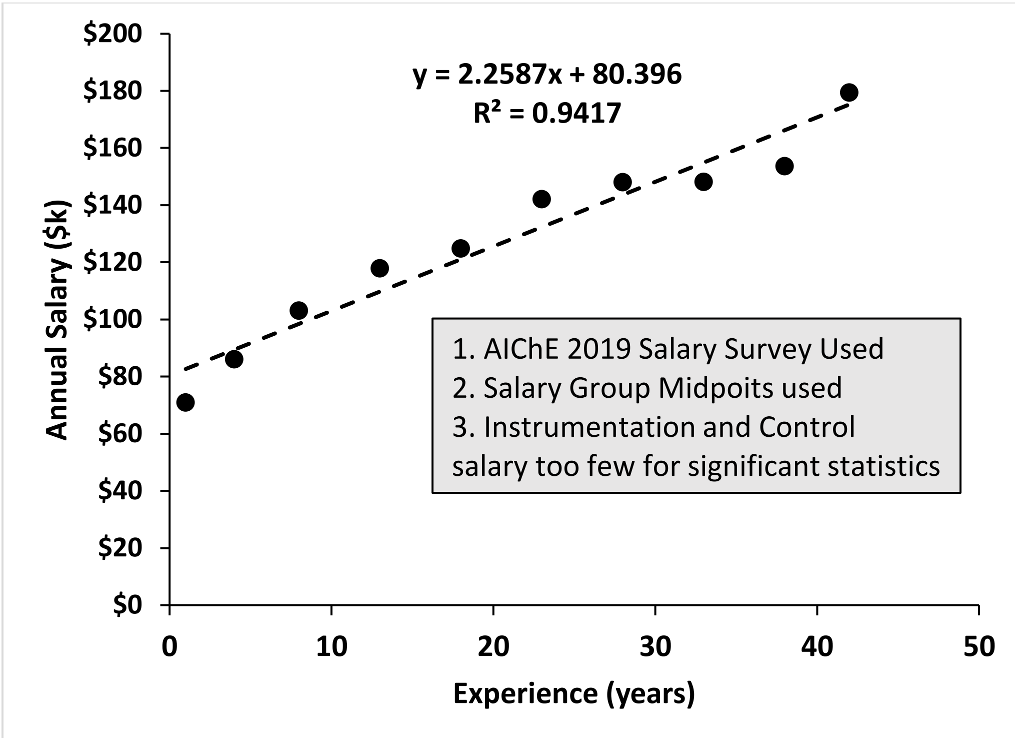

Figure 3 Data from "2019 AIChE SALARY SURVEY"[24]

Once this salary information is in hand and the experience level is determined, the employee cost can be derived. The hourly engineering cost calculation for a corporation depends on several things. Generally, the annual salary is divided by the work hours during the year and multiplied by the costs over and above the engineer's salary that it takes for a company to hire that person. Several different ways to arrive at this ratio are suggested; however, Hadzima estimates this ratio of total costs for an employee to the annual salary is about 2.7. [25] This figure is built up from the following cost categories: (i) Employment taxes and benefits, (ii) Rent, Equipment, etc., (iii) Management Personnel and (iv) Employee time is spent in non-billable technology development. These values are not static and need periodic revisions. Also, the engineering costs for large contractors may be similar to in-company resources while overhead costs may be lower for small contractors. In any case, an engineer who makes $100,000/year and works 2000 hours per year would cost the company about $135/hr. There will be some minimum level of experience required to complete an APC project. With the increase in the level of experience, the overall hourly cost will also increase. Also, the more experienced engineer will have more vacation and thus work fewer hours than 2000 hours/yr which increases the hourly rates. Costs for contract firms may be higher depending on the profit that the contract firms include in the labor cost. Some have placed the range for contract labor in the United States in the range of $200-250/hr. [26, 27]

2.5. Example Case Study

The following will be the start of an example where the capital installation costs can also serve to estimate the continuing maintenance expenses for the project. Here is an example of an APC that will have 2 MV and 2 inferred variables

