ADVANCED PROCESS CONTROL MAINTENANCE
CAPITAL PROJECT MANAGEMENT AND
CONTINUOUS IMPROVEMENT

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Abstract: The typical lifespan of Advanced Process Control (APC) projects has been reported to be 18 months to 48 months. This is relatively short considering the process units they serve have a life span of 20-30 years. Briefly, this indicates a major discontinuity in process industries. Most APC's obtain benefits by increasing throughput to the process units they serve. Nominal increases in capacity given for the APC project have been 3-5% based on several literature surveys and interviews with industry experts. The payout period, therefore, is very short, 2 months to a year, depending on the overall value of the product and the cost of the APC implementation.

The overall life span for a project that yields this high return in the process industries should be very long – approaching the life span for the equipment in the field. Further, the process of creation and abandonment of the APC project seems to be repeatable over several different industries.

Three separate but interdependent processes were identified as aims for this research. The aims of this research are:

- Aim 1. Maintenance – Mathematical models for optimum maintenance intervals and optimum cash flow from an APC are developed. These models are dimensionless to apply to a wide variety of industries.
- Aim 2. Capital – Models for developing the installation costs have been developed. Further testing is required to understand the variabilities of these models. These models consider workforce costs, workforce requirements, size of the APC, and steps required to implement the APC. The effects of the size of the APC and cash flow from the maintenance are explored on the overall return of the APC project.
- Aim 3. Continuous Improvement – This portion models the overall yield from an APC and potential follow-on increases due to organizational learning. The follow-on increases are bounded by maximum APC performance. This section explores the maximum APC performance as well as organizational learning curves as applied to the recalibration costs and how those costs affect the optimum recalibration intervals and cash flow from the APC.

Ultimately, implementing these activities has an impact on the life cycle of APC to that of the processing unit. This is beneficial to improve the cost-benefit of implementing APC and the efficiency of productivity.

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CHAPTER I

INTRODUCTION

Advanced process control (APC) is a supervisory software platform that allows us to increase capacity on equipment in manufacturing facilities. Advanced controls move the process around within the given constraints to find the optimum. APC projects are often thought of as a layer of control above the base regulatory control for a process, **Figure 1**. A common example of regulatory control is cruise control for a common motor vehicle. In a driverless car, there is a program or series of programs that keep the car on the road and within the posted speed limits and avoids obstacles, etc. Continuing the analogy, APC would be the controls on a plant needed to keep the plant within the normal operating parameters necessary for safe plant operation. Further, the APC program optimizes the plant operation to make sure an objective function (usually profit) is maximized. For the base regulatory control, the process engineer console operator, controls engineer, and operations staff go through a series of meeting discussions of the limits.

The control model contains all of the different types of APC contained in **Figure 1**; however, it is often used interchangeably with Model Predictive Control (MPC).

- Advanced Regulatory Control
- Model Predictive Control (MPC)
- Inferential Measurement
- Sequential Control
- Intelligent Control

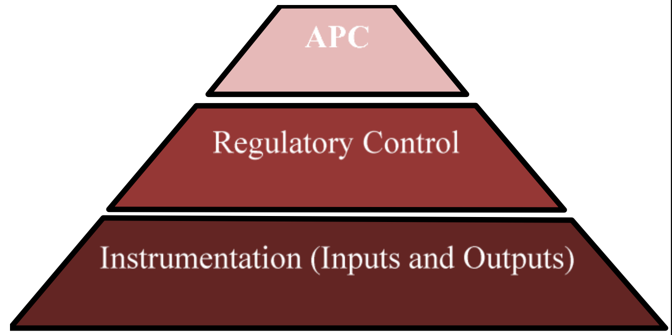

Figure 1 Relationship of APC to other elements of process control.

APC BENEFITS

The core of APC is the controller model, typically a linear local representation of the process (gains and dynamics), which is obtained by best matching the model to process responses from incremental changes in the manipulated and disturbance variables. Advanced controls move the process around within the given constraints of the process to find the optimum. The benefits of an APC may derive from several factors [1]. Bauer and Craig [2] identified many benefits through a survey by asking respondents to list the most important contributions of APC. These are listed below in their order of decreasing impact:

- Throughput Increase – Many that have estimated this increase is 3-5% [3, 4]. The improved disturbance rejection and process management of APC permit operation closer to the constraints on the process.
- Process Stability Improvement – This also permits the process to operate closer to constraints.

- Energy Consumption Reduction – Some report that energy reduction was the primary goal for the APC. Energy reduction comes from reducing the overall variability in processing the products.
- Increased Yield of More Valuable Products/Better use of Raw Materials
- Environmental Compliance
- Safety Increase
- Quality Giveaway Reduction – reduced variability means that there is less material downgraded to meet the product specification and that the setpoints can be moved closer to specification.
- Downtime Reduction – When a plant is more stable the usual downtimes will be fewer.
- Reprocessing Cost Reduction – Reduced variability will enable more on-specification time and thus reduce the amount of off-specification material to reprocess.
- Operating Manpower Reduction – At least one refiner has seen a reduction in manpower from the application of an APC [5].

In all cases, the assessment of the benefits should be on a consistent and economic equivalent basis that is well documented in a post-installation audit or site acceptance test (SAT) [6]. There are several examples of audits found in the literature on APC [3, 4, 7]. Some also attribute loss in confidence of APC success to lack of doing an audit [8]. In any case, the audit serves as a base document from which to compare performance and develop the decline models and should be a high priority for the owner/user.

Reasons for the Decline in APC Performance

When APC projects are installed, there is an economic benefit that generally equals about a 2-5% increase in throughput. However, the economic return from these projects is extremely short (4 months to 2 years). At the same time, the life of these projects is extremely short. Several articles report that after 18 - 24 months about 65% of the APC installations are performing at either pre-installation levels or have been removed [9-11]. When throughput rates and other attributes such as reactivity, efficiency, fouling, feed components, etc. of the process change, the model no longer represents the process. As the process characteristics deviate from those representing the model, control functionality degrades, and the equivalent economic benefit of the APC installation diminishes. Although there are diverse reasons for the performance shortfall, a primary reason is that the process characteristics drift from those that generated the controller model. Several events cause a decline in overall APC performance:

- Hardware or software changes – Changing instruments because of repairs can lead to different dynamics than the original APC was calibrated against. Software upgrades can also affect the overall function of the APC.
- Changes in process context relative to the original APC commissioning include:
- An increased model error introduced due to physical changes in the process responses/gains due to:
- Changes in equipment design, capacity and/or performance;
- DCS loop tuning changes (as the APC models incorporate the DCS control responses);
- Changes in responses/gains due to feedstock or product slate changes.
- Changes in APC design needs due to:
- Debottlenecking efforts eliminating some constraints and introducing new ones;

- Changes in product economics or utility costs that change the required optimizer drives (this can also expose the need for new constraints to be added).
- Changes in tuning needs which can be promoted by any of the 5 context changes above.
- Slow instrument maintenance practices of the underlying instrumentation or process.
- Knowledge of the Personnel Doing the Maintenance – Keeping experienced personnel in key areas that are familiar with the overall functioning of the APC. Additionally, planning and supply of the personnel may be a factor because other systems have the priority (e.g., instrumented shutdown systems).
- Equipment Wearing Out – Dirty services tend to affect the overall performance of control valves and instrument readings.
- Fouling of Plant Piping in Dirty Services – Reductions in flow areas and pump performance can affect the overall performance of the APC and thus contribute to the decline.
- Changes in catalyst reactivity, heat exchanger fouling, tray efficiency, etc.
- Fouling or wear and tear on equipment may not be sufficient to cause a shutdown to repair/clean equipment, but it might be severe enough to justify APC recalibration. Additionally, the decline in the APC may not match the overall turnaround schedule for the unit to repair the equipment affecting the APC. The APC recalibration will likely be independent of the turnaround cycle.

While all of these sources for the decline are identified, they are possible functions for later study on the parameters in the decline models developed. Three separate but interdependent processes i.e., maintenance, capital project estimation, and continuous improvement were identified and plans for modeling each system. Several interdependent sets of equations were developed in addressing the maintenance, capital project estimation, and continuous improvement of the APC. These interdependent equations form a whole for describing and optimizing the APC commercial space. These are described as aims below.

Aim 1. Maintenance of the APC

Typically, user sentiment may be a common measure of the overall decline in the performance of the APC i.e., it becomes harder to keep the APC on control, or several parameters are clamped. An approach to returning the APC to full functionality is a recalibration of the model i.e., retesting the process response and adjusting model coefficients to the best match. Maintenance of the APC or Recalibration has a cost, which is desirably avoided although recalibration can restore APC benefit. If recalibration is performed when the functional benefit of the APC installation is high, there is little gained from the recalibration cost. However, if recalibration is postponed, the loss of economic benefit of the APC installation can be greater than the cost of recalibration. A more rational economic basis is needed to trigger for APC maintenance grounded in functional performance, not intuitive sentiment. Based on that idea, first, an overall profit equation is developed (this report) and then a procedure is offered where the owner/operator can schedule recalibration to maximize the annual benefit to make the most effective use of the APC. Mathematical models for optimum maintenance intervals and optimum cash flow from an APC are developed. These models are dimensionless to apply to a wide variety of industries. Further testing is planned to ensure these models fit existing practices.

Aim 2. Capital Evaluation Process

Maintaining the APC after installation is critical and valuable to the process industries; however, the process starts with the capital evaluation process to put in the APC. Hence, APC maintenance and the capital process are interrelated. Specifically, the mental processes of Operations personnel planning in the maintenance required and estimating the budgets and time required for the maintenance in the production schedule. The cost for a specific portion of the capital estimation goes directly into the estimation of the maintenance.

The frequently encountered short life has a deleterious impact on APC reputation, which can be a barrier to management accepting it. However, this could be mitigated 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 capital expenditure (CAPEX) analysis.

Since the return period is short, there is a case for funding to come out of operational expenditure (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 aim intends to provide an overall procedure for CAPEX funding of APCs. The focus of this study is that the owner/operator will have expectations for maintaining the overall APC going into the project. The calculations are explored as well as the impact of uncertainty on the basis values. This 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 APC projects can be compared with other competing projects for the funding. Models for developing the installation costs were developed. These models consider workforce costs, workforce requirements, size of the APC, and steps required to implement the APC. The effects of the size of the APC and cash flow from the maintenance were explored on the overall return of the APC project. Further testing is required to understand the variabilities of these models.

Aim 3. Continuous Improvement

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 aim is not about how to estimate the financial benefit of installing APC and many others have provided methods. This is about including the necessary recalibration in 1) the Economic Evaluation that would justify the APC project, and 2) in the plant budgeting and scheduling. This aim breaks down the cost and income portions of the overall equations. Also, it shows the specific actions to take to improve APC returns over time and demonstrates where the owner-operator should prioritize their efforts for maximum benefit.

The major thrust of this aim is how to estimate required maintenance costs to sustain optimal benefit, and how to include these aspects in both the capital project planning and operation budgeting. Models are developed to calculate the overall yield from an APC and potential follow-on increases due to organizational learning. The follow-on increases are bounded by maximum APC performance. This aim further explores the maximum APC performance as well as organizational learning curves as applied to the recalibration costs and effect of those costs on the optimum recalibration intervals and cash flow from the APC. Using the guidance outlined in this aim, the process industries can capture this societal benefit and improve on the performance with continuous improvement.

Importance of This Research

The goal of this research is to develop processes to close the gap in the expected life span of an APC and the life span of a unit. The research seeks to find important independent variables that affect the overall outcome of the APC project life and formulate these into a generalized dimensionless equation. It seeks to determine the overall benefit as a function of industry. Modeling the rapid decline in performance and providing the process industries the capability (procedures and practices) to extend the life of the APC projects to the life of the facility are reasons to do the research. 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 [12]. 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.

CHAPTER II

BACKGROUND

II.1. THE FUNCTION OF APC.

The purpose of the APC is to maximize profitability within the plant limits. In a normal plant environment, there is an army of personnel working day and night to maximize the production of the plant. They cannot change the prices they get for the products or the feed steams. Process engineers make plots and charts and try to deduce patterns to make sure the maximum throughput is obtained.

There has been a small percentage of my career where the production of the plant was on allocation i.e., production was reduced for a short period when the economics for running the plant had gone negative. The administrators needed time to plan and reorganize the profit equation for the plant turned positive. This also involves determining the number of personnel that needs to be laid off so the equation would be positive.

Consider a single production plant like a Liquefied Natural Gas (LNG) where there is essentially one important function i.e., LNG production. Hence, the objective function reduces to throughput. As long as the cash generation equation is positive, the only direction is maximizing production, which is dictated by the variability. Placing an APC on that LNG plant reduces the standard deviation of the product flow rate by half. This reduction results in a 3-5% increase in production without replacing any equipment.

Consider two scenarios of process flows in an LNG plant **(Figure 2**). In both scenarios, flows have an average production capacity of X. In process Flow 1, the plant has twice the capacity of the feed system. In Process Flow 2 the feed system has twice the capacity of the plant. In Process Flow 1, the best variance the product is capable of is the variance of the Feed System. Plant capacity costs money. Hence, there is financial expenditure that is not returning any investment in Process Flow 1. Further, the LNG plant cost is significantly larger than the feed systems. Since economics favor Process Flow 2, most processes resemble Process Flow 2.

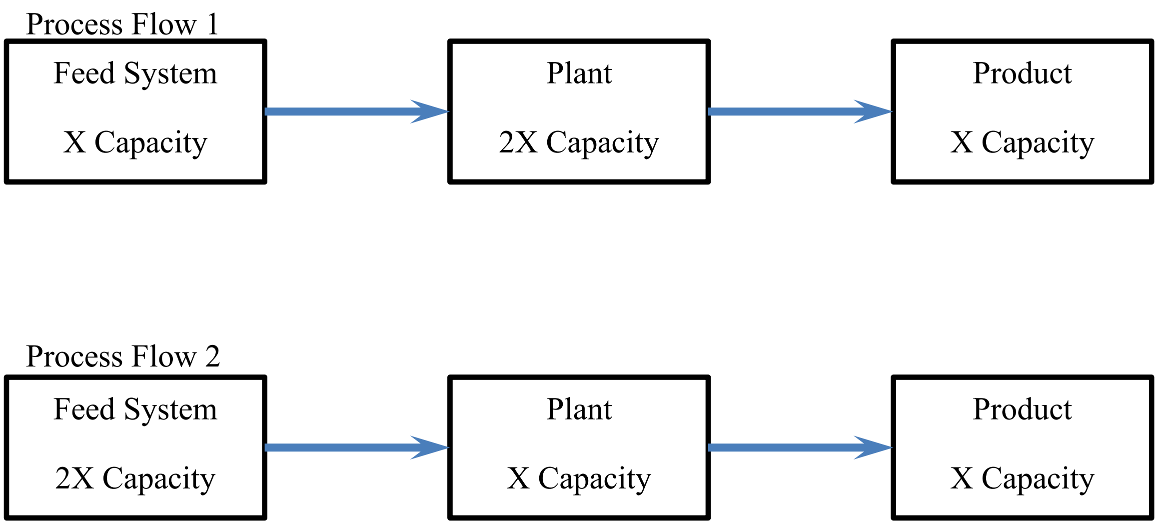

Figure 2 Capacity Variance Example

Process variance for the two cases is somewhat difficult to calculate from this scenario alone. Most plants are not a connected series of steps that have additive variances, the variance is not just a summation of different series of variables. There are different things built into most plants to cushion variances from excessive swings in upstream variables. These include drums or other devices that dampen the swings. Drums allow the levels to vary and thus reduce the variability of the liquid flow. There is large pressure containing vessels that allow pressure to fluctuate and thus make the flow stable. There are however pieces of equipment if the flow rate through them exceeds a certain point, they cease to function and thus have a specific capacity. Some of the equipment includes a fractionating tower, heat exchangers, compressors, and pumps. These are only a few examples of the limitations on equipment that are caused by pushing the flow rate higher in a process. Limitations on various parameters are made throughout the plant and most of the throughput are correlated directly to the production of a plant. Without exception, all of these limits are treated in consistent ways: A tolerable margin is established away from the limit. From experience, Process Flow 1 allows the lowest variance because it is not operating close to the limits.

However, Process Flow 1 cannot produce any more than the equivalent amount of the feed. There is little risk of violating any constraints that the plant capacity has because they are an equivalent 2X distant from the production. Application of an APC, in this case, can only optimize energy and any splits between products. Assumptions are that the reactor optimization is completed and can make exactly what was designed into the process.

Process flow 2 shows that the feed system is twice the capacity of process flow 1. The design of the plant in process flow 2 is approximately X. Design engineers are given a charge to make the plant of that size. There are no rewards given to the design engineers for designing a plant with less than X or for building excess capacity.

In industrial practice, the plant is handed over to operations. As long as the economic function is positive for running the plant, Operations focus on achieving the maximum output. Operations operate as close to the limits for each constraining parameter.

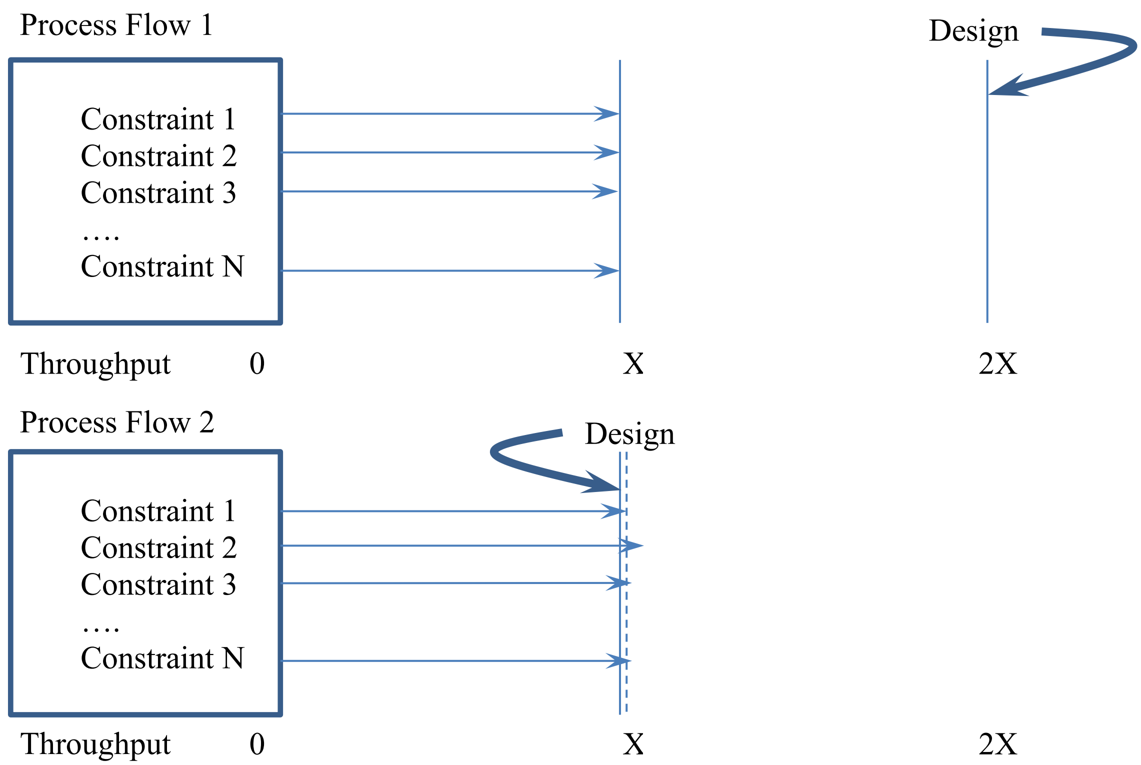

Figure 3 Schematic showing the Design considerations and Process Flows.

These constraining parameters are all correlated to the throughput. An acceptable tolerance is given from the limit to ensure the risk of shutting down the process is acceptable. The objective of Operations is to generate highest cash without shutting down the plant. The difference between where they operate and the risk limits define the acceptable risk. However, it is difficult for the design engineers to obtain the precise design criteria given for each system. They typically are good and get better with time to ensure that all working parts in the plant are designed to give exactly X throughput. Operations push the plant up those constraints that hold the plant back from producing more.

II.2. WHAT HAPPENS WHEN AN APC IS INSTALLED.

To understand what happens when an APC is installed, one has to evaluate each constraining variable and the margins defining the acceptable risk. Each constraint limit is located at a distance beyond the mean for the variable so that there is a low probability for the operations to trigger the limit. Each constraint will have a distribution based on the risk consequence for triggering the limit. Typically this risk acceptance is determined without a formal process to identify the specific percentage of variability (e.g., 0.95, 0.99, 0.999, etc.). It is usually a subjective limit set by operator based on confidence in controlling the situation. Some parameter receive formal attention through the process such as HAZOP, and Fault Tree Analysis and receive a formal risk designation.

An APC will reduce the variability of each of the parameters. The reduced variability allows the mean to move closer to the limit for that constraining variable. To ensure there is a consistent measurement of the expansion due to the APC, a consistent risk acceptance policy should be used before and after. Otherwise, there will be confusion over how much of the capacity increase was due to changing risk acceptance policy and how much is due to the APC.

The increase in the benefits of an APC is largely due to increases in throughput. If the. benefits do not result in increases in throughput the benefits are typically due to energy savings. The return for the APC will be significantly lower than expected. APC is viewed as a way to increase capacity in the unit without significant expenditure on equipment. If there is an expansion in a capacity beyond X capacity, expenditure to all the constraining systems will need to be made. The 3-5% throughput increase quoted for most units is worth a lot.

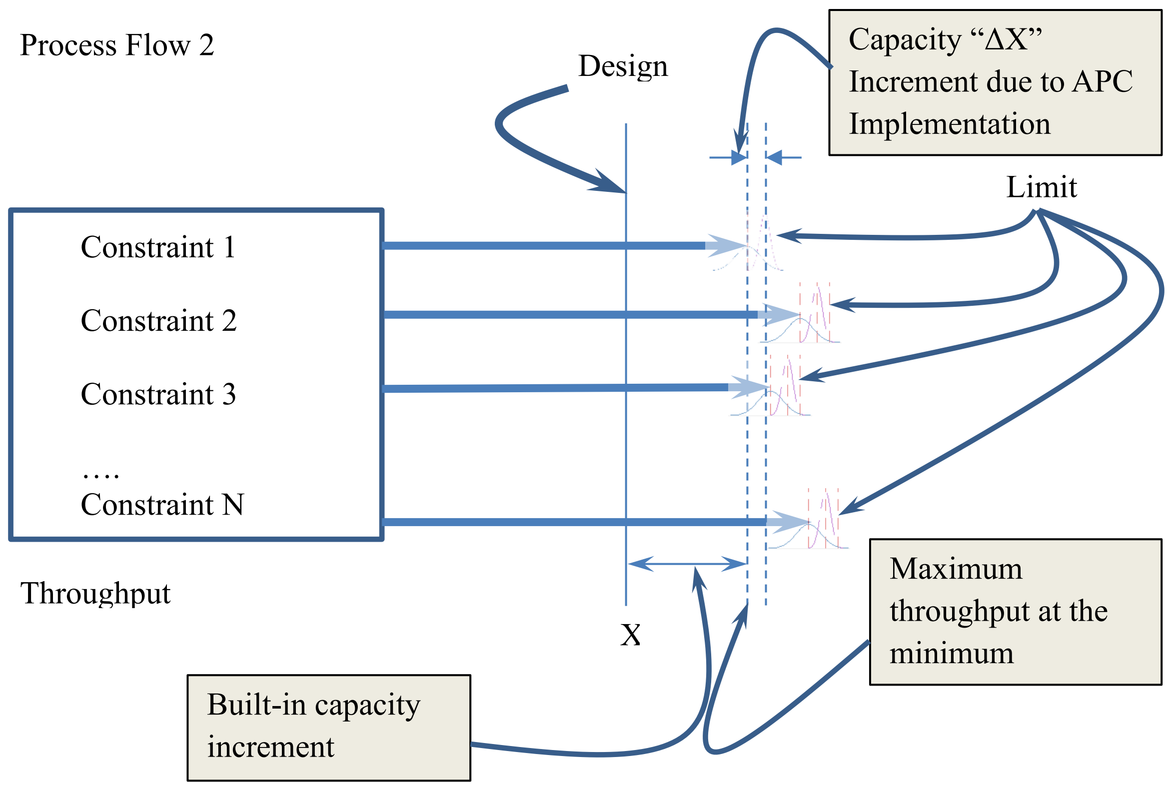

Figure 4 Constraints and acceptable risk

II.3. RETRIEVING INFORMATION ON APC PROJECTS.

Much of the information contained in the APC space is contained within the process industries. This is because the processes are large so creating an experimental bench that represents the field is too costly. Further, the organizations do not generally share information because there are competitive reasons for retaining the information and there are potential legal restrictions (anti-trust) for sharing the information. Literature searches combined with the procedures contained in the METHODS chapter were used to extract the information available to develop the models contained in this report.

That being said, there are always articles that are published for competitive reasons. When asked the authors can share additional information that is key to the overall conclusions in the published work. There is a substantial body of literature and discussion around how to do the interviews of the published experts to gain this additional information. [13-16] Additionally, I used my 38 years of practical experience of documenting meeting results and gaining acceptance of the decisions made in meetings. One of the principal items sought was a quantitative way to characterize the decline of APC and then a way to describe an optimum way to handle the maintenance. Further, there were no ways to identify the installation costs in published data and link those calculations with the optimum maintenance were also missing. Finally, there were ways to identify continuous improvement; however, these methods linking these methods to continuously improve an APC implementation were not found.

II.4. MAINTENANCE OF APC

My research into the life of an APC began in work for ConocoPhillips for several years, particularly in the investigation of the installation of an APC in the last location. During this period there was a dialog with the vendor Emerson on the life of an APC when installed. Lou Heavner was the representative expert at the time and introduced me to some of his experiences with the relatively short life of APC if there is no support (maintenance) to keep the APC operational. After my retirement from ConocoPhillips, I maintained friendship and personal contact with Lou. There are several conversations and documented interviews on the various subject throughout the references. Lou indicated that the half-life of an APC is 18-24 months if there is no support.[10] This failure rate was validated through literature review.

One article by David Shook was the source for several others showing the decline of APC performance over time [17]. David Shook showed that failures of APCs are much higher than originally anticipated. His estimates provided a range of values for qualitative analyses; however, a quantitative equation for the relationship was never attempted. A meeting was held with David Shook to discuss the paper and he confirmed the origin for the numbers [18]. This discussion followed the pattern summarized in the Methods Chapter. The origin of the numbers stating the failure rates was the collective experience of Matrikon control systems engineers over several years and several companies. David suggested the numbers presented in the article were conservative (low) for the failure rates. I described a case study at one site where he worked that the APC was removed after the original personnel involved in the installation moved to other sites. Dave said that this case was unfortunately the case with companies. One site installed the same APC three times. This was due to changes in personnel at the site. That being said Dave had one example where the corporate memory was held intact over several personnel changes. The same APC was in place for 15 years.

The same data presented by the collective knowledge of Matrikon in 2006 was reported by Honeywell 8 years later [9]. Honeywell presented the graph without attribution. At the very least, this is a broad agreement on the overall decline and failure patterns. There was an extended discussion of the data contained in this panel with Richard Salliss (the presentation author) and his designate, Gary Jubien on the source of the information and the interpretation of the data contained in the panel. Both Gary Jubien and Richard Salliss claim the information in the panel came from Honeywell's experience.

Gary Jubien in this interchange introduced the overall shape of the decline and a chart similar to that used in Figure 5. This is the concept of achieving 100% of the SAT performance at each recalibration. This decline and recalibration cycle is turned into the maintenance equations developed in the Maintenance Chapter.

An article by Allan Kern presented the decline curve that Dave shook had published but claimed that the failure rates are much higher than 65% in 2 years [11]. Instead, Kern claims that the failure rate is 80% in the first two years. This would tend to corroborate the discussion with Dave Shook that the failure rates reported in his 2006 article were conservative.

An article by Tom Fiske, while he was working for The ARC Advisory Group, has a very similar decline curve to the curves presented by Honeywell and David Shook [19]. It did not present specific numbers at specific times as the Shook / Honeywell data; however, Tom Fiske did indicate that APC may fall to zero in two years without maintenance. As with David Shook and Richard Salliss / Gary Jubien, a conversation with Tom Fiske was attempted without success. At the time of the potential contact, Tom was working for Yokogawa. Yokogawa was requesting payment for the time and as the research was self-funded it was decided to terminate the communication.

II.5. UNDERSTANDING FACTORS INFLUENCING APC

An article by Perry Nordh, Honeywell employee, presented the point of view of one who has worked directly with the implementation of the technology [20]. Perry started his career as an operator and then got his engineering degree. He brought to the discussion perspective that is valuable for the research. One of his emphasis was developing the operator skill in using the APC once installed. The article focused on management systems that are separate from the actual APC implementation.

Perry was interviewed 30 Aug 2019 [21] on several different areas of APC project implementation and operation. We first discussed the relatively high failure rates reported in previous references and interviews of David Shook and Richard Salliss. Perry commented that he knew both individuals and was familiar with their work; however, he was unfamiliar with the high failure rates. We discussed the work hour cost for engineers implementing the APC projects. I mentioned the factor of 2.7 [22] to escalate the salary to the actual employee cost. Perry's recollection of the escalation for Honeywell was about that figure. Perry mentioned that smaller contractors have an advantage over larger companies like Honeywell because smaller firms don't have the overhead burden represented in the 2.7 factor.

Perry was asked about the minimum variance for increasing the performance function. Perry noted that a 50% reduction in the standard deviation of the performance function was typically used to justify investment in an APC. This is consistent with several references [2, 23, 24]. Perry described the overall training that is usually given with all Honeywell APC's. The overall training usually lasts two days to cover all shifts. During those two days of training, each operator receives about four hours of training. There is a difference in training required for each operator depending on whether the operator has had experience with operating with APC before. If the operator has had experience with operating with an APC, the amount of training required to bring the operator up to acceptable performance is about 1/3 as much training required if an operator has had no prior experience with APC.

Human Factors – The overall human factors were grouped into two areas: human-human interface and human-machine interface. Between the two Perry estimated that the overall factors would be about equal between the two.

- Human-Human interface – Perry agreed that the human-human interface was a significant factor. An example of a human-human interface discussed was a particularly objectionable controls engineer dealing with an operator. Perry said that he had observed this in the installation of an APC. The controls engineer had commented that nothing is going to be done today because X is on the control board. Perry said he enquired X how they were going to get things done that day and X said he wanted to see three conditions satisfied. As soon as those conditions were satisfied, the project moved ahead with X on the control board. Ways to quantify the Human-Human interface was not discussed but could be the subject of a future research conversation.
- Human Machine Interface – There were two examples given for the human-machine interface in the discussion. The first reference to human factors in the nuclear industry [6], with the primary focus on the safety of the nuclear power generation when employing APC. The second reference discussed was the Marathon survey of different versions of DMC (competitor) on the human-machine interface [7] (panel 40). Perry said that it was a little hard to tell the specifics of the survey, but it appeared to be an attempt to measure the human-machine interface differences. Ways to quantify the Human-Machine interface was not discussed but could be the subject of a future research conversation.

Perry was asked about a survey similar in scope and breadth as the Japan study of APC. Perry was not aware of any similar survey for APC's in North America.

I interacted with Ken Praprost of ABB on 27 Mar 2020. The discussion originated with an article published by ABB in "Efficiency up, emissions down Achieving higher power plant performance with advanced process control."[1] The article dealt with subjects around the implementation of Model Predictive Control (MPC). MPC is a form of Advanced Process Control APC. Ken worked on the article in question with the three authors. In addition to working with ABB, Ken had worked with Matrikon in Canada. Ken worked around David Shook. We discussed the declines in the performance of APC for different types of units. The declines mentioned in the paper by David Shook tends to be 2-3 years for about 65% of the units to reach zero performance. Ken discussed that the decline rates for most power generation facilities are not as steep as those experienced in the article. We discussed declines in LNG plants. There is an example by Andrew Taylor of an LNG plant APC installed. The plant showed a 20% decline in throughput after 1 year in operation. We discussed that the place where APC's were turned off in terms of decline from APC seemed to be similar. Discussions with others (Marathon, Shell, etc.) seemed to indicate that where an APC is turned off seems to follow the same pattern. The program becomes increasingly difficult for the operators to keep on and then ultimately it is turned off. Ken Praprost of ABB mentioned the need for having good metrics for making sure the APC is kept running after installation. Marathon refinery in Corpus Christi, TX echoed the notion of having a sophisticated key performance indicator (KPI).

Ken discussed the wide variety of objective functions for power generation facilities. Examples of the objective functions are:

- Power generation rate – Maximize the generation of power
- Power generation efficiency – maximize the power generated for the energy consumed.

Ken said that for a similar sort of parameter of an LNG plant, a 2% increase may be expected from power plants. Ken mentioned that a key for the success of an APC is having a Subject Matter Expert available to ensure that it stays operational. Success is marked by the engagement of these individuals after implementation.

II.6. APC IMPLEMENTATION ISSUES.

Ken Praprost of ABB mentioned that there were two styles of implementation of the APC. The first style was to go directly to the input of the devices that were being controlled. This took more up-front programming to make this type of installation work. The primary reason is that the base level of controls needed to operate successfully when the APC was turned off. This type of installation seemed to decline more slowly than simply overlaying the APC on top of the base level controls (second type). This second type was easier to engage and disengage the APC. We did not discuss the relative decline rates between the two types of power generation installation described.

There have been a few review articles discussing the benefits of APC and problems with implementation. One article provided a survey-based economic assessment of APC and provided a framework [2]. Based on economic analysis, Bauer and Craig gave an overview of sources of benefits for an APC and problems with implementation [2]. Further, there was a discussion of the overall benefit from a reduction in the variability. This gave rise to the derivation of the maximum yield based on continuous improvement.

A number of reasons for the decline of the functionality of APC were also given. This was the first paper reference on the subject referenced by Dr. Russ Rhinehart.

In the Handbook of Liquefied Natural Gas [25], a chapter (Chapter 6) described the overall structure of an APC capital project in an LNG plant. Specifically, the phases of the project were broken down with good explanations of the activities established within the phase. The overall structure compared well with other references on projects for APC projects. Further, it broke down the APC project into the sections inside the typical LNG process. The benefits are also summarized along with a cookbook on how to compute the benefits. There were case histories of APC implementations at LNG plants. There are lists of MV, CV, and DV for all the typical sections of an LNG plant.

To provide some of the challenges around MPC, the authors described best practices around APC implementation [26]. There was a two-tower example with seven MV. Inferential variables were discussed. The overall project steps for capital were discussed and the work contained in those project steps. Inferential variables are typically correlations of lab quantities that are correlated to process variables. Lab values are typically specifications for the product in refineries. Examples of these quantities are 5% Distillation point, 95% distillation point, API gravity, cloud point, etc. The creation of inferential variables takes a significant amount of work and thus affect the price of an APC significantly. Automatic step testing is compared to manual step testing as an improved technique for implementing an APC project. The experience of engineers implementing the APC is also discussed. The cost of implementing an APC is partially affected by the cost of manpower. The cost of manpower has been a function of the experience of those implementing the APC. One of the authors, Mark Darby was interviewed about the contents of the article. Notes were made of the interview and shared with Mark for comment. Mark made additions and corrections to the notes. The notes and commentary are in the files. Relative sizes of the APCs were discussed and their impact on the cost of implementing an APC.

An article by a self-employed engineer who implements APC programs [27] focused on the overall structure of an APC project. The article made sure that maintenance was integrated into the overall structure of the project. The author felt that the inclusion of maintenance in the structure was key to the overall success. There were no specifics to the execution of the maintenance program. The key steps to a project were listed in the article. Maintenance inclusion was one of those steps.

Another report focused on the management systems that need to be in place for the successful implementation of an APC [28]. There was a section on the making sure the key performance indicators (KPI) are functioning correctly and are displayed to different audiences within the organization. There were elements of the human-machine interface in the article as well as management systems. The article also had a section on inferential variables. The section focused on ensuring the correlations were still valid for the current data. A specific analysis was recommended to test the validity of the data.

II. 7. CAPITAL ESTIMATION.

For capital estimation of an APC installation there are several components to the overall structure of the project:

1. Worksteps needed to complete the project. There were several documented workflows in the published literature. A wide variety of steps are used by different authors in the

process industries; however, a consistent set of work steps have been proposed based on a comparison of different literature sources. The synthesis of this consistent workflow is detailed in the Capital chapter.

2. The work hours to complete the work step – These values were unavailable in published literature. The amount of work needed to complete each step was developed through a series of interviews and Delphi-like (see later section on Delphi) discussions with both technology providers and owner-operators. A consistent workflow along with the work required to complete each step. The work required to complete each step is in part a function of the size of the APC involved. There are different standard gauges for size recognized in the process industries the manipulated variables (MV), controlled variables (CV), and disturbance variables (DV). The pricing has generally focused on MV for correlation of the cost.
3. The cost of the work per hour to complete each work step – Generally, there are two sources of personnel to draw upon for completing any project within the process industries: In-company resources or contractors. The hourly rate at which they are each charged to the project is different depending on the calculations. In-company resources are easily calculated by a company if they are using their proprietary data; however, salary information can be converted to an hourly cost for in-company resources. All owner-operators employ varying combinations of contractors and in-company resources depending on the strategy selected to operate the company.
4. Cost of Ancillary Services and Devices – The licensing fees are the only item in this category that were consistent. Licensing fees also vary with the global contract that technology providing firms have with the owner-operating firms.

In one of the extensive studies [29], a research group in Japan analyzed the performance of 305 APC work. They were characterized by the numbers of manipulated variables (MV), controlled variables (CV), and disturbance variables (DV). One of the main elements they reported based on the conversations with practitioners (vendors) is that MV has been the primary key variable for the pricing of APC work. The key scaling variable focuses on the capital work of the research by scaling the estimated cost of an APC. They discussed the overall decline in APC performance over time. The authors made the point that things change in the plant fouling, tuning, etc. These changes affect the functionality of the APC and some possible solutions were recommended. While these authors gave very specific sizing information, this sizing information was not correlated to installation cost or recalibration cost.

Searches for other surveys found describing sizes of APC installations were not found in other areas of the world. There may be surveys not in the public domain such as Solomon Associates [30]. Solomon regularly does refining studies where the data are available for participants that pay[31]. These data were not available through normal resources available to Oklahoma State University. There are articles on the installation of various projects. A few of those projects are listed below:

There was a case study reported on using APC for a crude distillation unit installation by Honeywell of an APC project in Russia [4]. The installation was on a combination of an atmospheric tower and a vacuum tower in a refinery. The article described in detail the implementation and listed the MV, CV, and DV for the installation. The significant portion of the article besides the process for implementation of the project was a detailed description of the Site Acceptance Test (SAT). The best APC performance is on the SAT. Hence, the SAT is critical in the overall comparison of the decline of the APC over time. The assumption in my research is that the recalibration of the APC brings the performance back to the SAT. They also discussed the implementation of inferential variables. Detailed descriptions were given for the development of these parameters. The time to zero performance is difficult to judge for power generation facilities because most units are turned off in the area of 50-70% of SAT performance. This usually happens 4-5 years (or even longer) after the APC was installed.

Another article described the installation of a Closed-loop identification at the Hovensa Refinery project in the Virgin Islands [32]. This project described the MV, CV, and DV for the project. This also described automating the step testing for the project. This would be an improvement for continuous improvement to decrease the continuing costs for the APC project.

A documented discussion with Lou Heavner developed the overall outline of the project workflow [33]. In this workflow, each step was estimated per MV. Lou Heavner explained that Emerson estimates APC work to complete the steps using this size parameter. The data for this workflow was then discussed with the owner-operator at Shell (Berry Cott)[34] Barry commented on the overall workhour factors for each step and updated some of the factors based on his experience.