Table 4: 2 MV and 2 IV, without OPC Cost

#	Line Item	Units	From Table 4	Quantity	Multiplier	Item Total
1	Licensing Fee for Controller	MV	1500	2	1	3000
2	Per Seat License Fee	Seats	500	2	1	1000
3	Open Platform Communications (OPC)	License	10000	0	1	0
4	Configuration Costs	hr	40	1	135*	5,400
5	Pretest	hr	24	2	135*	6,480
6	Inferential Variables	hr	80	2	135*	21,600
7	Control Design/Simulation	hr	20	2	135*	5,400
8	Step Testing/Model Identification	hr	44	2	135*	11,880
9	Documentation and Training	hr	48	1	135*	6,480
10	Commission and Test	hr	24	2	135*	6,480
11	Site Acceptance Test	hr	18	2	135*	4,860
12	Control Performance Assessment	hr	40	1	135*	5,400
Total						77,980

*See Section 2.4 (Internal resource charged at $135/work hr)

Note that step testing on Item #8 is highlighted. This will be used to calculate the optimum recalibration interval and calculate the decline in average performance at the time of the recalibration (Section 8).

3. Continuing Expenses

Thus far, we have detailed an approach to arrive at the one-time costs for an APC to go into the overall capital calculation. We now need a way to arrive at the continuing expenses. Continuing expenses generally fall into two different categories: recalibration expenses and continuing licensing fees that are intended to maintain the software and software installation.

There is going to be some decline in the APC performance over time, because of a diverse set of reasons. The process becomes dirty and control valves start to perform in ways less desirable than the APC was originally trained. The piping is rerouted. The catalyst reactivity or tray efficiency changes, etc. The faster APC performance declines the more frequently recalibration the APC will be needed to bring it up to the site acceptance test (SAT) performance. The recalibration is a continuing, but periodic expense. A model for the decline and ways to determine the optimum recalibration expense has been proposed [28, 29].

This model combines the decline in performance with costs to bring the performance back to the SAT performance to arrive at the optimum interval. The authors modeled the progressive decline in the economic benefit of an APC installation over time with a power law, a simple relation that seemed to match notional, subjective representations that were revealed by industrial experts.

$$B(t) = a - bt^p \qquad (1)$$

Where B is the economic benefit of the APC, $/time interval (a rate), t is time, and a, b, and p are model coefficients. The initial benefit $B(t = 0) = a = B_0$. Exact values for a, b, and p would have to be evaluated in a post-implementation audit, and subsequent periodic audits that revealed the progressive functional decline.

The model can be scaled to provide a dimensionless relation as

$$B'(t') = 1 - t'^{p} \qquad (2)$$

Where $B' = B(t')/a$ and $t' = t/t_0$ and $t_0 = \sqrt[p]{a/b}$ is the time for process drifts to make the economic benefit of the APC installation hit zero (not the point in time that it placed off-line such as when the maintenance aggravation became unacceptable).

Since there is rarely access to, or publication of proprietary information, this dimensionless model serves as a reasonable representation of how the decline concept is revealed. Also, since the APC is usually turned off prior to hitting zero functional benefit, the right-hand portion of the curve is somewhat uncharacterized. A discussion among experts seems to reveal that tis model is realistic, and that the p-value might be between about 2 and 5.

Using Model (2), the optimum time period for recalibration, ${t_R}^*$, can be analytically derived. The result is

$${t_R}^* = t_0 \left(\frac{C}{B_0 t_0} \frac{(p+1)}{p}\right)^{\frac{1}{p+1}} \qquad (3)$$

Where C is cost of a recalibration exercise. With a variety of reasonable values this deterministic relation indicates that the optimum time interval for recalibration, ${t_R}^*$, should be about 30 to 60% of t_0, the time when the benefit would drop to zero. Even with t_0 being about 24 months, the ${t_R}^*$ values might range from 3 to 12 months, depending on expected values of Equation (3) coefficients over the next operating interval. When the expected life of an APC project is on the order of years, a recalibration every 6 months or so, is often unexpectedly frequent to plant managers. Similarly, when the plant turnaround interval might be 5 years for major maintenance and renovation, the frequent recalibration of the APC is often unexpected when management is considering capital projects.