Data from several aspects were discussed in detail with another technology provider, Mark Darby [35, 36]. There were two sessions of about two hours in length each. One of the important topics was the sizes of APC. Mark agreed that the overall sizes of APC noted in the Japan survey were small [29] compared to his experience. Mark provided an example of one APC project that had near 100 MV. Mark mentioned that if the APC is too small there may need to be additional levels of optimization placed in the hierarchy above the smaller APC to ensure a global optimum. Mark Darby had his version of workflow and that is presented in Chapter VI while comparing it with other workflows. Mark also details the ranges for contract engineer costs. These are compared to in-house engineers that are employed to complete APC projects.

I discussed with Ken Praprost of ABB about the capital investment required in the facilities over and above the capital required for servers, etc. said that sometimes there were modifications to valving and other instrumentation that was required to put the APC in place; however, most of the time the installation relied on the infrastructure that was already in place.

II.8. CONTINUOUS IMPROVEMENT

Continuous Improvement has been part of my career since the beginning. It is difficult to know exactly where it began; however, it is difficult to define for in terms of a professional experience because specific elements that comprise continuous improvement are not well defined. Even extant definitions in literature are sometimes difficult to understand as the definition from Wikipedia shows [37]:

"A continual improvement process, also often called a continuous improvement process (abbreviated as CIP or CI), is an ongoing effort to improve products, services, or processes. These efforts can seek "incremental" improvement over time or "breakthrough" improvement all at once, Delivery (customer valued) processes are constantly evaluated and improved in the light of their efficiency, effectiveness, and flexibility."

This document seeks to define continuous improvement in terms of costs and benefits of the APC. Specifically, this would mean the decrease in the cost of implementing and maintaining the APC over time and increasing the benefits derived from implementing the APC over time.

II.9. COST ESTIMATION

Accumulation of knowledge along the way increases a company's ability to produce goods and services at lower rates by decreasing costs. The Boston Consulting Group put together relationships that define this learning relationship along with the cumulative production of units[38, 39]. Many companies compare themselves to experience or learning curves. Some regulatory agencies also use learning curves.

Through a discussion with Dr. Alex Kalafatis [40] (director of product management for APC products, AspenTech) a presentation on Chevron APC programs in the production areas [41]. Contained in this presentation were activities for automatic recalibration was presented. Kaylin Buscovich gave the presentation. This was a technical presentation looking at the necessary variables needed to be in place to make sure there was a successful program. There were several different parts of Chevron reviewed from enhanced oil recovery, LNG, and mid-stream business applications. Kaylin also has experience in chemicals applications. The primary focus of the presentation was a continuous model updating. The issue here was the elimination of downtime for the recalibration of the model. The desire for the tool is to ensure there is a continuous calibration of the program to account for different technical variables. A list partial of those technical variables is provided below:

- Feed Rate
- Feed Composition
- Product Demand
- Product Specifications
- Flow Regime
- Exchanger Fouling
- Degradation of Catalytic Activity
- Valve Wear
- Seasonal Weather

The overall variables above were inputs to the APC models that needed to account for various effects in the plant. Constraints for all the variables may need to be adjusted over time. Updating the model with continuous model calibration. The claim was that this was less aggressive than the standard periodic step testing. The implication was that the periodic step testing could be eliminated; however, that claim was not explicitly stated in the presentation. The point here is that automatic recalibration was being used on an APC. The period of which is much less than 6 months.

Another example of using automation to reduce the cost of implementation of APC is automating the step testing required for both recalibration and installation of an APC. Mark Darby discussed the benefits and concerns of automatic step testing in an article [42] and an interview [35]. Additionally, a significant reduction in costs was identified in another specific project using automatic step testing [32]. Following is the question put to one of the authors and response on the role of automatic step testing:

Question

Reduced time to do the step testing – The reduction in time to do the step testing was highlighted. This appears to be an evolution in the overall implementation of MPC's. Can this be placed in the overall evolution of an experience curve? An experience curve says the cost is reduced by 20-30% for every doubling of the quantity of MPC's being installed.

Response:

[Rohit] That is an interesting perspective. Never thought of it that way. I would consider the demonstration of closed-loop step testing as a true step change in the evolutionary process of MPC's. Closed-loop testing was sort of the holy grail of process control and was always viewed with suspicion. Applications like these started demonstrating that closed-loop testing could work and save a lot of time as well. This to me was a major realization for the industry.

II.10. BENEFITS

In continuous improvement not as much attention is paid to increasing the benefits over time; however, there were some direct references in some of the literature already reviewed. Gary Jubien directly referred to the continuous improvement of the base APC performance by clearly separating recalibration to bring the APC back to the site acceptance test (SAT) performance from increasing the performance above the original installation. [43] Further, David Shook referred a benefit increase for about 10% of those implementing APC. [17] Andrew Taylor specifies about 10-15% improvement for subsequent revamps of APC implementation for continued improvement of the benefits.

[44] This experience that was quoted was about 1/3 of the more than 100 projects he has completed.

II.11. CROWD KNOWLEDGE – DELPHI STUDIES

In summary, there were 198 references examined. This includes both journal articles and books as well as documented discussions with various authors and recognized industry experts. Where the literature failed to yield sufficient information, the procedure in Methods chapter was employed to discuss with the author or their delegate to gain additional information. Despite the barriers documented in Methods, information was gleaned from the combination of the literature search plus the documented discussions to assemble systems of dimensionless equations to sufficiently describe the APC space.

II.12. MINIMUM NUMBER OF PEOPLE TO INTERVIEW

There were varying opinions on the number of people to interview. Some indicated 3-7 people were adequate[16] but others promote a larger number [15, 45]. While there does not appear to be an optimum number in the survey. Dr. Robin Hanson suggested that there is no optimum number [46]; however, there is a point of diminishing returns. [47] Dr. Jon Ramsey suggested keeping the number around 13 to keep the amount of data manageable. Some numbers in examples given by one of the originators of the techniques Norman Dalkey gave an example of one with seven people.[13]. Karl Mattingly (CEO Dysrupt Labs) seemed to be a proponent of smaller groups (3-6) [16, 48] and indicated that six may be optimum.

The techniques learned in studying the Delphi Study methods were employed; however, a full-scale Delphi Study was prepared for but not attempted upon the direction of my professors. The discipline in documenting the conversations and reviewing the interview content with the person being interviewed greatly improved the accuracy of the communication and served as a source of information

This was an exemplar article to show the application of the Delphi method [13]. It is by the fathers of the modern application of the Delphi technique. The article presented examples of questions for the Delphi technique. It also presented methods for managing the rounds of a Delphi study. The example presented a Delphi study to arrive at a quantitative result. The example showed convergence of the group estimates through several rounds of the study. The goals were to ensure there was no bias by keeping the responses separate (blind).

CHAPTER III

METHODS

III.1. INTRODUCTION.

The objectives of this study are to create a system of quantitative protocols for managing APC that are applicable across several industries. The end goal that these protocols are to significantly reduce the overall APC failure rate and thus increase the productivity of the process industry. To facilitate the use and comparison of APC operation, dimensionless numbers are a key requirement of the objectives. The protocols include specifically the maintenance of the APC but also extend to continuous improvement and other management systems. Data for conducting this research are scattered in several parts of the process industries. Data are being collected all the time through detailed distributive control systems and are available on the companies' historians. Analyses of this data are being completed by controls and process experts on a continual basis. Collecting this data of experts across the process industries spectrum coupled with literature reviews is the primary method for collecting the data for this analysis.

Populations of Experts within the Process Industries

There are two basic populations of expertise within the process industries:

- Technology Vendors – APC technology is sold to the process industry through major providers of the technology. Examples of firms that supply technology are Honeywell, Aspen, Emerson, Yokogawa, etc.   These companies not only have the personnel to develop the technology but also have the personnel to install the technology. There are also third-party vendors that have developed niche expertise at installing the technology.

- Owner-Operator – This includes the owners of the equipment on which APC is applied. Examples of companies in this category are as follows: Oil and gas firms (Exxon-Mobil, Shell, ConocoPhillips, Marathon, etc.), pulp and paper, Liquefied Natual Gas (LNG)

Each of these different groups has a different perspective on various aspects of the APC function. Technology vendors have different expertise in implementing projects.

III.2. BARRIERS TO INFORMATION EXCHANGE

Most of the literature is burdened by restrictions in flows of information – Companies are not very willing to share information widely for two reasons:

- Company Proprietary information – Companies usually consider the information associated with highly technical details of a process to be proprietary in the highly competitive world of producing processed products. Detailed technical articles are produced from time to time, but the intersection of the technical details and the strictly commercial details (cost of doing the project, the value of the incremental production, etc.) are not published.
- Antitrust Laws – Antitrust laws prohibit the exchange of commercially relevant information. Commercially relevant information typically extends to include

technical information about the processes. Specific technical information can be released when the risk of violation of the antitrust legislation is low or the release of the information has some competitive advantage for the company.

III.3. PRECEDENCE FOR BROAD EXCHANGE OF INFORMATION

There is a precedence for the broad exchange of information across an industry. The Solomon Study of Refineries covers 85%-95% of all Refineries Worldwide Share information in a blind study.[31, 49] Doing a similar survey with a limited quantity of experts (a Delphi study) where the participants are blind from communicating with one another, and the researcher (Stephen Mayo) is committed to not sharing the identity of others responses, would parallel the requirements of the Solomon study.

III.4. OBTAINING EXPERIMENTAL TEST DATA IS ALSO PROBLEMATIC

The information to solve this problem lies in the companies' files, corporate memory, and operating data that employ this technology and need to be organized. No designed experiment is possible because 1) The units are on the order of several hundred million – billion-dollar investments and companies that build them expect them to return the maximum amount possible. Experimentation is not viewed favorably. 2) The programs cost $50,000-$500,000 and are thus out of the range of academic funding.

III.5. GETTING THE DATA IS UNCONVENTIONAL

Getting the data is unconventional but has precedence in research. Research of the existing literature coupled with interviews of key personnel will prepare a base of experience on which to develop and generate a study based on crowd knowledge [50]. The typical application of crowd knowledge will be assembling a series of guided questions for experts in the area – a Delphi Study [13, 14, 16]. This technique is used extensively by the Rand Corporation in defense studies [13, 51, 52] and in locating lost vessels [53]. Further, this type of crowd knowledge is also used extensively in the medical industry [54]. The accuracy of crowd results is high and would be expected to be high for this application with the inclusion of experts across the industry [16, 50].

III.6. INTERVIEW PROCESS

The typical interview procedure employed to get information to pursue a particular subject in the overall process is as follows:

1. Develop a list of questions through discussions with advisors or with other persons of interest – This list of questions can be general enough to get the discussion going but specific enough to zero in on the specific issue in question.
2. Plan and agree on the scope of the discussion with the person being interviewed – The detailed list of questions were sometimes mailed out in advance of the interview; however, answers within the discussion could negate the need to complete the line of questioning laid out in the plan. Sometimes, the person in the interview brought up issues that were important for other areas of the research, and the total line of questioning was abandoned and the new line of questioning was pursued.
3. Have the discussion ensure that all the points agreed on with the advisor were touched on. Explain during the discussion that the discussion will be documented

and that the person being interviewed will be able to change anything in the meeting notes that are not appropriately documented.

4. Document the interview

5. Send the meeting notes to be reviewed.

6. File the corrected document in the appropriate reference catalog (e.g., Endnote)

CHAPTER IV

APC MAINTENANCE

IV.1. INTRODUCTION.

As the process characteristics deviate from those representing the model, control functionality degrades, and the equivalent economic benefit of the APC installation diminishes. An approach to returning the APC to full functionality is a recalibration of the model i.e., retesting the process response and adjusting model coefficients to the best match. Recalibration has a cost, which is desirably avoided. But, recalibration can restore APC benefit. If recalibration is performed when the functional benefit of the APC installation is high, there is little gained from the recalibration cost. However, if recalibration is postponed, the loss of economic benefit of the APC installation can be greater than the cost of recalibration.

Typically user sentiment may be a common measure of the overall decline in the performance of the APC i.e., it becomes harder to keep the APC on control, or several parameters are clamped. However, a more rational economic basis is needed to trigger for APC maintenance grounded in functional performance, not intuitive sentiment. Based on that idea, first, an overall profit equation is developed and then a procedure is offered where the owner/operator can schedule recalibration to maximize the annual benefit to make the most effective use of the APC.

IV.2. A DECLINE MODEL FOR APC FUNCTIONALITY

The APC functionality decline over time is commonly represented with a very gradual initial decline after commissioning, followed by a rapidly increasing decline toward zero [9]. Others have supported the shape in private communication. A concept is that as an attribute of the process diverges from the original, control gets worse. If one attribute contributes to functionality and gets worse linearly in time, then decline model for the APC benefit would be

$$b(t) = b_o - \alpha t.$$

Where $b(t)$ is the economic value per time associated with the benefit, which might have the economic equivalent units of $/year. But, if the loss in equivalent economic value increases with the deviation from performance, then

$$b(t) = b_o - \alpha t^p \tag{1}$$

Here, p might have a classic value of 2, a quadratic penalty. If the number of attributes that cause the decline increase in time, then the model is more complicated.

The decline curve representations by the experts are notional, meaning that they represent a notion of the decline from their experience. To date, there is no definitive mechanistic basis from which to derive and validate a certain mathematical model for the APC functional decline, and many mathematical models do an adequate job of describing the notional representation of experience. The power law decline of Eq. (1) seems to be as good a model as any to match the notional representations of the decline. It is the simplest of several we considered and the most convenient for determining an optimal schedule. When considering the consequence of several p-values, experience seems to suggest that the net decline can be represented by a value between 2 and 5 [55, 56].

Consistent with the notional graphs, we will accept that, if there is no APC maintenance, the functionality decreases to zero. The controller probably will be turned off before it completely degrades. We will set the time to zero functionality as t_0, meaning

$$b(t_0) = 0 = b_o - \alpha t_0{}^p.$$

Using dimensionless variables $\tau = t/t_0$, and $\beta(t) = b(t)/b_0$, Eq.(1) takes the form,

$$\beta(\tau) = 1 - \tau^p \tag{2}$$

The benefit is a consistent sum of all the benefits claimed for the project at the site acceptance test.

$$Site\ Acceptance\ Test\ Benefits = b_0 = \sum_{k=1}^{m} b_k \tag{3}$$

b_k = individual type benefit for a period, \$/year. Normally, when an APC is justified, there will be a benefit that accumulates all the independent factors (e.g., throughput increase, product giveaway, environmental, safety, etc.) are added together. Note that these factors are all on a consistent basis. Some of the individual components may be inversely correlated (e.g., moving the process closer to the limits will increase throughput but have negative consequences for safety or environmental).

m = the total number of benefits claimed for the APC project justification. This has a minimum of one and a maximum of the categories for benefits (e.g., throughput increase, product giveaway, environmental, safety, etc.).

The time during this period of decline is scaled. Immediately after the site acceptance test $\tau = 0$. When the benefits of the process decline to pre-SAT levels, then the APC value is zero, then $\tau = 1$.

The fraction of the economic rate of the benefits to the SAT implemented benefits is defined as β. The Equation (1) model places all industries on a common basis where the benefits are scaled to the same value and the decline to zero is scaled to the same value.

With $p = 2$, a quadratic decline model, the overall decline to zero is illustrated in **Figure 5**: The scaled variables are each on a 0-1 basis. Based on the literature review and communication with several APC experts, this period of decline is on the order of 2-3 years without maintenance, $t_0 \approx 2.5\ years$. It could be quicker depending on several factors listed in Section 2.2. The APC is usually turned off prior to the point of the benefit becoming zero; so, the lifetime would be less than the 2.5-year decline to zero functionality. Recalibration can often retrain the APC model to represent the new process behavior. This recalibration repeats the step testing of the inputs to obtain a new model. Then the APC can perform near or equal to that established at the site acceptance test.

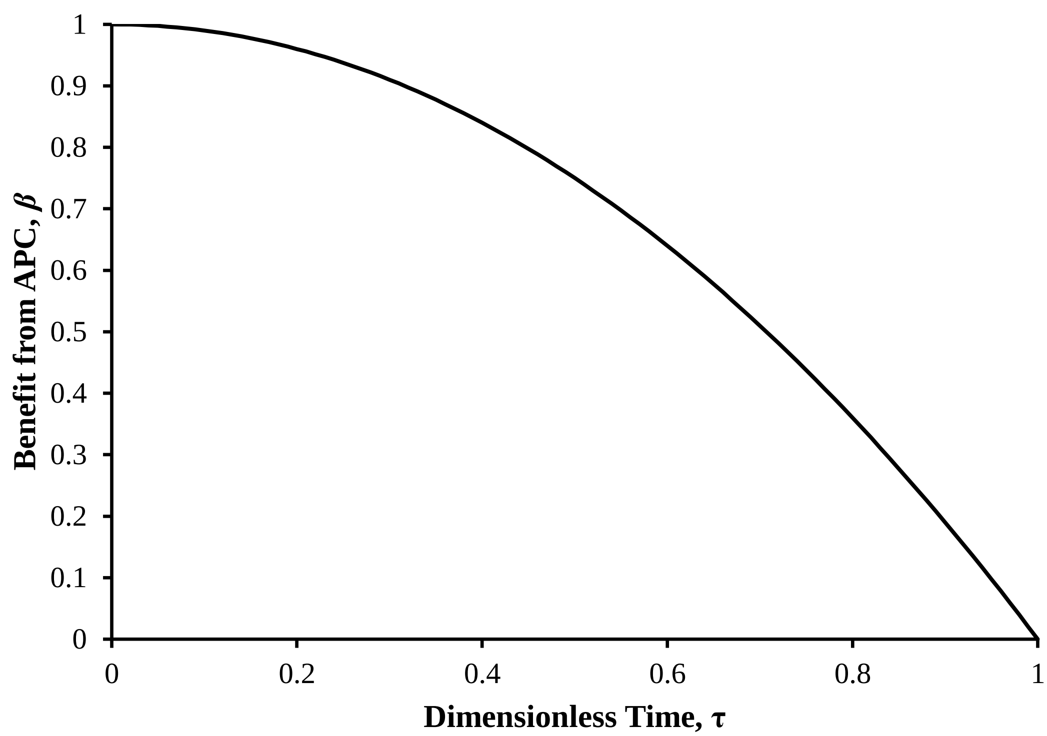

Figure 5 Nominal Quadratic Decline Curve to Zero

If the Owner/User recalibrates at the time when the overall performance reaches zero an overall performance curve for illustration and two recalibration events will look like the illustration in **Figure 6**. Please note that this is an idealized representation. There is zero time for the recalibration, no change in the return to full benefit, no change in the decline rate or t_0

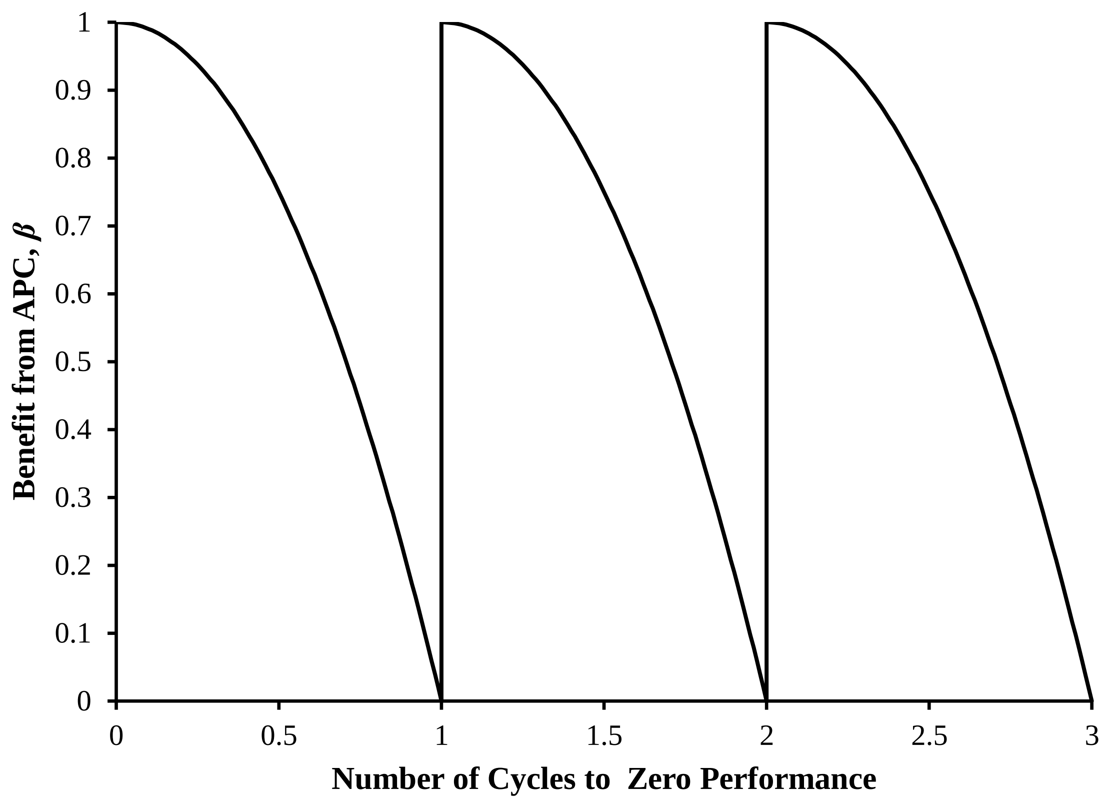

Figure 6. Multiple Decline Curves with Recalibration at τ=1, and 2.

The maximum benefit value is 1.0 and there are three cycles shown for emphasis. Some have estimated the p-values to be as high as 5, for assets where the owner/operator has dedicated APC support staff on-site [55]. **Figure 7** reveals the effect of the p-value on $\beta(\tau)$. With increasing p-value, $\beta(\tau)$ has a lower rate of decrease initially and a precipitous decrease later.

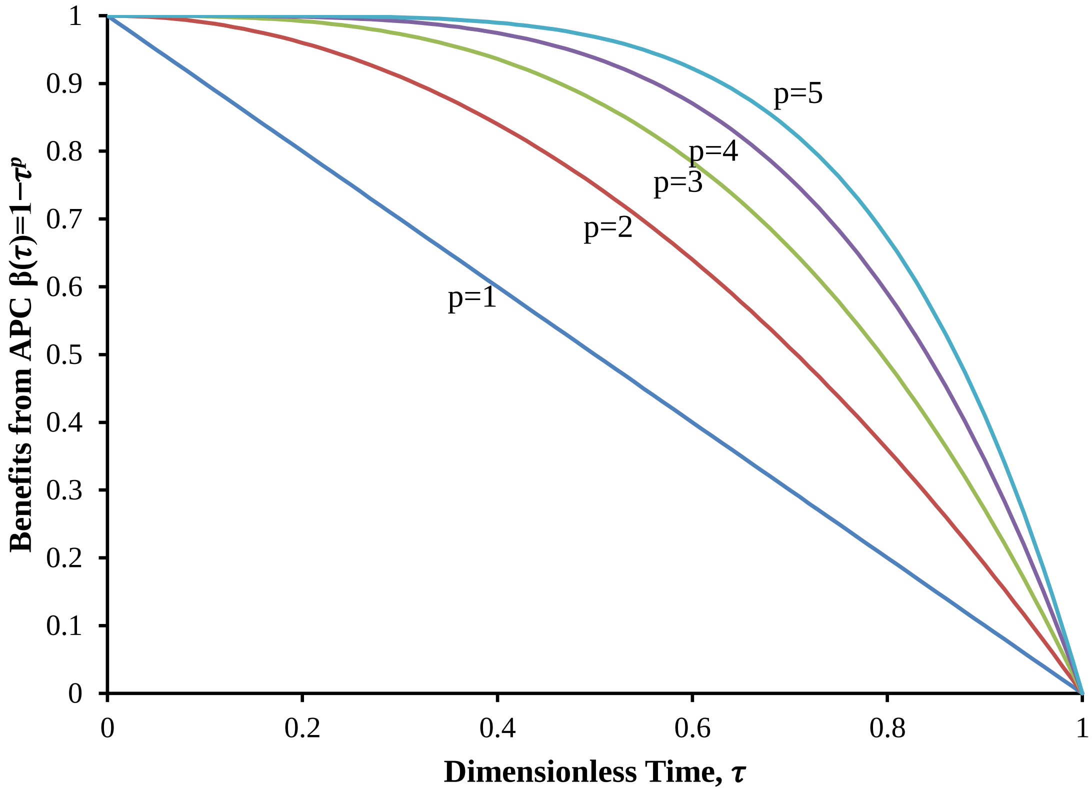

Figure 7. Decline Curve Comparison

IV.2.1. Defining Assumptions

The basis for the subsequent analysis includes:

- An APC will not improve over the course of the decline unless new elements are added. This is a design change. We will only consider the design as originally constructed.
- Any APC will decline in benefit from the Site Acceptance Test to Zero over a period of time, t_0.

- The model for the decline is Equation (2).
- When the decline reaches the same benefit as not having the APC, the APC benefit is zero.
- When the APC is recalibrated, the benefit returns to the SAT value. The recalibrated benefit may be more or less depending on the process changes that have happened.
- The time, t_0, which represents $\tau = 1$ is application specific.
- The p-value for the shape of the decline curve is also application-specific.
- The time that represents $\tau = 1$ after sequential recalibrations will be statistically similar for any one particular installation.

IV.2.2. Calculating benefit over a calibration cycle

Based on a general approach to calculating averages, for regularly repeated recalibrations that bring the APC function back to the Site Acceptance Test (SAT) level, the average scaled benefit rate is given by the relationship:

$$\beta_{avg} = \frac{\int_0^{\tau_R} \beta d\tau}{\int_0^{\tau_R} d\tau} = \frac{\int_0^{\tau_R} \beta d\tau}{\tau_R} \quad (4)$$

τ_R = The fraction of the project lifetime without calibration to initiate recalibration, $\tau_R = t_R/t_0$. The subscript R on τ_R denotes the value of τ when recalibration occurs. For example, if the time for benefit of an unmaintained project to go to zero is two years and the APC was recalibrated at one year, the τ_R would be 0.5.

Substitute $\beta(\tau)$ from Equation (2) into Equation (4), and integrate:

$$\beta_{avg} = 1 - \frac{\tau_R^p}{p+1} \quad (5)$$

Figure 5 reveals results for the APC recalibrated at different values of τ_R

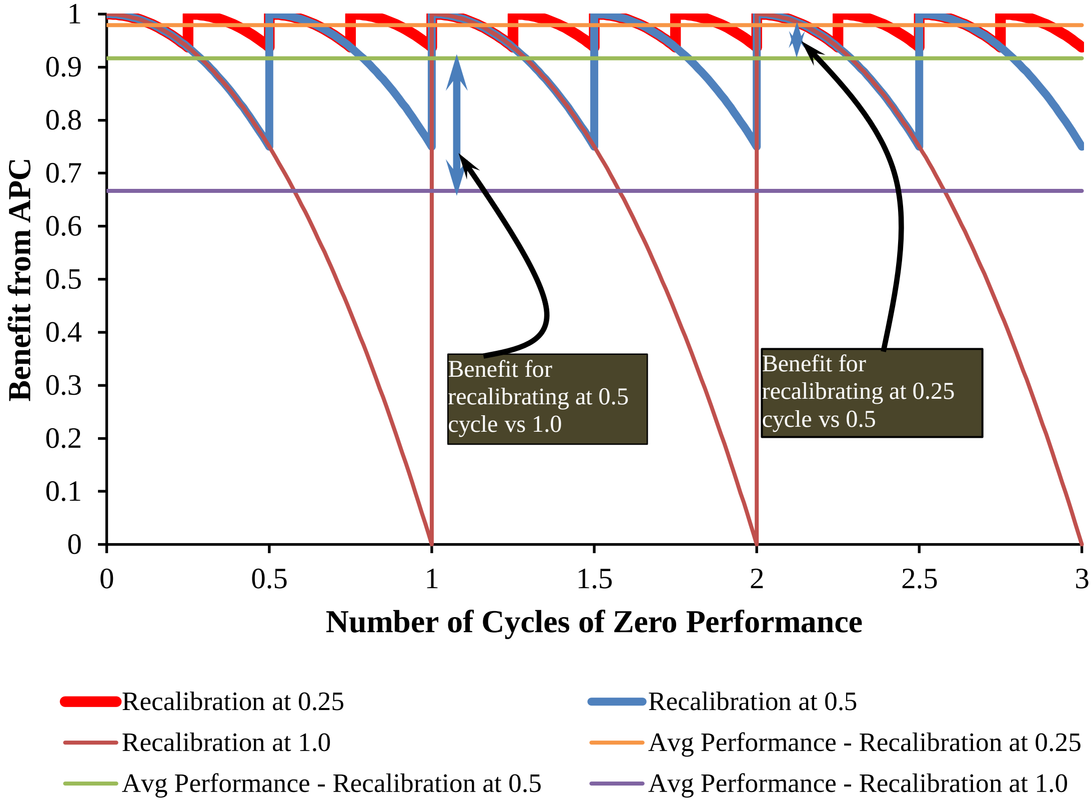

Figure 8. Recalibration Frequency Change on Scaled Benefit when p = 2.

For the example, p =2 was chosen and similar graphs can be obtained for other p values. **Figure 8** also shows the diminishing returns for recalibrating more frequently. The average values for the repeated calibrations are shown by the horizontal lines.

IV.3. DETERMINING THE OPTIMUM FREQUENCY FOR RECALIBRATION

The question for the optimum frequency to recalibrate the APC now needs to be answered.

IV.3.1. Determining The Costs

There will be costs for doing the recalibrations during the overall process of maintenance.

Each one of these recalibrations takes from 1-2 weeks to complete for the normal process. The process of recalibration of the APC can be shortened considerably by employing automated recalibration techniques; however, the time is usually on the order of half of the manual mode.

Assuming the costs for recalibration remain constant, *C* is the cost of one recalibration. If recalibrations are done at regular intervals, then the overall effective number of recalibrations per t_0 interval is:

$$N = \frac{1}{\tau_R} \tag{6}$$

Then, the cost of recalibrations over the $\tau = 1$ cycle is $NC = \frac{C}{\tau_R}$.

One can include the licensing and maintenance costs for the software. If L is the license annual fee, then the added cost over a τ cycle is Lt_0. The software licensing and maintenance costs will not affect the overall optimum schedule; however, it will affect the overall profit of the APC. The total expenses for maintaining the APC is then the following:

$$Maintenance\ expenses\ over\ a\ t_0\ period = \frac{C}{\tau_R} + Lt_0 \tag{7}$$

There are some perpetual licenses; however, it would appear the amount is small and these perpetual licenses were being phased out for at least one supplier of APC software [57]. Inclusion of the licensing and maintenance fees may be prudent to accurately account for those costs in the profit equation.

Combining the average economic equivalent value of the average benefits and the overall cost will give us an overall annual cash flow profit, P, for the APC when recalibrated on the τ_R schedule:

$$P = \left(1 - \frac{\tau_R^p}{p+1}\right) b_0 - \left(\frac{C}{\tau_R t_0} + L\right) \tag{8}$$

t = Time, the unit time

t_0 = Time to zero benefits from the APC, unit time

τ_R = Dimensionless recalibration time, t/t_0

p = Decline shape factor, dimensionless

c = Cost for one recalibration, $

b_0 = Benefits from the APC at the site acceptance test (SAT), $/unit time

L = Licensing fees for maintaining the APC software, $/unit time

Equation (8) assumes that the overall investment has been sunk in the APC, and this is an analysis of the optimum cash flow is based on the post-capital expenses. In this analysis, we are assuming the overall inflation factors for all the terms are equivalent. The equation numbering is consistent with the first part of the article.

Assuming that all factors are constant, and that τ_R is the single decision variable, the optimum of the profit can be found by the analytical method of setting the derivative of Eq. (8) to zero:

$$\left.\frac{dP}{d\tau_R}\right|_{\tau_R^*} = 0 = -\frac{p{\tau_R^*}^{p-1} b_0}{p+1} + \frac{C}{t_0 {\tau_R^*}^2} \tag{9}$$

Hence, the optimum recalibration time is the following:

$$\tau_{R\ Optimum} = {\tau_R}^* = \left(\frac{C}{b_0 t_0}\frac{(p+1)}{p}\right)^{\frac{1}{p+1}} \tag{10}$$

$${t_R}^* = t_0 \left(\frac{C}{b_0 t_0}\frac{(p+1)}{p}\right)^{\frac{1}{p+1}} \tag{11}$$

Equations (10) & (11) show that the optimum values are a function of C, b_0, t_0, and p.

We need to check to see if the solution is a maximum or a minimum by checking the second derivative of Eq. (8) with respect to τ_R:

$$\frac{d^2P}{d\tau_R^2} = -\frac{p(p-1)\tau_R^{p-2}b_0}{p+1} - \frac{2C}{t_0\tau_R^3} \qquad (12)$$

Based on Eq. (12), we can guarantee that for all $p \geq 1$, profit is at a maximum because the second derivative will always be less than zero.

IV.3.2. Calculating the Optimum Profit

The optimum annual profit can now be calculated by substituting ${\tau_R}^*$ in Equation (10) into Equation (8). The following two forms of the equation are obtained:

$$P^* = (1 - {\tau_R^*}^p)b_0 - L \qquad (13)$$

$$P^* = \left(1 - \left(\frac{C}{b_0t_0}\frac{(p+1)}{p}\right)^{\frac{p}{p+1}}\right)b_0 - L \qquad (14)$$

where P^* is the optimum annual profit based on the optimum schedule for recalibration.

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.

$$\Pi = \frac{P^*}{b_0} \qquad (15)$$

$$\Pi = 1 - {\tau_R^*}^p - \frac{L}{b_0} \qquad (16)$$

$$\Pi = 1 - \left(\frac{C}{b_0t_0}\frac{(p+1)}{p}\right)^{\frac{p}{p+1}} - \frac{L}{b_0} \qquad (17)$$

We have now expressed the entire APC cash flow profit in dimensionless terms. Nominally $0 < \Pi < 1$. As a mathematical matter if either C or L are large relative to b_0, Π can be less than zero; however, most companies would choose not to continue with the APC if Π is negative.

The same procedure of these series of equations can be applied to any process. An owner/operator can provide the values for C, L, b_0, p, or t_0, or an alternate decline model. While deriving above mathematical expression, time was used as the for finding the optimum recalibration interval. The same analysis can be extended to several criteria such as performance, cash flow, benefit, for triggering maintenance. If someone wants to observe the economic impact, they can use Eq. (16) which relates the optimum cash flow to the optimum recalibration period. Eq.(2) does the same for the decline in performance. Those are of use to translate the reschedule period to an alternate trigger for recalibration.

IV.4. IMPLICATIONS OF THE EQUATIONS

Based on the developed overall equations, many conclusions can be made. One use of the developed equation relates to the profit. **Table 1** was constructed to show the relative effects of changing the different inputs to the dimensionless profit equation.

Column 1 of the table shows the power values of the decline model that seem reasonable (for p = 2 or 3). One finding is that if the $\frac{C}{b_0 t_0}$ values are less than 0.01, then Column 5 shows that the dimensionless profit numbers are greater than 0.92 (92%) of the SAT benefits claimed for the installed project. (They cannot sustain the SAT value because of the gradual decline in functionality and periodic recalibration costs.) As the $\frac{C}{b_0 t_0}$ values grow, there is a decline in benefits. When the $\frac{C}{b_0 t_0}$ values grow to 0.1 the dimensionless profit drops to around 70% of the SAT claimed benefits. Anticipating values for the periodic recalibration cost and the economic equivalent benefit will reveal the portion of long-term benefits to be expected.

Table 1 Examples showing the effect of C/b_0t_0 on τ_R^* and Π Sensitivity

p	$\frac{C}{b_0 t_0}$	$\tau_R{}^*$	Effective number of Maintenance Intervals per Cycle, $= 1/\tau_R{}^*$	***Π*** Assuming $L = 0$	***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

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

Third, the last two columns of the table reveal that changes of ± 0.1 to the scaled recalibration interval have a relatively low impact on the overall value of ***Π*.** This is good news. If the optimum calibration interval is $\tau_R{}^* = 0.5$ then recalibrating at values of $\tau_R{}^* = 0.6$ or $\tau_R{}^* = 0.4$ do not have a significant impact on the expected economic benefit. If the value $\tau_R = 1$ represents a 2.5-year life, then $\tau_R{}^* \pm 0.1$ represents a several month interval. The calibration can be scheduled at convenient times.

Fourth, knowing the exact power of the decline curve model is not essential. The middle two rows of the table compare the *Π*- and $\tau_R{}^*$-values when p=2 and 3. With $\frac{C}{b_0 t_0} = 0.01$ the *Π*-values are 0.94 and 0.96, and the $\tau_R{}^*$-values are within the uncertainty that has an inconsequential impact. With $\frac{C}{b_0 t_0} = 0.1$ the Π-values are 0.72 and 0.78, and the $\tau_R{}^*$-values are well within the uncertainty that has an inconsequential impact. Approximate knowledge of the p-values will be adequate.

Fifth, Column 4 shows that the optimum number of recalibrations is from 2 to 8 over the nominal 2.5-year period of the functional life if unrecalibrated. This indicates that a recalibration interval could be between 3 to 12 months, which is much more frequent than turnarounds for physical process major maintenance. The APC major maintenance schedule should not be expected to match the plant turn-around schedule.

Sixth, 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 $p = 2$ or 0.75 for $p = 3$, the value of Π will be zero. This means for purposes other than throughput requirements the value of the APC needs to be well known by the owner/user. Safety, environmental and quality reasons for the benefit tend to be more variable and difficult to assign economic value than throughput considerations.

IV.4.1 Graphical representation.

Using Equation (10) in the dimensionless form, the effect of recalibration interval on the profit was estimated for various values of $C/(b_0 t_0)$ with p = 2. ln these calculations, the licensing cost (L.) was considered to be negligible. The optima for each of these curves rest on a fairly flat area of the curves, then the curves decline in a steep pattern on either side of the flat portion. The locus of all recalibration optima is presented showing the point at which recalibration occurs too frequently or too infrequently. Similar trends are observed for other p values with each line shifting on the x-axis, **Figure 9**.

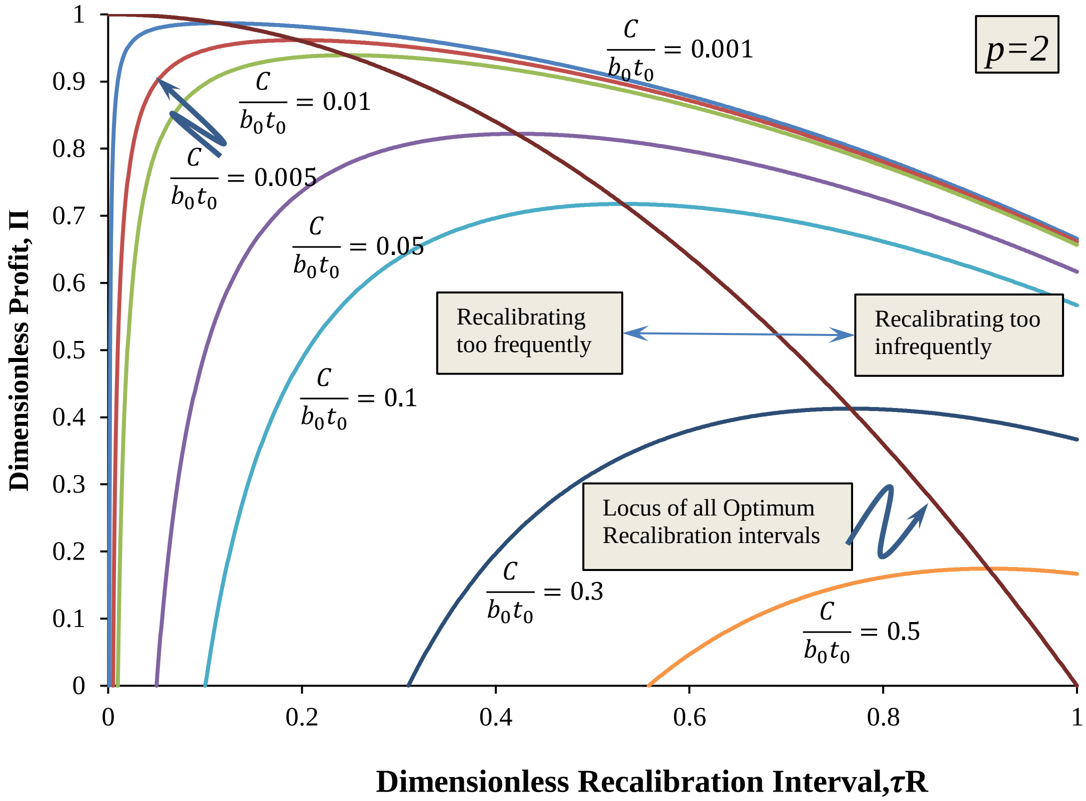

Figure 9. Profit Optima with p=2 for different values of C/b_0t_0

Negative dimensionless profit numbers are not shown under high recalibration frequencies (low intervals). Further, the optima are close together for low values of $C/(b_0t_0)$ (0.001 - 0.01) and the optimum dimensionless profits are very close to these ranges. Some of the takeaway messages are as follows: fiat optimal region indicates that the exact timing for the recalibration is not essential; the exact functionality of the decline curve is not important, and a substantial uncertainty on the $C/(b_0t_0)$ value is not critical.