Following is the cash flow profit equation [28]:

$$P = \left(1 - \frac{\tau_R^p}{p+1}\right) b_0 - \left(\frac{C}{\tau_R t_0} + L\right) \qquad (4)$$

Where P is the time-average of the net benefit (in \$/unit time), t_0 (in time units) is time for the APC project to decline to zero benefits, τ_R is the dimensionless recalibration time as a fraction of t_0, p is the dimensionless decline shape factor, c is the cost (in \$) for one recalibration, b_0 is the benefits (in \$/unit time) from the APC at the site acceptance test (SAT), and L is the Licensing fees (in \$/unit time) for maintaining the APC software.

The first part of the equation is the expected benefits that will be the income adjusted for the decline to where recalibration is done to bring the performance back to SAT, the average benefits over a recalibration period, not the maximum initial SAT benefits. The second part is the expenses for the recalibration and the licensing fees for maintaining the software.

By substituting the optimum recalibration interval into the cash flow profit equation, two forms result.

$$P^* = \left(1 - \tau_R^{*\,p}\right) b_0 - L \tag{5}$$

$$P^* = \left(1 - \left(\frac{C}{b_0 t_0}\frac{(p+1)}{p}\right)^{\frac{p}{p+1}}\right) b_0 - L \tag{6}$$

Now if we define a new term which would be the fraction of the expected profit with no costs and no decline to the overall function of the APC.

$$\Pi = \frac{P^*}{b_0} \tag{7}$$

$$\Pi = 1 - \tau_R^{*\,p} - \frac{L}{b_0} \tag{8}$$

$$\Pi = 1 - \left(\frac{C}{b_0 t_0}\frac{(p+1)}{p}\right)^{\frac{p}{p+1}} - \frac{L}{b_0} \tag{9}$$

p is the decline parameter and is always >1. This is based on the owner-operator/maintenance practices unit type and rate of the process deviating from the initial behavior. Calculations on one large LNG plant have shown values for *p* and t_0 to be 2 and 2.2 years respectively [30, 31]. Some have found values as high as 5 for *p* [32]; however, for initial estimates, a value of 2 or 3 could be used. With these equations, the evaluation for gauging the cost-benefit ratio is possible.

3.1. Sensitivity to Uncertainty in Parameter Values

The **Table 5** shows values for the sensitivity of the Π value based on *p* and $\frac{C}{b_0 t_0}$. This also shows some interesting conclusions from the overall equations. This table was constructed to show the relative effects of changing the different inputs to the dimensionless profit. The first column shows the decline shape factor *p*. This column describes the relative shape of each decline curve. Values for p seem to be bounded by 1 and about 5 based on values tested by others. Values for *p* need to be determined by each operating unit type. Within each decline curve, there are variables that determine the optimum for the maintenance interval. The $\frac{C}{b_0 t_0}$ ratio will determine exactly the optimum recalibration interval along that shape value curve. Additionally, when an optimum recalibration interval is selected, the error in the overall dimensionless profit is shown. This sensitivity is to show how flat the overall optimum value and how sensitive the profit is to extension or contraction of the inspection interval.

Table 5 Examples showing the effect of $\frac{C}{b_0 t_0}$ on τ_R^* and *Π* Sensitivity

p	$\frac{C}{b_0 t_0}$	τ_R^*	Effective Maintenance Intervals per period t_0	*Π* Assumes $\frac{L}{b_0} = 0$	*Π* Sensitivity	
					$\tau_R^* - 0.1$	$\tau_R^* + 0.1$
2	0.0010	0.11	8.74	0.98690	0.98000	0.93083
	0.0100	0.25	4.05	0.93918	0.93110	0.92463
	0.1000	0.53	1.88	0.71769	0.70875	0.70614
	0.6667	1.00	1.00	0.00000	-0.00939	-0.01074