IV.4.2 Example Calculation:

The owner/operator must choose the most appropriate values of C, b_0, L, t_0 and n

that represent their process. It does appear from the notional publications that $n = 2$ is the most appropriate for the decline curve; however, higher estimates are possible. What this means for implementation is the following: for the decline to zero time of two years, performing the maintenance every six months would appear to be appropriate. This would imply costs for doing the maintenance must be very low.

- Estimation of C: The costs to do a step testing regime would occupy an engineer 1-2 weeks. Assuming that engineer earns $200,000/year, and a factor of 2.7 times the base salary to get to the total employee cost [22], two weeks of engineering time would cost about $21,600. If step testing is done during production with small changes that do not cause economic upsets, then the process cost of recalibration is zero.
- Estimation of the optimum long term benefit: Assuming that the period $\tau = 1$ is 2 years and $p = 2$. The amount of total return that would be supported by this maintenance fee would be $2.076 million or $1.038 million/yr. The optimum cash flow would then be 0.9375*1.038 million/yr or $973,000/yr. Any capital projects basis should not be based on the SAT initial expectations, but on the benefit after the decline and recalibration costs are considered.

IV.5. DISCUSSIONS

IV.5.1. Maintenance Techniques

The maintenance techniques are two-fold for attempting to maintain the overall APC performance at the SAT performance level. Following is a brief description of each of the maintenance techniques.

- Step testing – This is the same sort of step testing that was initially used to install APC in the first place. This step testing can be done with either an automated program or manually. The automated programs that can halve the time of manual testing. In any case, the time of recalibration is dependent on the number of loops involved in the step testing.
- Comprehensive Program to Tune the Underlying PID Controllers – Typically with the installation of an APC, retuning all the underlying PID controllers involved in the APC will be required. Continuing maintenance of the PID controllers can serve to prolong the overall system or can reset the performance to something close to what was done for the APC initially. The reasons for re-tuning the base level PID controllers are the same for recalibrating the APC models.

IV.5.2. Experience Reduction in Recalibration Cost

While deriving the above equations, the cost for recalibration is assumed constant. However, the recalibration cost should decrease with increasing experience. Boston Consulting group studied several different modes for the reduction in the cost to produce different products [38, 39, 58]. In this case, the product would be recalibrated APCs. The cost of producing these products decreased by 20-30% for every doubling of production. Additional research needs to be completed to develop specific curves for different units (e.g., FCC, LNG, etc.) to check if there are unit-specific decline rates for these curves. Decline rates as high as 50% for each doubling has been seen for hard drive production. The research will need to focus on the overall trends seen. Adaptive modeling and step testing are two methods for recalibration. Adaptive modeling may be an evolutionary development in technology to reduce the cost of doing the recalibration.

IV.5.3. Turnaround Times vs APC Maintenance Intervals

Typical maintenance shutdown intervals for refinery and LNG facilities are very long and getting longer and far exceed the typical length of the uncalibrated APC time to zero benefits. Times for many refineries and other process times are listed in **Table 2**. Typical $\tau = 1$ lengths for APC projects are on the order of 1.5-3 years [9, 10, 19]. The turnarounds and the recalibrations, therefore, need to be decoupled.

Table 2. Unit Turnaround Times

<table>
<tr><th>Unit</th><th>One US Refiner [49]</th><th>European Refining Study [59]</th><th>Performance Management [60]</th><th>Risk Management [61]</th></tr>
<tr><td>Crude Unit</td><td>4</td><td rowspan="4">3-6</td><td>>4</td><td></td></tr>
<tr><td>Fluidized Catalytic Cracking Unit</td><td>5</td><td>3.5</td><td></td></tr>
<tr><td>Delayed Coking Unit</td><td>5</td><td></td><td></td></tr>
<tr><td>Reforming Unit</td><td>2</td><td></td><td></td></tr>
<tr><td>LNG Gas Trains (Major Turnaround</td><td></td><td></td><td>6</td><td rowspan="3">2.7 years Limited in general by the LNG Subcooling</td></tr>
<tr><td>LNG Gas Trains Turbines</td><td></td><td></td><td>5.5-6</td></tr>
<tr><td>LNG Gas Trains Hot Gas pass</td><td></td><td></td><td>3</td></tr>
</table>

The future trend is for even longer turnaround intervals. Jakubowski and Karlsson suggest turnaround intervals as high as 8 years may be possible [59]. Internal inspection of some vessels currently is listed as 10 years; however, even that could be breached if the risk profile of the vessels is low enough.

IV.5.4. Monitoring

At the site acceptance test (SAT) there will be information taken to show that the installation meets the project objectives. One of these objectives will be the value of the benefits generated by the project. A method to calculate this benefit over time should be implemented to track this variable as the decline occurs in the overall performance. This way the owner/user will be able to track the performance and develop the decline curve for the process they have. A good way to do this is to enable a calculator within the DCS to provide that information on a real-time basis. One has to perform rigorous detailed SAT calculations open loop in process engineering reports (daily, weekly, or monthly). Once the basis has been calculated in the SAT, the performance can be calculated online using the SAT methods with a tag to track the benefits.

This could form the basis of a data collection process to be used later to catalog the industry data and make sure there is a sound basis for optimization. There are analytical techniques employed here were the optimum maintenance period can be established. When these maintenance period analyses are employed more APCs can continue to operate within processes. Other factors such as management systems and technical support may impact the overall function of APC life.

Note that the derived maintainance equation assumes that the overall investment has been sunk in the APC, and this is an analysis of the optimum cash flow is based on the post-capital expenses. In this analysis, we are assuming the overall inflation factors for all the terms are equivalent.

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CHAPTER V

MODEL INSENSITIVITY

V.1. INTRODUCTION.

Advanced Process Control (APC) is the industrial term for a control system that includes model predictive control (MPC) as well as other features such as supervisory setpoint optimization and data reconciliation. MPC typically uses a linear and stationary model for feedforward-tempered, multivariable, constraint-handling, horizon predictive control. Typically giving better control than single loop PID or classical advanced techniques (cascade, ratio, override), APC permits operating a process closer to constraints, which can be translated to an increase in throughput (or equivalently lower waste) and lower operating expenses [2, 20, 27, 62]. Although relatively expensive, APC can have a pay-back time of less than a year [3, 63], making it economically attractive.

Unfortunately, processes change in attributes due to reactivity changes, raw material compositions, fouling, efficiency, etc.; and the process can change in operating points due to market shifts in yield distribution or product demand. As these changes happen, the original MPC model progressively becomes less tuned to the process [19, 64]. And, as the process continues to drift toward other behaviors, the linear stationary model progressively becomes dis-functional – sluggish, too aggressive, poorly predicting feedforward impact, continually requiring operator intervention, and/or etc. In some instances, portions of the controller are sequentially turned off. But, eventually, the entire APC is placed off-line [10, 17].

Recalibration could restore full economic benefit. In recalibration, the models are refreshed by step testing and the structure is reviewed to ensure that input and controlled variables are still relevant. Recalibration is not a trivial economic cost, but it costs less than the initial installation. One question is, what is the optimum recalibration interval?

In [65, 66] the authors modeled the progressive decline in the economic benefit of an APC installation with a power law, a simple relation that seemed to match notional, subjective representations that were revealed by industrial experts [10, 17, 19].

$$B(t) = a - bt^p \tag{18}$$

Where B is the economic benefit of the APC, \$/time, 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

$$B'(t') = 1 - t'^p \tag{19}$$

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 [65]. Also, since the APC is usually turned off prior to hitting zero functional benefits, the right-hand portion of the curve is somewhat uncharacterized. A consensus of experts [17, 19], however, indicate that the decline starts gradually, then accelerates. And discussion among experts [55, 56] seems to reveal that the p-value might be between about 2 and 5.

Using Equation (11), the optimum period for recalibration, $t_R{}^*$, can be analytically derived. The result is [65] where C is the 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 36 months, the $t_R{}^*$ values might range from 3 to 12 months, depending on expected values of Equation (11) coefficients over the next operating interval. When the expected life of an APC project is 36 months, 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, restoration, and renovation, the frequent recalibration of the APC is often unexpected when management is considering capital projects.

There is uncertainty in the values used in Equation (11). After each recalibration, the plant situation changes. One question that needs to be answered is how sensitive is the recalibration interval to uncertainty in the coefficient values of Equation (11)? It is not too difficult to do either a numerical or analytical propagation of uncertainty exercise on Equation (11) to answer that question, but there is another question to come.

Other decline models may be more appropriate, such as a logistic model that indicates a similar initial decline (slowly then accelerating), but at the end asymptotically approaching zero benefits rather than crashing to zero.

$$B(t) = \frac{1}{1+e^{s(c-t)}} \tag{20}$$

Here “s” is a scaling factor and c is the time when the economic benefit is 50% of the initial value.

Figure 10 compares the power-law (solid line) and logistic (dashed line) decline models. The power-law decline is cubic ($p = 3$) with $t_0 = 30$ months. The logistic model with $s = 0.35$ month^{-1} and $c = 22$ months is a reasonable approximation. Note that for any set of choices for p and t_0, a set of logistic model coefficient values can be found to provide similar early-stage decline. There is inadequate data to indicate the post-50% behavior.

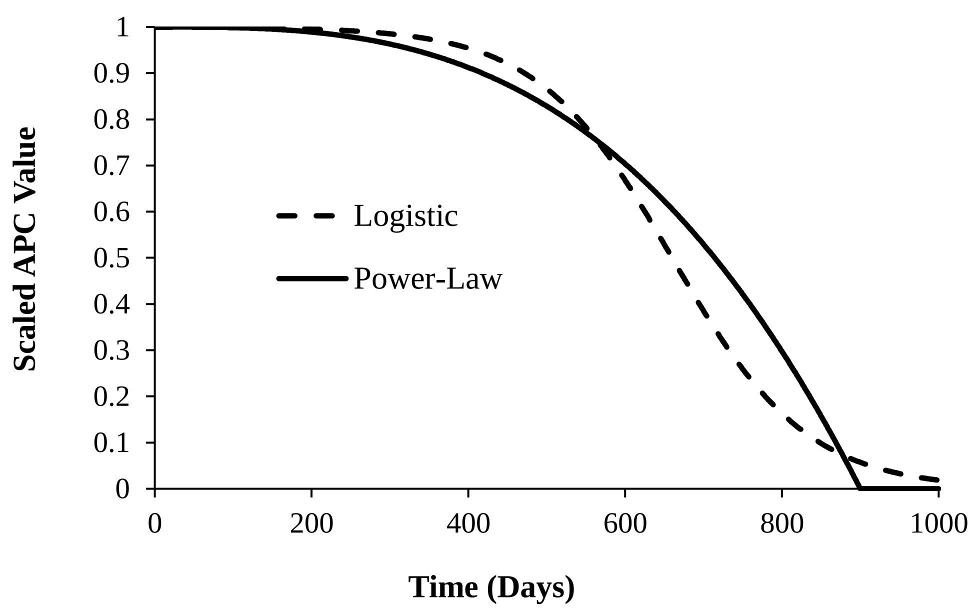

Figure 10. Decline Models (Power-Law solid curve, Logistic dashed curve).

Decline Equation (20) is not as mathematically convenient for determining the optimum time interval for recalibration, $t_R{}^*$. And, there may be a collection of alternate models that might provide a better representation of the decline, which include step reductions in $B(t)$ in response to changes in raw material, scheduled product distribution, or equipment or piping changes. Such models may not have a smooth decline, nor an analytical optimum.

So, another question is how to determine the optimum within uncertainty for non-analytical decline models? A procedure provided by [67] is employed in this study.

V.2. METHOD

I use an optimization method, in which the objective function (OF) is the overall benefit (economic benefit of the APC installation over time, less the cost of each recalibration) as measured by net present value (NPV) over a 10-year horizon. The ideal optimum for the recalibration schedule will be from Equation (3), but this might not be true if the decline model is not the ideal power-law, also with uncertainty in coefficient values and events in the future. Accordingly, the decision variable (DV) is a multiplier for the Equation (11) $t_R{}^*$ to correct the number of days to begin the next recalibration.

At each day during the simulation horizon, the values for each model and economic coefficients are randomly sampled from a range of possible values (about $\pm$15% of nominal). The nominal values, in Table 3, are representative of values reported in numerous publications or presentations [68].

Table 3 Nominal Economic and Model Values.

Capital	400,000	$
License	1,000	$/month
Vmax	100,000	$/month
Recalibration	120,000	$ per event
APC Life	15	Years
s	0.35	logistic decline model scale factor, months^{-1}
c	22	logistic decline model center, months
ADR	10	% per year, discount rate
p	3	power-law decline model power
t0	30	power-law decline model time-to-zero, months

Because of the uncertainty in coefficient values over the next recalibration interval, the OF is stochastic. In any particular 10-year simulation for NPV calculation, the vagaries of coefficient values will lead to a stochastic outcome. **Figure 11** presents one realization.

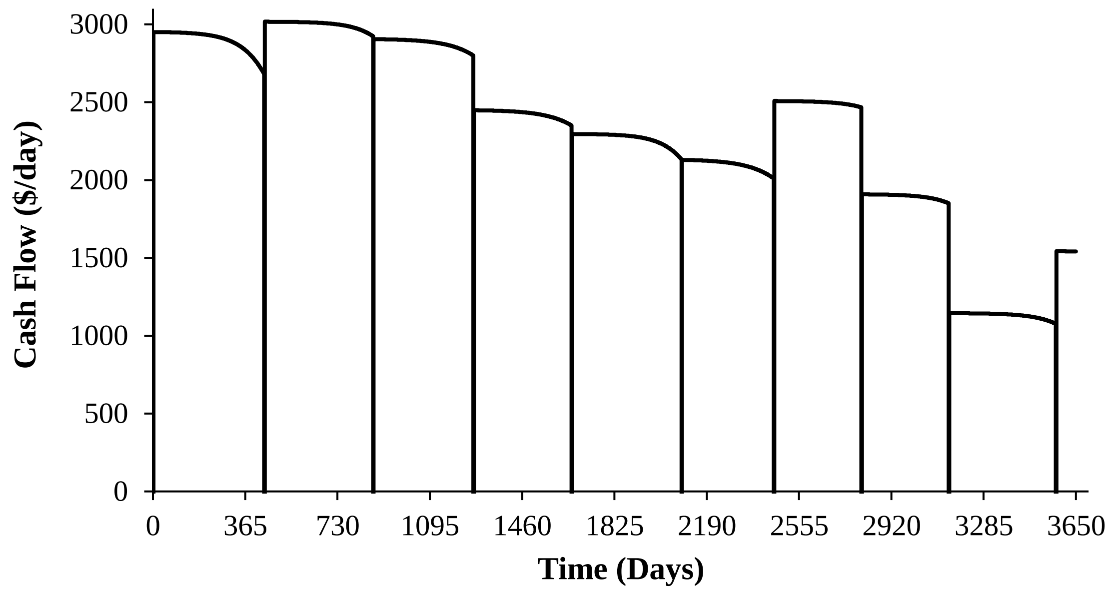

Figure 11. Daily Cash Flow over a Ten-Year Horizon.

The vertical lines represent recalibration events, a negative cash flow. The tops of the shapes represent the economic benefit of the APC project. Note the irregularity in the shape of the decline in each interval and the irregular length of the recalibration interval are due to the ±15% period-to-period vagaries in the model coefficient values.

The NPV horizon is 10 years (3650 days). Each interval begins with a calibration exercise which restores the economic benefit to its maximum possible given the vagaries of the time. Without recalibration, the economic benefit would decline toward zero. Note also that the time duration of the last interval is about 2/3rds of the others and does not close with a recalibration. Depending on the vagaries, a particular realization might have the last recalibration just one day before the end of the 10-year horizon. If this happens, the last calibration is a cost that is not recovered. Alternately, the last interval might be nearly complete, and the 10-year NPV horizon end just prior to wasting investment in a final recalibration. Even with no uncertainty on coefficient values, the deterministic optimization has discontinuities in the OF, as shown in **Figure 12**.

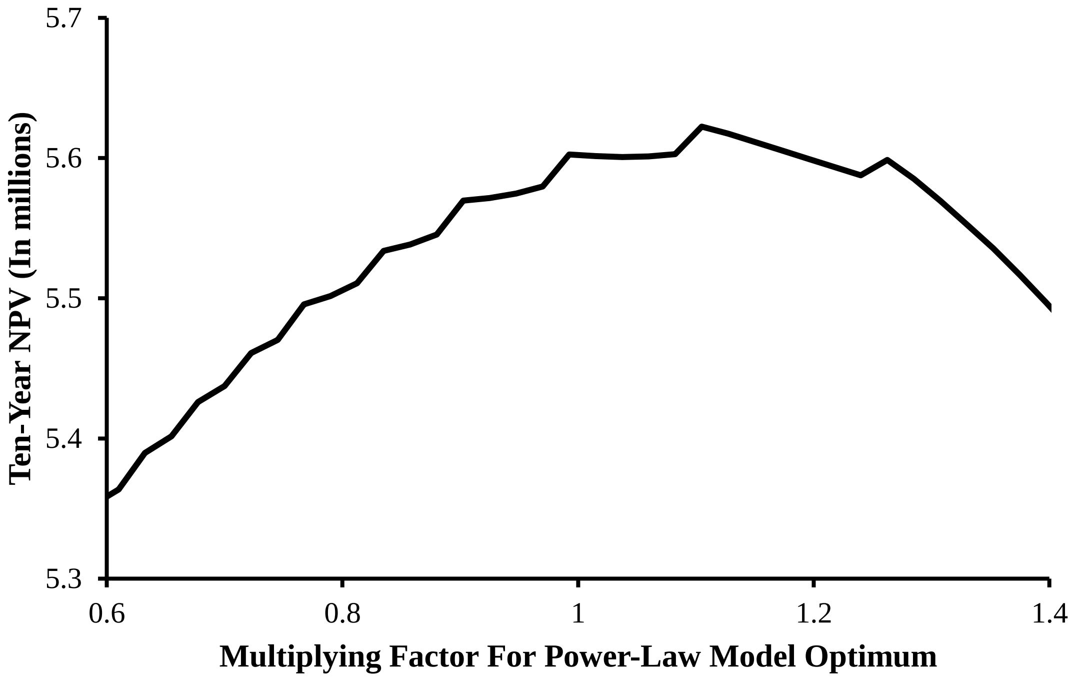

Figure 12. NPV with respect to the multiplier for τ_R^* A deterministic study.

Although time seems to be a continuum variable, the schedule must be discrete. Here, the optimum time to recalibrate is discretized by days. Because of this, the optimizer senses flat spots, where small changes in the DV does not create a new day, and the OF remains the same. So, an optimizer needs to be able to handle discretization flat spots, as well as multiple optima with discontinuities.

The OF is stochastic, with DV flat spots between discontinuities. Many standard optimizers cannot cope with such OF aberrations.

This study uses a multiplayer, direct-search optimizer to search for the optimum. This study uses Leapfrogging [69] a technique in which the worst player leaps over the best player to a random location in the reflected DV space. Before a move, however, the OF value of the best player is reevaluated, and the worst of replicate evaluations is used as the player value. If what was the best player does not remain the best, use the remaining best player to guide the search. Since the OF is stochastic, conventional criteria for convergence cannot be used. This work uses a steady-state identifier on the iteration sequence of the worst OF value to determine convergence [70].

V.3. RESULTS

The dotted curve in **Figure 13** presents NPV with respect to the multiplier value for the power-law model to determine the recalibration interval. The dotted line is generated by incrementing the multiplier value from 0.25 to 2.5 and calling the simulation to generate the associated NPV. Since each simulation is comprised of a unique confluence of randomized coefficient values, the curve is a stochastic response. Each replicate of the curve generates a trend with a unique ‘noise’ pattern. Each peak and valley on the curve is a phantom appearance of what it could be. With no uncertainty, the curve is a smooth concave trend between the local high and low values.

The vertical axis is the Net Present Value (NPV) as the measure of project goodness. The horizontal axis is a multiplier for the power-law optimum day to recalibrate.

If, for instance, Equation (11) indicates to recalibrate after 500 days, then a factor of 1.2 means wait 600 days.

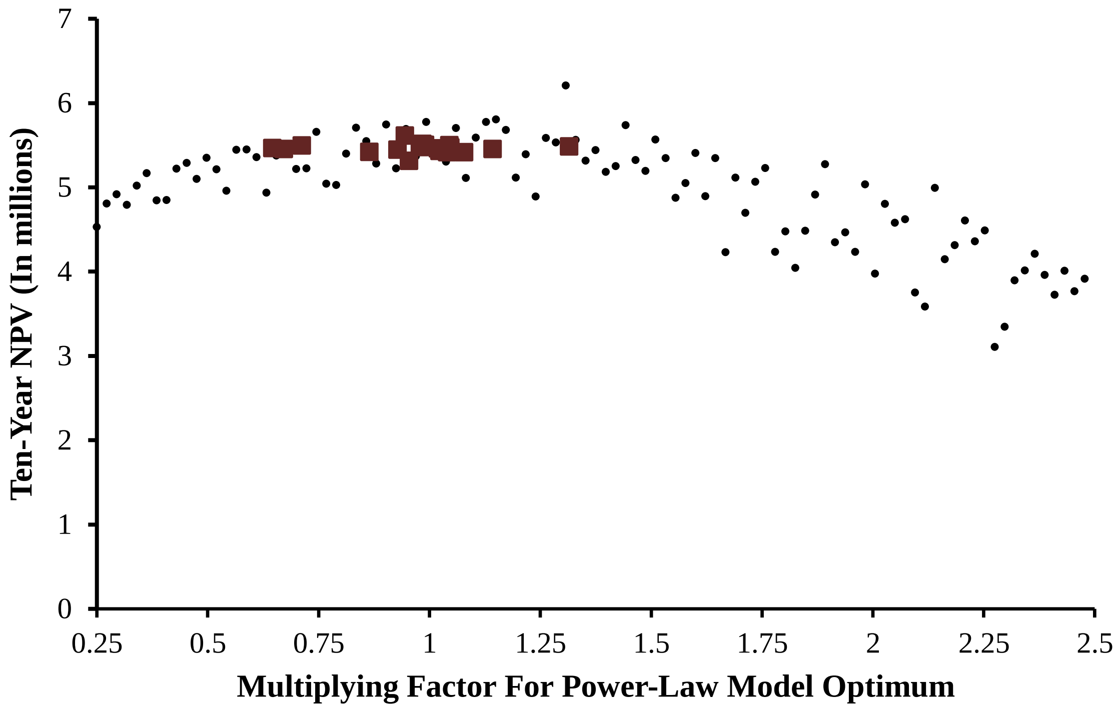

Figure 13. One NPV realization and Player Positions at Convergence.

The large dots in **Figure 13** are the converged player positions (multiplier values and associated NPV values) from one Leapfrogging optimization. No particular player is statistically superior to another; as a result, the optimization does not converge to one point. Convergence stops the leap-overs when there is no statistical improvement in the worst player outcome. Here, the results indicate that any recalibration period from about 75% to 125% of the nominal $t_R{}^*$ predicted by Equation (11) is as good as another. There is not a single point best because of uncertainties over the future horizon of each recalibration period.

V.4. DISCUSSION.

This case study affirms the findings of [67] and demonstrates an approach to optimizing and assessing convergence on a stochastic function, which is characteristic of economic optimization with uncertainty.

Although Leapfrogging [69] was used here, it seems logical that any multiplayer optimization algorithm (particle swarm, differential evolution, etc.) could be employed. Although one particular method for identifying a steady-state was used here [70], it seems that any legitimate technique could work as well.

The center of the range of player values is nearly 1. This means that the power law approximation to the actual decline leads to a very good estimate of the optimum time to reschedule, even if the power-law is not the true mechanism of decline in the simulation. The range of players is about 0.75 to 1.25, and all have about the same NPV value. In this particular simulation, the nominal optimum interval for recalibration is 434 days. The range of players indicates that any recalibration day within 326 to 543 days is essentially the same for NPV economics. This is good news.

There is significant flexibility in scheduling a recalibration. The graph indicates that if the recalibration period is extended to be 2 times the optimum, however, the NPV loss can be significant. A message to those running APC is to do the recalibration.

The uncertainty in economic factors is ±15%. But, the message is not changed with alternate reasonable values in forecasting events. The specific values of the capital and recalibration costs, of the annual economic benefit, and the rate of decline associated with a particular operation can affect the optimum recalibration schedule, but the concepts and methods of analysis remain the same. For a variety of "givens", the results consistently indicate a recalibration period between 75% and 125% of that indicated by Equation (3) is fully acceptable, and best within uncertainty.

Monitoring the change in APC benefit over time is an essential aspect of monitoring the APC operation. Don't stop observing and auditing the APC application after the site acceptance test. As discussed earlier, the decline in performance is slow at first and then accelerates to make that concave down structure in the decline curve as represented in Figure 1 One major LNG plant was shown to have a 20% decline in performance after one year [62]. This performance was consistent with a 2.2-year life and a p coefficient value of near 2 [56].

Expect that experience after each recalibration will lead to lower recalibration costs and improved APC performance [38]. The recalibration costs of this study are based on employee-guided recalibration. There is a movement toward automatic recalibrations, as demonstrated on both [41] and larger installations [32, 42].

It seems reasonable that one could observe model error distributions over time and trigger recalibration on model error [41], or trigger recalibration when monitoring the weekly performance value of the APC project shows it to be declining. But today, conventional practice does not use such.

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CHAPTER VI

APC CAPITAL EVALUATIONS IN THE PLANT ENVIRONMENT

VI.1. INTRODUCTION.

The Operating Expense (OPEX) budget process 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 in this category of funds than for the Capital Expense (CAPEX) budget. The company rules, which should adhere to the taxation policies, around improvement of the process, and the depreciations are followed. The procedure usually follows practices around the ethical treatment of the funds.

This chapter provides an overall process for CAPEX on APCs. The calculations are explored as well as a variability for the different parameters. 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. Different scales to determine the scope of the APC project are presented. 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. Expectations that should be taken before a project is undertaken are defined in this article. The focus is on ensuring 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.

VI.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.

VI.2.1. Scaling Capital Costs

Much of the expenses and the one-time expenditure are scaled by the size of the APC. 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 [29].

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 14**, 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 aworldwide implementation of APC. In general, the primary variables in the overall cost of an APC are the MVs, the APC outputs that cause a 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 [4, 32] and 24 for a hydrotreater [71].

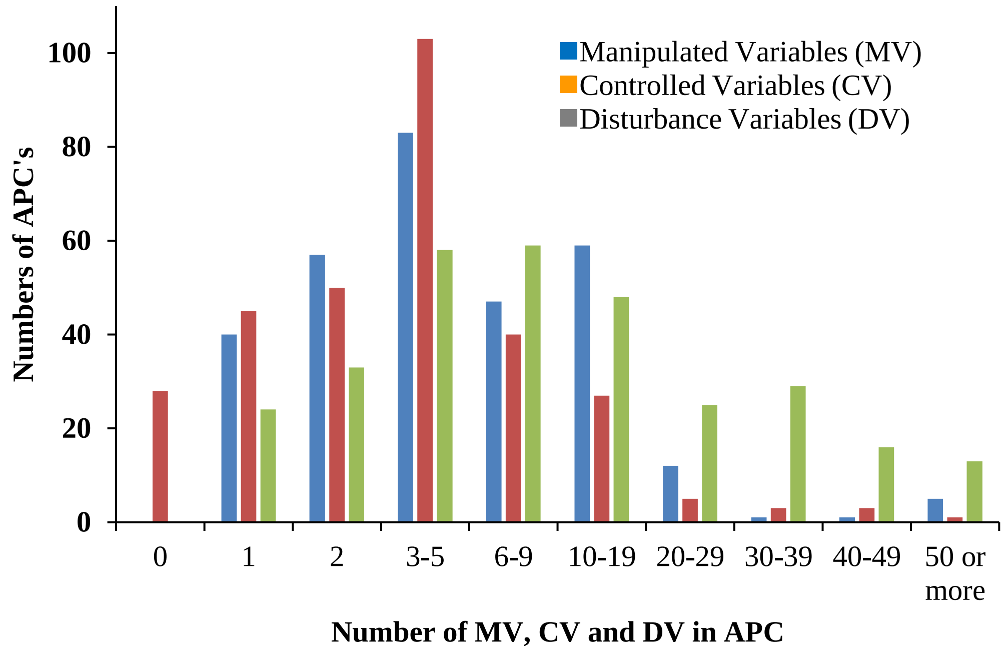

Figure 14. Distribution of number of APCs with the number of MV, CV and DV [29]

In addition to these variables, there are special controlled variables that require significant attention. These are referred to as inferred variables. Some refer to these inferred variables as “soft sensors” [4]. 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 4**, some of the inferred variables that have been used in regulatory control or in conjunction with an APC are listed.

Table 4 Examples of Inferred Variables

Stream/Product	Inferred Variable	Reference
Diesel	Initial Boiling Point	[4]
Diesel	End Point	[4]
Diesel	Vaporization up to 360°C	[4]
Jet	95% Distillation Point	[32]
Kerosene	End Point	[4]
Kerosene	Cloud Point	[4]
Kerosene	95% Distillation Point	[32]
Kerosene	Flash Point	[72]
Naphtha	95% Distillation Point	[72]
Residuum	Kinematic Viscosity	[4]
Vacuum Gas Oil	Initial Boiling Point	[4]
Vacuum Gas Oil	End Point	[4]
Vacuum Naphtha	95% Distillation Point	[32]
Reactor Effluent	Ethylene Selectivity	[73]
Stabilizer Bottom	Sulfur Content	[71]

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 [74, 75]. 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 [75].

VI.2.2. Workflow

Based on the literature review on the APC project workflow, various steps involved in the process are detailed in **Table 5**. These are written from the beginning of the work to the end of the APC project.

Table 5 APC Project Workflow Steps

<table>
<tr><th rowspan="2">Workflow Step</th><th colspan="4">References</th></tr>
<tr><th>[1]</th><th>[27]</th><th>[26]</th><th>[23]</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 the dynamic model.</td></tr>
<tr><td>4</td><td>Plant Step Test</td><td>Plant testing to generate the data required to develop a dynamic model of the process</td><td>Plant Testing</td><td>Designing the real-time database – Includes step testing</td></tr>
<tr><td>5</td><td>APC Controller Development</td><td>Model identification to develop a dynamic model using plant test data.</td><td>Model and Controller development</td><td>Designing the real-time database / Model-based control</td></tr>
</table>

Workflow Step	References			
	[1]	[27]	[26]	[23]
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 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 15** 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) usually are adequate.

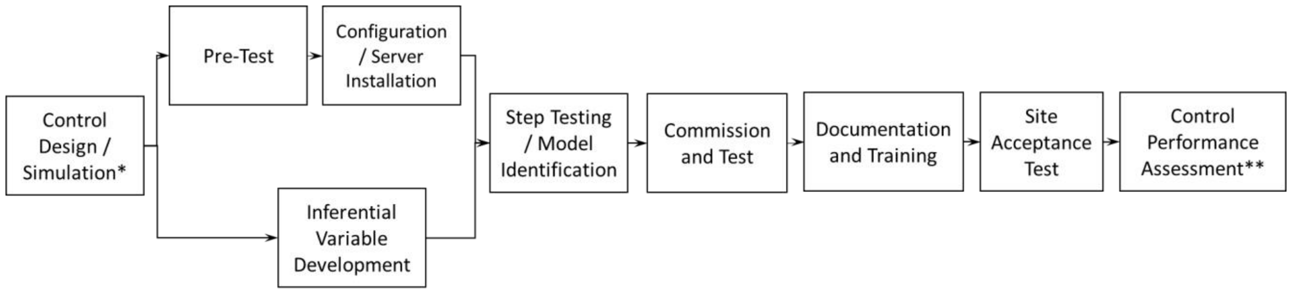

Figure 15. APC Development Workflow Chart. *This step could include Hardware Upgrades. Also, the need for inferential variables. ** This step is optional but recommended

Following is a description of each stage in Figure 11

1. <u>Control Design/Simulation</u> –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 [1]. Based on these analyses two simultaneous steps are pursued.

2. <u>Inferential Variable (IV) Development</u> – 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. <u>Pre-Test</u> – 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 [32, 42]. 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 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 [20]. 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 [76].

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 [4, 77, 78]. This point has been falling out of favor[35]; 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. [4]

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 [4] or economic assessment [2]. 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. [4]

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.

VI.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 6)** 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 6 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 the controller scope (LIC, PIC)
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[32, 42]; 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.

#	Line Item	Unit	Quantity	Comments
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." [79] 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.

VI.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 16**. [80]

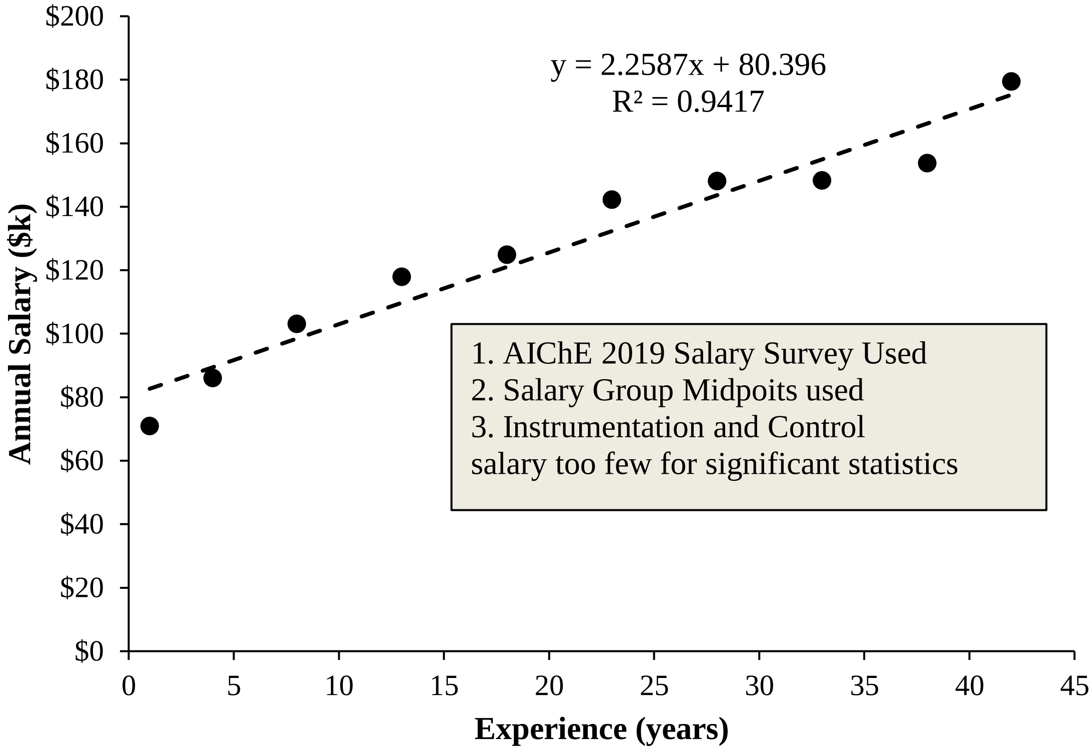

Figure 16. Data from "2019 AIChE Salary Survey"[80].

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. [22] 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. [36, 81]

VI.2.5. Example Case Study

The following is an example where the capital installation costs can help estimate the continuing maintenance expenses for the project. In this example of an APC project, there are two MVs and two inferred variables. Cost estimation is shown in **Table 7**.

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).

Table 7 Example Calculation - 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 2.3 (Internal resource charged at $135/work hr)

How does the Cost Estimation Model Stand Up to Actual Data?

Most members of the process industries were circumspect about releasing commercial information on estimation to compare the estimates against actual data from installed APC projects. Some data were developed through an article describing APC installations in the pulp and paper industry in Brazil (Cenibra company). The data were acquired through personal correspondence. The initial publication listed the projects for which there were cost data [68, 82].

Figure17 shows the comparison to two different sets of cases to the actual data presented by Ronaldo Ribeiro: One set of data represents a range of manipulated variables (MV) based on a contractor cost of $225/hr. The second set of data shows a curve with a slope prepared from $135/hr. The $135/hr represents internal company costs for an engineer making $100,000 annually.

The analyses of these data from Brazil shows the following:

1. The correlation to the MV is a valid conclusion by the providers of technology and the owner-operator model developed for the cost model of the APC. Note that for this small data set the correlation coefficient is high (0.9865). A larger dataset of installation costs compared with the major variables contained in this report would further validate the crowd knowledge values and regional differences.
2. The slope of the cost relationship is bounded by the two cases (using contract manpower and using in-company resources). It is difficult to know the exact nature of the APC development contract because of confidentiality concerns. The slope could also be identified more precisely with a larger dataset or with a larger crowd knowledge sample.
3. There may be as yet unexplained geographical differences for implementing APC in Brazil. The size of the intercept was discussed with other resources in the USA[83]. There was agreement that "set up costs" for Brazil would be higher for engineers coming from the USA; however, the size of the setup costs would be much lower than that exhibited in the chart.

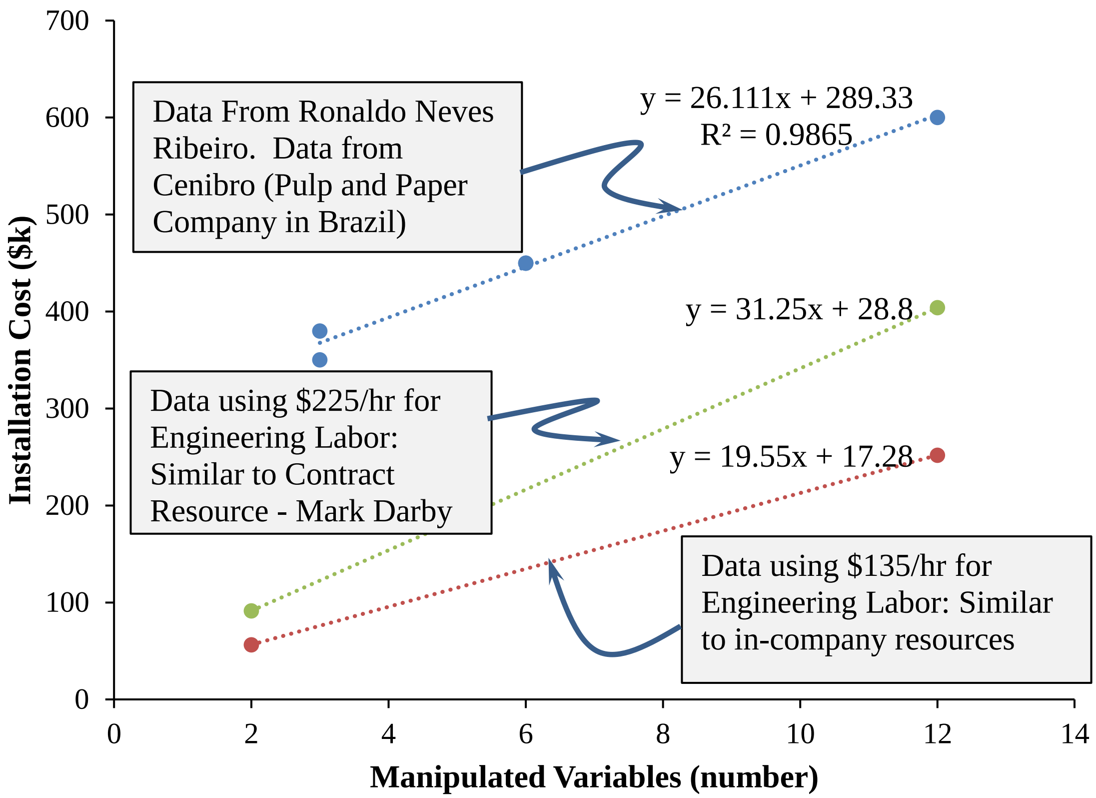

Figure 17. Comparison of Cenibra (Brazil) data with Cost Model.