3	0.0010	0.19	5.23	0.99302	0.99040	0.98883
	0.0100	0.34	2.94	0.96076	0.95599	0.95485
	0.1000	0.60	1.65	0.77935	0.77068	0.76964
	0.7500	1.00	1.00	0.00000	-0.01457	-0.01558

There are several conclusions from the table. First, for reasonable power values i.e., 2 or 3, there is a narrow range of $\frac{C}{b_0 t_0}$ values result in dimensionless profit numbers near the expected APC performance. If the $\frac{C}{b_0 t_0}$ values are less than 0.01, then the dimensionless profit numbers are > 92% of the SAT benefits claimed for the installed project. If the $\frac{C}{b_0 t_0}$ values are much larger than 0.01, there is a significant decline in benefits. When the $\frac{C}{b_0 t_0}$ value is 0.1 the dimensionless profit drops to around 70% of the SAT claimed benefits.

Second, an increasing *p* value increases the dimensionless profit. The relative effect of the n value is low when the cost is low relative to the effect of $\frac{C}{b_0 t_0}$. For example, increasing n from 2 to 3 at 0.01 $\frac{C}{b_0 t_0}$ value, increased the dimensionless profit from 0.939 to 0.961 (a difference of 0.022). When the $\frac{C}{b_0 t_0}$ value of 0.1 the same increase in $\boldsymbol{\Pi}$ is from 0.718 to 0.779 (a difference of 0.061)

Third, large changes to the number of recalibration intervals have a low impact on the overall value of $\boldsymbol{\Pi}$. Values of the number of recalibrations range from 4 to nearly 9 when the $\frac{C}{b_0 t_0}$ value is ≥0.01. These differences may pay out the additional effort for the increased number of recalibrations. It depends in part on the value of $\boldsymbol{b_0 t_0}$.

Fourth, the optimum cash flow of putting in an APC may be zero if the maintenance costs are too high. For example, if the cost to benefit ratio is 0.67 for n = 2 or 0.75 for n = 3, the value of Π will be zero. This means for purposes other than throughput reasons the value of the APC needs to be well known by the owner-operator. Safety, environmental and quality reasons for the benefit tend to be more variable than throughput considerations. Risk analysis includes procedures to include economic values for safety or environmental reasons usually involve the probability of certain events happening. Risk is the probability of the event multiplied by the company value of the event. Each company will typically have its own proprietary method for determining these costs for the base safety or environmental events.

4. Maintenance Program and Cash Flow – Sample Calculation and Planning

This section presents a calculation of the critical capital parameters based on our project with 2 manipulated variables and 2 inferred variables. The value of $500,000 is commensurate with several projects of this size mentioned in the literature [33, 34]. The maintenance frequency and the maintenance cost must get programmed into the budget and the operating schedule. Below is a sample calculation estimating the budget:

a) Estimate $\boldsymbol{t_0}$ – The general time to zero performance listed in the literature is 2-3 years [1, 35]. For our calculation, 2.22 value was selected based on an LNG plant data in the literature [30].

b) Calculate $\frac{C}{b_0 t_0}$ –The quantity for c is taken from line 8 in **Table 5**. To replicate the SAT performance, the plant must be recalibrated to the current plant conditions. The calculation is $\frac{C}{b_0 t_0} = \frac{\$11,880}{\frac{\$500,000}{yr} \times 2.22yr} = 0.0107$

c) Estimate the decline curve – As stated above, 2-5 is the range of practical values for *p*. This value should be determined for each owner user; however, initial estimates will serve for planning purposes. Based on the calculation of the LNG plant we used 2 for *p*.

d) Calculate the Optimum Interval in dimensionless terms $\tau_R{}^*$ - Using Eq.(2) with the t_0 period of 2.22 years,

$$\tau_R{}^* = \left(0.0107 \frac{(2+1)}{2}\right)^{\frac{1}{2+1}} = 0.252 \text{ and } t = \tau_R^* \times t_0 = 0.252 \times 2.22\, yr = 0.56\, yr$$