VI.2.6. Continuing Expenses

Thus far, we have detailed an approach to arrive at the one-time expenses 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.

The equations governing the continuing expenses are covered in the Maintenance Chapter. Repeating them here would be a duplication. The optimum interval and the maintenance cost can be derived from the capital equations and are thus interdependent calculations.

VI. 3. MAINTENANCE PROGRAM

VI.3.1. Sensitivity to Uncertainty in Parameter Values

Table 1 shows values for the sensitivity of the Π value based on *p* and $\frac{C}{b_0 t_0}$. 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, some variables 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.

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 Π 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 Π. 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 $b_0 t_0$.

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. Hence, 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 comprises of procedures to include economics of safety or environmental reasons with 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 proprietary method for determining these costs for the base safety or environmental events.

VI. 3.2. Sample Calculation and Planning

To better understand the developed model, a sample calculation of the critical capital parameters based on our project with 2 manipulated variables and 2 inferred variables is provided in this section. The value of $500,000 is commensurate with several projects of this size mentioned in the literature [68, 84]. The maintenance frequency and the maintenance cost are programmed into the budget and the operating schedule. Below is a sample calculation estimating the budget:

a) Estimate t_0 – The general time to zero performance listed in the literature is 2-3 years [17, 19]. For our calculation, 2.22 value was selected based on an LNG plant data in the literature [56].

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 $\frac{C}{b_0 t_0} = \frac{\$11{,}880}{\frac{\$500{,}000}{yr} \times 2.22 yr} = 0.0107$

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 (or 6.7 months) is based on manual step testing. Significant savings could be achieved through automatic step testing [32, 41, 42]. 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

$$(0.93981-0.92463)\times\$500{,}000 = \$7{,}590/\text{yr}.$$

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.

VI. 3.3. 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 monthly because companies will analyze books monthly and the payout period was so short for this example. A project life of 15 years was chosen because a typical unit life is 20 years and this is putting an APC five years after the unit was started.

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 $3.4 million, **Table 8**. 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 8 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 [85]
Internal Rate of Return (IRR%)	600%	The analysis was done per month. The value here is the annual equivalent rate.[85]

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 declined to zero then the credibility of the people that proposed the high return project is in jeopardy. It is essential to strategize the APC recalibration as a planned event before the APC is adopted and recognition that the APC value could decline to zero if recalibration is not done.

VI. 3.4. Continuous Monitoring

The optimal recalibration schedule was estimated from a generic model, Equation (1), which qualitatively matches general experience. Utilizing Equation (1) is using *a priori* (without experiment) theory. Exact experience, specific to a particular process, 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, one should use their best extrapolation of experience when including the decline model and optimum recalibration schedule in capital planning. But once installed, we strongly recommend weekly monitoring of the APC performance to monitor the changes that will happen, and adjust a recalibration interval based on this *a posteriori* knowledge, rather than sticking to the *a priori* model necessary for capital planning.

VI. 3.5. Continuous Improvement

In the next chapter, I discuss the continuous improvement, which 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 is defined by experience according to learning curves. The decreased unit cost for recalibration has the net effect of increasing the return by decreasing the cost and increasing the Π value. Second, there can be an improvement to the income by taking learnings 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 study; however, the owner/user must have active programs to address each component (income and cost) to realize continuous improvement affects.

CHAPTER VII

CONTINUOUS IMPROVEMENT

VII.1. INTRODUCTION.

General industrial practice is focused on the reduction in the standard deviation and a reduction of 50% in the standard deviation is generally thought of as creating a viable APC project [3, 5, 6]. There have been successful projects with lower reductions in the standard deviation [4]. However, one has to consider the initial variability and the limit specification in calculating maximum yield. Reviews of the literature showed there was an inconsistent parameter description. Since there is no systematic analysis of such issues, a dimensionless equation for the overall yield is developed based on the initial variability, the limit specification, and the reduction in the standard deviation. A dimensionless yield equation is developed to show the major inputs. This yield equation is a combination of policy that is required for a common basis, the reduction in the overall variability of the process and the initial variability of the process before the APC is applied. The maximum yield for an APC can be achieved is discussed and how further increases in throughput fit within this maximum throughput. Further, there is an operation that may be included in the overall yield of an APC. In this study, I examine what portion of an increase in throughput should be applied to the overall yield.

This is in continuation to the equations developed for determining the optimum maintenance for APC to the equations for determining the value for continuous improvement on the APC system. Briefly, there are two major inputs to the overall profit equation developed in a prior work: 1) the cost of doing the recalibrations on the APC to bring it back to the site acceptance test performance and 2) the benefits from the APC. In the prior work, both parameters were assumed to be constant. This paper examines the net effect of a continuous improvement system to both lower the costs of the maintenance and improves the benefits of the APC application. In this study, we demonstrate why the application of the continuous improvement process drives maintenance intervals in the opposite direction as the trend for turnarounds and why APC maintenance and unit turnaround scheduling should be decoupled.

VII.2. IMPROVEMENTS IN PRODUCTION STANDARDS

Most of the benefits of APC's come from reducing the variability. Various references list benefits from 3-5% of production for improvement. Sometimes the improvement is listed as a reduction of the standard deviation. Bauer and Craig list a wide variety of descriptions for the increase in production.[2] The variability in the numbers is due to a lack of a standard narrative around the improvement and how to characterize the increase.

Consider a case where the valuable product from a unit is 10,000. For example, it could be finished gasoline, specialty chemicals, or electricity from a generator. Variations in most process data follow a normal distribution function. Based on typical standard deviations reported after installation of an APC [56, 62, 86], one could estimate the standard deviation (SD) using normal distribution function. A similar analysis can be made with other distribution functions based on checking the distribution of process data. To demonstrate the effect of SD on production, an SD before APC installation ($\sigma_{Initial}$) of 370 and 55 increases in production were used a case study. Also, a single 5% increase in production from 10,000 to 10,500 was considered. Using the built-in function for calculating the inverse of the cumulative normal distribution function in MS Excel, NORM.INV (probability, mean, standard_dev), standard deviation after installation (σ_{APC}) can be iterated for various probability upper limit values (**Table 9**). The values for the limits, standard deviations, and ratios of standard deviations are shown in **Table 9**. For example, at 10604 there is 5% of both the curves greater than 10604. The ratio of standard deviations for that point is 66/370 or 0.18. For this reduction, it requires a greater than 80% reduction in the standard deviation; however, if we specify the limit at 0.99 (1% greater than the limit) the limit is 10861. The ratio of the standard deviations is 155/360 or 0.42 (a 58% reduction in the standard deviation). This is close to the values reported across literature at a 50% reduction in the standard deviation. Figure 18 illustrates how the ratio in SD varies for various probability limits. The amounts of the SD to effect this change are listed. The consistent specification is the percentage that is greater than the specified limit.

Table 9 Effect of probability limit on APC SD with a 5% increase in performance function $\sigma_{Initial}$ is 370

Probability Less Than Limit	Upper Limit	σ_{APC}	$\sigma_{APC}/\sigma_{Initial}$
0.95	10604	66	0.18
0.99	10861	155	0.42
0.999	11143	208	0.56
0.9999	11376	236	0.64

The absolute numbers are notional; however, within typical values for increases in the throughput due to employing APC on a unit. The improvement in performance function from the unit is therefore

$$Improvement = B - A \tag{21}$$

where A represents an average initial rate for the unit before application of the APC and B represents the average final rate after the application of the APC. **In Figure 18**, B - A is 500 for a 5% improvement. Also, A is at the optimized base case and both B and A have the same fraction greater than the limit.

Now if there is a limit beyond which is a defined population such that the same fraction of data are beyond that value and the numerical value of the limit is the same for both the pre-APC operation as the post APC operation then the following is true:

$$Improvement = K\sigma_{initial} - K\sigma_{APC} \tag{22}$$

where K is a proportionality constant, $\sigma_{initial}$ is the SD before an APC is installed, and σ_{APC} is the SD achieved after implementation of the APC. **In Figure 18**, $K\sigma_{initial}$ *is the difference between 10,000, the initial average, and the 10861, the upper limit of 99% confidence.* When the performance function increased by 5% due to APC, $K\sigma_{APC}$ the difference between 10,500, and 10861. Proportionality constant K is Z for the limit basis. For example, for a limit that is based on 5% beyond the limit, K is 1.6449 which increases to K is 2.3263 for 1% beyond the limit.

Equating Equation (21) and Equation (22):

$$B - A = K\sigma_{initial} - K\sigma_{APC} \tag{23}$$

Factoring out the standard deviation for the pre-APC operation ($\sigma_{initial}$) and the proportion constant, K, the equation now looks like this:

$$B - A = K\left(1 - \frac{\sigma_{APC}}{\sigma_{initial}}\right)\sigma_{initial} \tag{24}$$

The term $\left(1 - \frac{\sigma_{APC}}{\sigma_{Initial}}\right)$ is the fractional improvement in the SD due to implementing the APC. This is typically estimated to be 50% for the application of an APC. The maximum yield is where the post-APC, operations SD approaches the minimum.

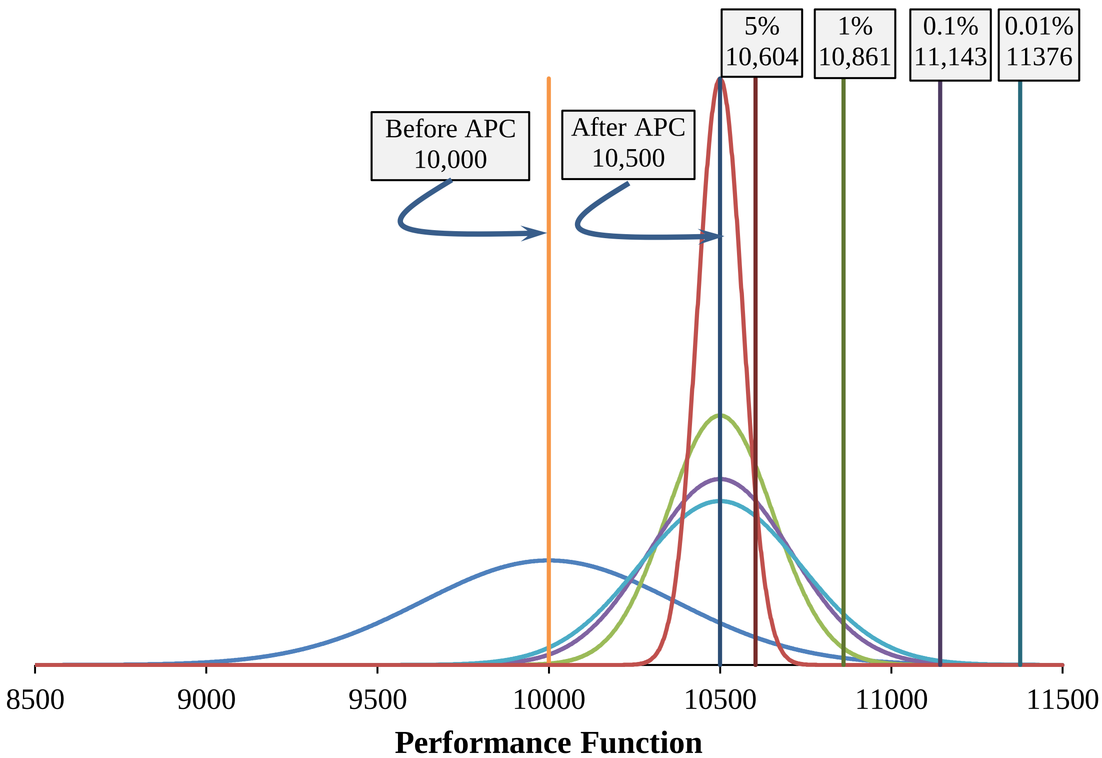

Figure 18. Normal distribution of performance function before and after application of APC with a 5% increase in performance function with various probabilities of improvement.

Throughout this analysis, the performance is used as an example of the improvement. Quite often the performance function can reduce to the production such as in an LNG plant[62], heat rate from an electrical power generation facility [87] or brix (grams of sugar per 100 grams of aqueous solution) [88] for a sugar plant [86]. If there is a function that represents the process profit as a function of production to ensure the inclusion of other variables such as energy cost or safety and product giveaway.

VII.3. DERIVATION OF APC YIELD.

Yield is defined as the fractional increase in the rate for application of an APC. Derivation of the APC yield is based in part on defining three parts about the overall process. The three parts of the operation that need to be defined are the following:

- Initial statistics - Average flow rate before the APC is installed and the standard deviation before the APC is installed.
- The basis for the limit – This is usually a policy statement about where the limit is measured and should be identified in terms of a % of the deviation (e.g., 5%, 1%, 2σ, 3σ, etc.)
- Expected Reduction in Standard Deviation – This may be an expectation of the technology employed or an estimation based on historical trends (discussed in more detail later)

Equation (24) has the units of the performance function. To develop a dimensionless equation for use in all processes, it divides the initial average throughput A. Then the fractional improvement in the throughput due to the APC.

$$Yield = Y = \frac{B-A}{A} = K\left(1 - \frac{\sigma_{APC}}{\sigma_{Initial}}\right)\frac{\sigma_{initial}}{A} \qquad (25)$$

Equation (25) can be interpreted as the production of three terms, and stated as:

$$Yield = Proportion\ Constant\ \times\ Standard\ Deviation\ Reduction\ \times$$
$$Initial\ Coeffient\ of\ Variation\ (24)$$

Proportion Constant is typically considered as the Z for measurement of the variability in a normal distribution. The selection of which Z value to choose is a policy decision for the organization involved. What one company calls 3% maybe 5% for another organization. However, for all these increases in throughput to be measured consistently, there needs to be a consistent value to be selected. There needs to be a common basis for the limit in industry narrative. In the literature, there is no common basis, except by Friedman and Martin for 95% case [30] K= 1.6449. It appears like many use 99% K= 2.3263 as a common basis. The 99% is used in various tests for confidence. However, still others discuss 3σ (K = 3.0) as the limit (99.87%)[89]. **Figure 19** shows the variability of K versus the fraction of data less than the limit (probability). When setting up these upper limits, one has to consider the risk and safety aspect of the process [90]. In any case, the guidance into the appropriate limits needs to be completed.

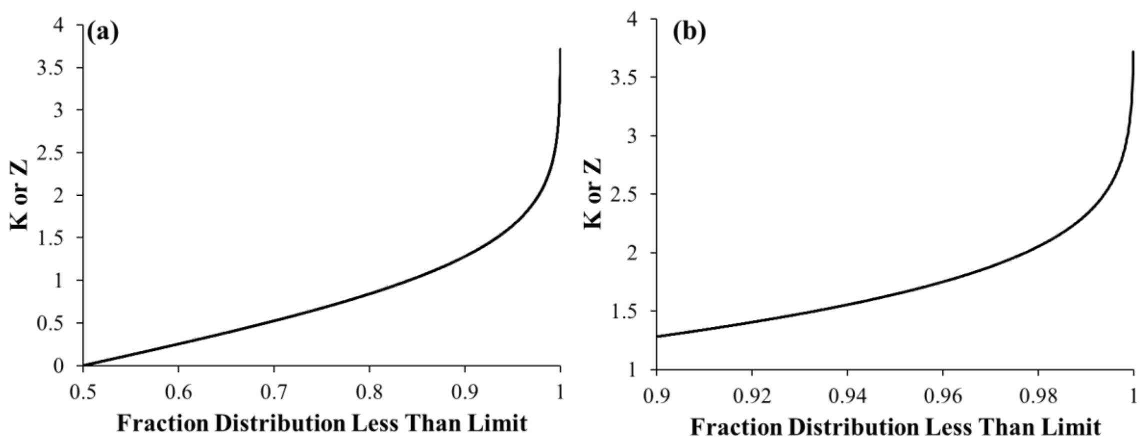

Figure 19. Effect of the fraction of distribution less than the limit on the proportion constant K (a) Full Range. (b) expanded view of the region between 0.9 and 1

As the distribution selected approaches 0.5 (50%), the K approaches zero, **Figure 19a**. This means that for policy purposes, the K selected should be in the range of those in

Figure 19b. Specifying a distribution of less than 0.5 makes K negative and thus does not have a basis. Once this policy is set the only way to change the limit is to change the physical parameters of the plant. This is an expansion of the process unit and thus outside the scope of this paper. A key assumption with this measurement is the physical plant remains constant.

Standard Deviation Reduction – There may be guidelines for each APC technology on the reduction to the SD reduction that can be achieved. There are many documents for estimating the overall decrease in standard deviation. This decrease is estimated to be 50% in several documents. An overall yield equation based on the initial variability, the limit specification and the reduction in the standard deviation has been developed. This is derived later in the document. This relationship is dimensionless. Generally, the narrative in the industry focuses only on the reduction in the standard deviation. There should be a change in the narrative to include a discussion of the other two parameters. A reduction of 50% in the standard deviation is generally thought of as creating a viable APC project [23, 24, 91]. There have been successful projects with lower reductions in the standard deviation [92]. The yield represents the starting point for the continuous improvement of the income.

Initial Coefficient of Variation –the higher the initial variability the higher the yield from the APC. The dimensionless initial variability is the coefficient of variation.

VII.3.1. Maximum Yield and Bounds for Future Improvement

One could expect the existence of a maximum yield that is available for the APC based on throughput when the variability after implementation of the APC is at a minimum.

The minimum variability of the throughput is equal to the minimum measurement variability of the throughput. Some have labeled this minimum variability as the “best operator” variability [23, 93]. The ratio yield to the maximum yield is achieved by the APC variability to the minimum variability yields by the following equation:

$$R = \frac{Y_{APC}}{Y_{max}} = \frac{\sigma_{initial} - \sigma_{APC}}{\sigma_{initial} - \sigma_{min}} \tag{26}$$

where σ_{min} is the SD values when the best operator is used. The limit on Equation (26) is 1.