The value of 0.56 yr is about every 6.7 months. This value is based on manual step testing. Significant savings could be achieved through automatic step testing [5, 16, 36]. If the costs are reduced for the recalibration, the optimum period will also shorten.

e) Calculate the Operations (OPEX) Budget – The average annual budget for maintenance on the APC is, therefore, \$11,880/0.56 or \$21,214. Since 0.56 is close to 0.5 placing two recalibrations in one year is more practical (\$23,760).

f) Calculate Net Cash Flow - Using Eq.(8) or Eq.(9) the net rate from the project is calculated. From the optimum $\tau_R{}^*$ of 0.252, the optimum Π is calculated to be 0.936. That would make the average cash flow from the project (at the optimum recalibration schedule) to be \$468,248. This would account for the decline and maintenance costs.

g) Check Assumptions and Consequences – Not every operation can be conducted exactly planned. **Table 6** lists some of the consequences to the overall net cash flow for varying from the optimum. For doing the recalibration 0.1τ later than the optimum time the effective annual cash flow effect would be (0.93981-0.92463)*\$500,000 or \$7,590/yr. The consequences for this case are relatively low for not hitting the exact optimum. The delay of 0.1τ is equivalent to about 5 days of production from the APC. For short durations, delay in the recalibration may be possible, but the value of the APC will drop to zero in 24 months with no recalibration. Ensuring the recalibration is performed to keep the APC function high is essential.

As demonstrated, the overall profit depends on the value of material processed. This example shows the calculations that need to be evaluated to do budgeting and planning for process operations.

5. Capital Calculations

Now we can put together a project summary for those prioritizing the CAPEX budget. The cost of capital is usually a number specified by the company. It usually represents the cost to the company for providing those funds for the project. The incremental income is discounted by the number of periods. In this example, the analysis was done on a monthly basis because companies will analyze books on a monthly basis and the payout period was so short for this example. A project life of 15 years was chosen. This life was chosen because a typical unit life is close to 20 years and this is putting an APC five years after the unit was started up.

The sum of the initial investment plus all the discounted cash flows back to the present represent the net present value of the investment to the company. So, in this case, the investment of the \$77,980 has netted out \$3.6 million. Another way to look at the investment is to change the discount rate until the net present value is zero. This modified discount rate is called the internal rate of return (IRR). Both the net present value and the IRR are used by companies to prioritize projects.

Table 6 Hypothetical Project Summary

Item	Value	Comments
Investment	$77,980	Cost Estimate
SAT Benefits	$500,000	
Average Return ($/yr)	$468,248	Net cash flow
Cost of Capital	10%	Annual Interest Rate
Project Life(yr)	15	180 Months
Net Present Value	$3,406,000	Cash flow analysis done per month and then annualized [37]
Internal Rate of Return (IRR%)	600%	The analysis was done per month. The value here is the annual equivalent rate.[37]

Programs like this are typically classified as a capital improvement; however, the payout can be within one year and thus the capital analysis a moot exercise

From the example case study, the consequences of delaying the recalibration are small with small deviations around the optimum recalibration time; however, if the decision to delay recalibration until the functioning of the APC has dropped to zero then the credibility of the people that proposed the high return project is in jeopardy. It is essential to plan the APC recalibration as a planned event before the APC is adopted and recognition that the APC value could drop to zero if recalibration is not done.

6. Continuous Improvement

This article treats the recalibration cost and the income from the APC project as constants. There are two primary ways that continuous improvement can be made to a project. First, experience at conducting the recalibration process can be modeled according to learning curves. The decreased cost for successive recalibration has the net effect of increasing the return, the Π value. Second, there can be an improvement to the income by taking understanding from each recalibration-operation cycle and implementing those learnings in either additions or deletions from the APC structure. An additional 10-15% may be possible over the SAT income. Detailed discussion is beyond the scope of this document; however, the owner/user must have specific active programs to address each component (income and cost) to realize continuous improvement affects.

7. Continual Monitoring

The optimal recalibration schedule has been estimated from a generic model, Equation (1), which qualitatively matches general experience. Using Equation (1) is using *a priori* (without experiment) theory from generic experience applied to a particular project. Exact experience, specific to a particular process, the APC implementation, and within the context of a particular company would provide a better model. This would be *a posteriori* knowledge. However, one cannot know the after-implementation rate of decline until after application. Accordingly, you should use your best extrapolation of past experience when including the decline model and optimum recalibration schedule in capital planning. Similar unit experience at the same site or at other sites would be a good approximation. Failing that, the general 2-3 years would be another good approximation.

But once installed, we strongly recommend weekly monitoring of the APC performance to monitor the changes that will happen, and to adjust a recalibration interval based on this *a posteriori* knowledge, rather than sticking to the *a priori* model necessary for capital planning.

8. Conclusion

The decision to implement APC requires a continuum analysis from the inception through to operations. To maintain APC operations for a long duration, maintenance must be continued for the life of the project, and this must be included in the capital estimation decision for implementation. The purpose for long term maintenance is to ensure the project continues for the life of the operating unit. The cost of the initial step testing protocol can be used as a good first approximation for the periodic maintenance. These regular maintenance intervals can be estimated through Equation (2).

Fortunately, the optimum has a fairly flat response to the recalibration time in the vicinity of the optimum. This allows for operational flexibility to do the APC maintenance and make initial estimates relatively insensitive to the exact recalibration schedule.

The one-time cost depends on:

1. The technology costs – This depends in part on the contract that is made with the technology provider.
2. Labor hourly cost – Different guidelines are available in the literature; but one guideline is given here.
3. The size of the APC – there are different size parameters. Based on diverse sources the preferred index is the manipulated variable plus any inferential variables that may need to be created.
4. Any equipment changes that are required to make sure the technology works need to be included.

This document presented one form for estimating the one-time costs; however, there are different styles of contracts not considered in this document that will approximate the same cost.

We demonstrated estimating the optimum cash flow for the project. This includes estimates for the recalibration expenses and estimates for the optimum recalibration interval. This optimum recalibration interval is useful to know when the project is installed because the owner-operator will already have this programmed into the project thought processes. The above one-time expense plus the regular maintenance can be combined in either the net present value or the internal rate of return calculation to give a score for the project. Many companies will use both for determining if the project is funded.

Be sure to include the needed recalibration operations in the plant budgeting.

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Author Bios

STEPHEN M. MAYO has 38 yrs. of industry experience, and his research is focused on getting the most out of advanced process control. His career has included process engineering and management roles around the world in several different countries in ethylene, refining, LNG, and oil and gas production. Mr. Mayo earned an MBA degree from Oklahoma State University, where he is a chemical engineering doctoral candidate. He is also a registered professional engineer in Oklahoma. stephen.m.mayo@okstate.edu

R. RUSSELL RHINEHART has experience in both industry (13 yrs.) and academe. He has served as the Head of the School of Chemical Engineering at Oklahoma State University, President of the American Automatic Control Council, and Editor-in-Chief of ISA Transactions. He is a Fellow of both ISA and AIChE, a CONTROL Automation Hall of Fame inductee, and has received numerous teaching and innovation recognitions. Dr. Rhinehart has authored textbooks on engineering statistics and nonlinear regression modeling, and engineering optimization. Now 'retired' he is working to disseminate techniques with his web site, www.r3eda.com, books, handbook chapters, and articles. rrr@okstate.edu

SUNDARARAJAN V. MADIHALLY is a Professor in the School of Chemical Engineering at Oklahoma State

University. He worked in the industry for 2 yr prior to obtaining a PhD in chemical engineering. He has published numerous articles and proceedings related to his research in tissue regeneration, as well as novel educational paradigms in biomedical engineering. Recently. he published the second edition. of his textbook. Principles of Biomedical Engineering. Dr. Madihally has received numerous teaching and mentoring awards, including the AIChE Outstanding Advisor Award. sundar.madihally@okstate.edu