Graphical representation of learning to increase yield

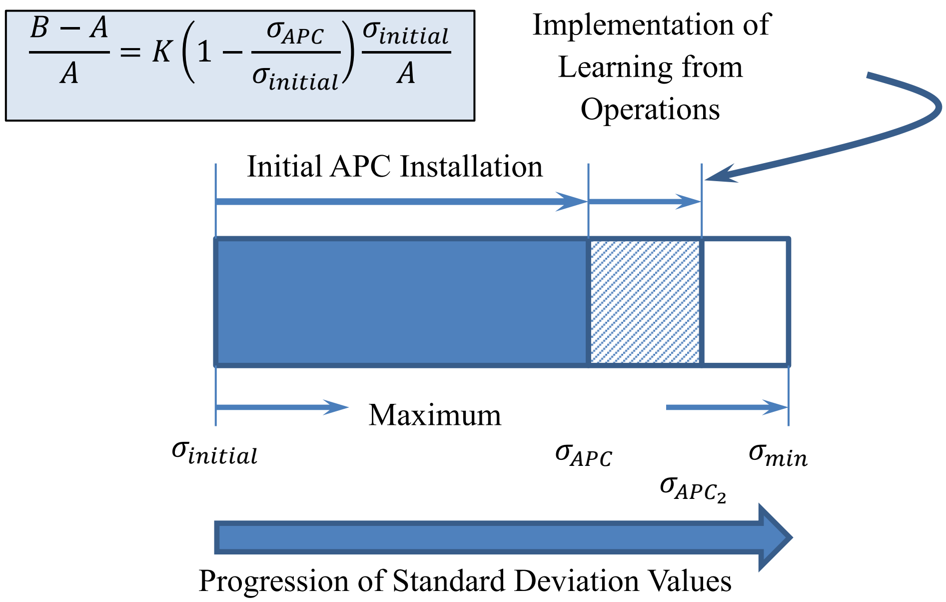

Figure 20. Graphical representation of learning to increase yield

Figure 20 shows a pictorial interpretation of the initial implementation and subsequent implementation of learning. The initial reduction in the standard deviation is approximately 50%. Some others have claimed that subsequent increases in throughput will be an additional 10-15%. The first step in increasing the yield is labeled σ_{APC_2}. As the owner-operator learns more and more, it becomes increasingly difficult to approach the best operator operation with ever more increasing modifications of the APC. Modifications of the APC may be with technology or by changing the set of manipulated variables. Irrespective of the methodology, the yield has a limit.

VII.3.2. Sources of Variability

The sources of variability can be thought to contain two parts, **Figure 21**:

Part 1 is the variability due to the measurement. For example, variability in turbulence across an orifice. This causes variability in pressure drop measurement across the orifice and cascading effect on the variability due to the overall fluctuation. Although ensuring that the process accounted for this variability is difficult, this variability is the source of the minimum variability used to find the maximum yield.

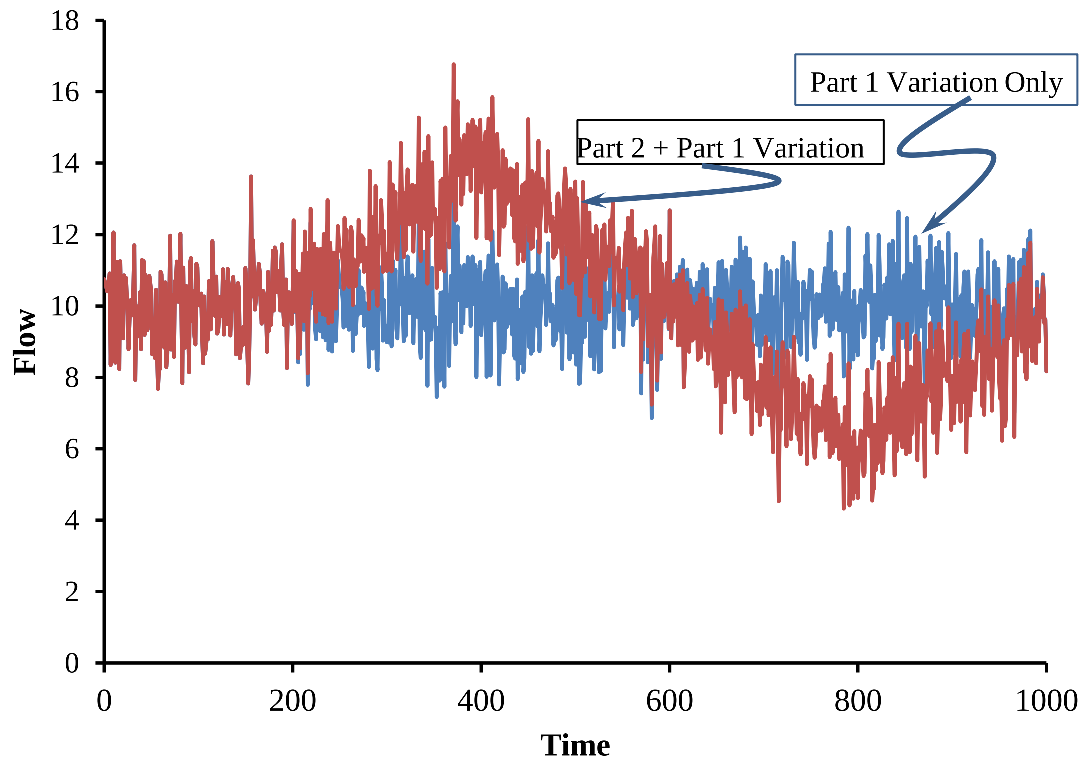

Figure 21. Comparison of Part 1 and Part 2 Variation

Part 2 is the variability due to external factors. Part 2 variability arises from upstream variable changes (pressure, level, temperature, etc.). Reduced variability of the APC makes sure the control takes variability in these parameters into account.

The statistics for the two curves are shown in **Figure 22**. The blue curve could be pushed to a higher rate to take advantage of the lower variability. This was a 56% reduction in standard deviation the possible increase inflow would be 30%.

In **Figure 22,** the 99% limits are shown for each curve. Part 1 only distribution shows a limit that is 3 less than the Part 1 plus part 2. The narrower distribution could be pushed to the right to increase the production. However, there are several sources for the limitations on the throughput. Two examples are given below

i) There may be real limitations on production throughput. This limitation value may be based on downstream equipment or may be based on a limitation of the unit for safety issues (e.g., blocked outlet, erosion, etc.). In most cases, the variability reduction allows a closer operation to the limitation developed for safety issues. The operation closer to this the limit must be determined by traditional means of evaluation (e.g., HAZOP, Fault Tree Analysis, etc.).

ii). The flow rate may be a surrogate for another limitation in the process. These limitations may be on the concentration of a specific contaminant, the temperature of a stream goes up too high because heat exchange capacity is too low, or other such process limitation correlated to throughput. In this case, the lower variability of the throughput will allow a closer operation to this surrogate throughput limitation.

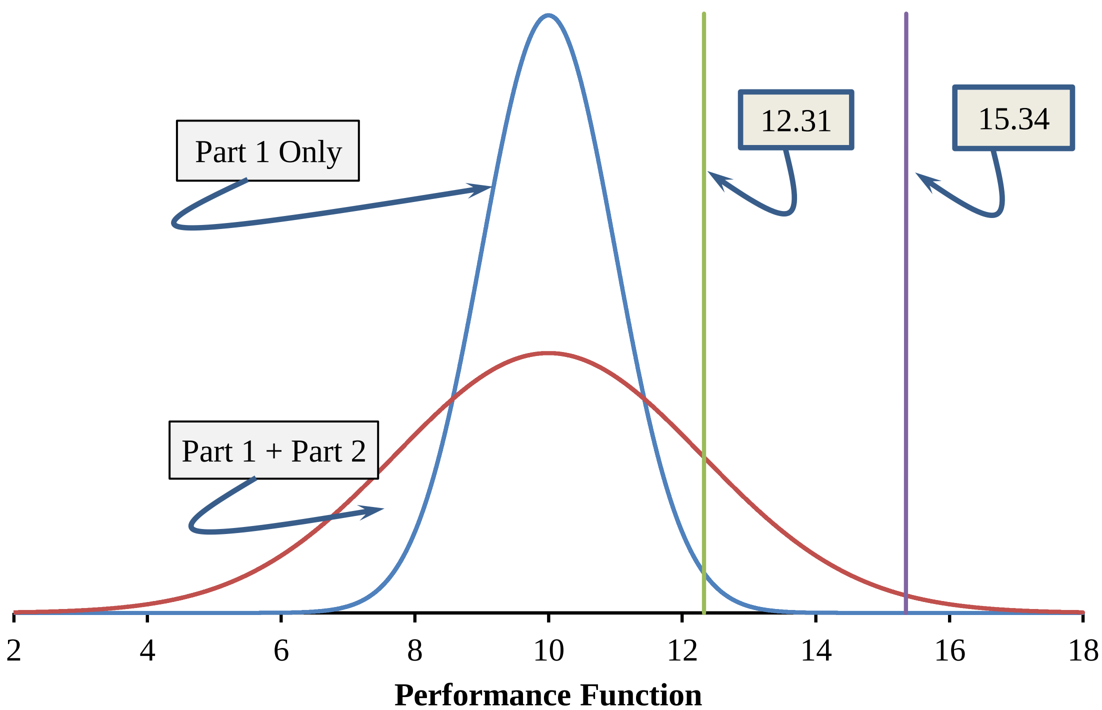

Figure 22. Comparison of Distributions for Part 1 and Part 2 Variation

VII.3.3. Optimizing the Base Inflates the Estimation of Benefits

Some yields for APC production increases have been quoted as high as 5-10% in the Bauer and Craig survey. While this is possible depending on the parameters of equation (5), larger figures approaching 10% could include optimizing the base case as described in **Figure 23**. This involves a two-step process of:

1. Moving the process closer to the maximum rate of the unit (obtaining an optimized base case). This movement is the result of establishing a consistent probability for establishing the limits. This process does not change the distribution about the mean production rate.

2. Applying the APC – This second step involves applying the variability reducing technology available in the APC. The increase due to the APC is appropriately applied to this step only.

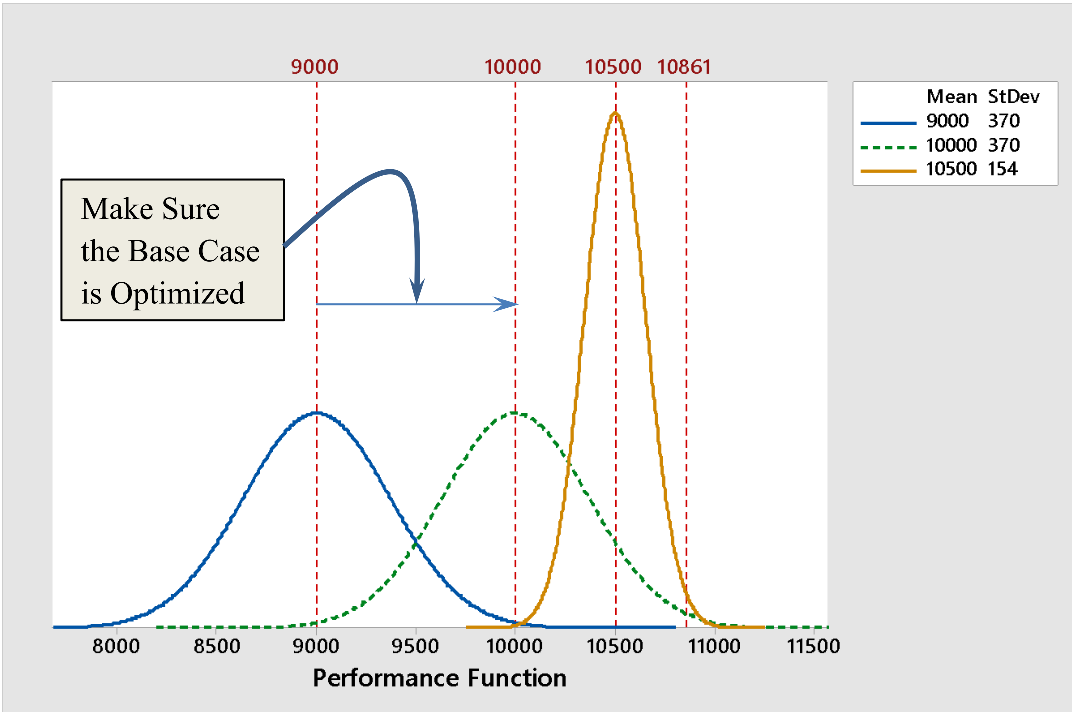

Figure 23. The Effect of Including Optimizing the Base in the Benefit Calculation

Optimizing the base is an activity that should occur independently of applying an APC. While the increase may be attributed to projects that install an APC, the inclusion of step 1 effects may inflate the overall effects of the project. Please note that the overall increase for the project described in Figure 8 is 10500-9000 or 1500. Of this 1500 increase, 66% can be appropriately attributed to the optimizing the base. The remaining 33% can be attributed to the APC.

VII.3.4. Optimization of Maintenance Interval

Previously, we have published the derivation of the dimensionless equation for the income side of continuous improvement [66]. A similar analysis can be applied to the cost component of the profit equation. In Equation (8), costs are represented by the term

$$\left(\frac{C}{\tau_R t_0} + L\right)$$

Based on the study for maintenance in Chapter IV, the optimum interval $\left(\tau_{R\ Optimum}\right)$ is given by Equation (10) and the optimum profit (P^*) is given by Equation (14). With experience, C decreases, and b_0 increases. The Boston Consulting Group established in the 1970s a relationship in the incremental cost for producing different items because of learning how to do things better [39, 58, 94]. This accumulated knowledge results in a 20-30% drop in the incremental cost for producing a product (typically) for every doubling of cumulative production[95]. In all the calculations for the optimum cash flow, the cost for doing the maintenance on an APC was treated as a constant.

If each installation is unique, then the learnings on the unit reduce to a very simple equation on the overall cost of recalibration for an APC will be as follows

$$\frac{C}{C_0} = N^a \tag{27}$$

N is the number of recalibrations and if there are identical installations across a company on different types of units, then N is the sum of the recalibrations across all the processes.

C is the current cost and C_o is the initial cost.

a is the curve exponent for the decline curve exhibited. For a 70% decline curve i.e., a 30% reduction for every doubling or $\frac{C}{C_o} = 0.7$, the right-hand side of the equation is $2^{\boldsymbol{a}}$.

Therefore, the calculated value of a is -0.514. Similarly, the value of ***a*** for an 80% curve is -0.322.

Consider a case where the initial cost of APC recalibration is $20,000 and the time interval of recalibration is 8 months. Based on a typical 15-year (or 180 months) life cycle of a plant, there are 22 recalibrations. Assuming an 80% curve, the cost at the end of the plant life can be calculated using Equation (12) as

$$C= \$20,000\times 22^{-0.322} = \$7,400$$

Since it treats each installation as a unique product, the obtained value represents a best-case scenario on the overall decline of the costs. For large companies that wish to share information across several different sites the calculation for N needs to sum up all the installations of similar types. Equation (12) becomes significantly more complex if a company has several installations of the same APC. Where learnings from one site are applied at another. The decline in overall maintenance cost per recalibration is, therefore, an active process. Repeating the same recalibration process as initially conceived will result in the same performance repeatedly. The technology for decreasing the cost is increasingly automated. There are several examples where automation of the initial installation is automated[26, 32, 41], and this can be extended to the recalibration process. There is also an example where the recalibration is completed with automation. The decline curve for costs has yet to be calculated for APC installations.

VII.3.5. Enhancing Profit from the Process

Through repeated evaluations of the APC, more income is expected to be generated from the process. This comes from additional parameters or deletion of parameters from the set of manipulated variables (MV). The additional amount that can be achieved over time is about 10-15% [44]. This amount is not achieved over the first iteration and may require subsequent iterations. Additionally, moving the distribution closer to the limit based on the policy decisions discussed in the first part of the paper becomes harder and harder. The nominal 10-15% from experience may be impossible based on the limit chosen. Hence, making sure the limit and definition of the limit need to be chosen with care.

Based on conversations with industry practitioners this increase over time is likely to be asymptotic and thus follow a form near to the following:

$$\frac{Y_{CI}}{Y_o} = 1 + k_1 e^{\frac{k_2}{N}} \tag{28}$$

$\boldsymbol{Y_{CI}}$ is the continuous improvement I for each step. Note that the $\boldsymbol{I_{CI}}$ goes up in steps for each recalibration.

$\boldsymbol{Y_o}$ is the initial yield for the APC for each τ=1 period.

$\boldsymbol{k_1}$ represents the maximum improvement possible over the duration of the installation. This value will be 0.1-0.15 unless there are other limitations to the over-expansion of continuous improvement as discussed in section 2.3.

$\boldsymbol{k_2}$ is the exponent factor based on the experience of continuous improvement within the owner/operator. $\boldsymbol{k_2}$ will always be less than zero.

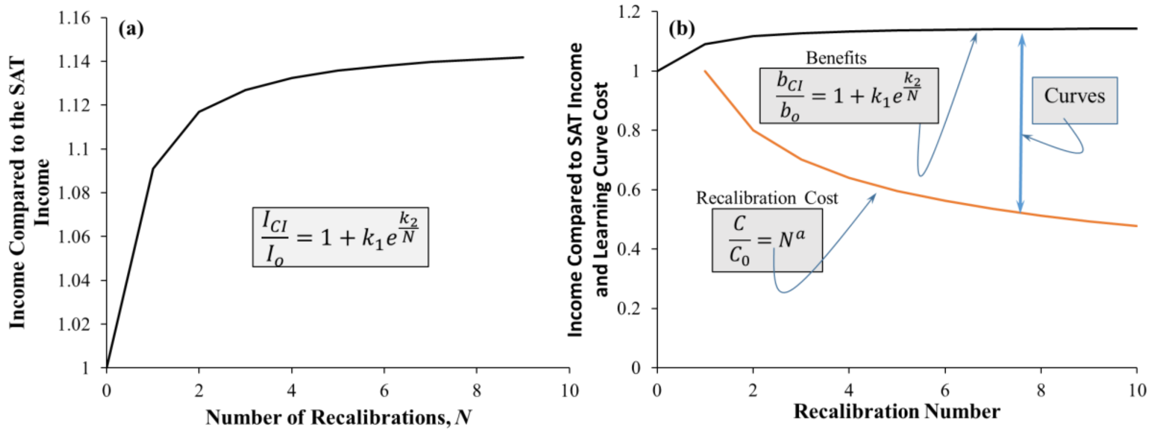

Figure 24. Continuous Improvement Parameters (a) Continuous Improvement of APC Yield over SAT. (b) Income and Recalibration Cost.

The effect of the number of recalibrations on the yield compared to the site acceptance test (SAT) yield is shown in **Figure 24**. Hence, Equation (27) sets the general trend of continuous improvement. The discussion on limits to continuous improvement addresses why there are limits to the continuous improvement income.

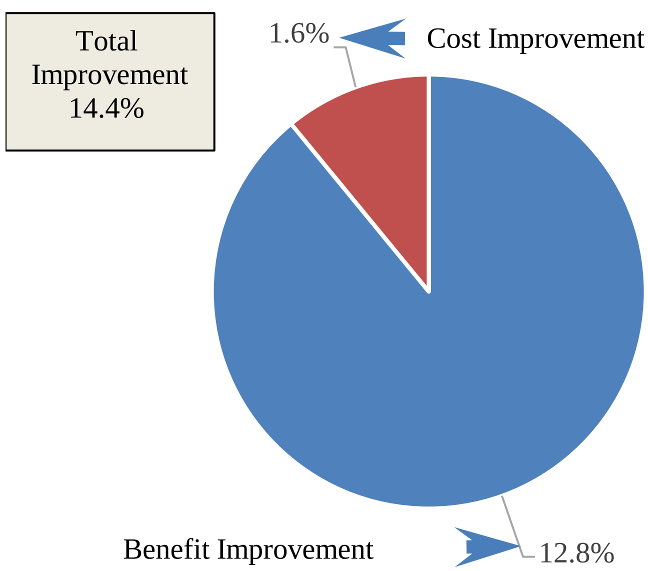

Figure 25. Relative Increases Due to Continuous Improvement.

This asymptotic relationship is likely to occur because it becomes harder and harder to increase the yield up to the maximum yield.

VII.3.6. The Effect of Continuous Cost and Income Improvement on the Recalibration Interval – Decoupling from Turnarounds

The net effect of combining continuous improvement to both cost and income over time is that both curves will diverge, Figure 24b. Increases to the income and decreases to the cost in equation (9) drives the interval down. Generally, keeping a unit on-line longer maintains cash flow from a process. The tendency is to increase the interval for turnarounds[59]. This means that an active improvement to the APC income is driving the interval for doing the recalibration in the opposite direction as the efforts to increase the turnaround. Further, there is an evaluation of typical turnaround times and nominal recalibration times that show these should be decoupled [66].

Based on the relationships for the throughput yield improvements and cost reductions from learning curves an example project with a 15-year life was estimated for continuous improvement. The net present value was estimated for a small APC installation with 2 MV and 2 inferred variables. Briefly, an estimate of about 14.4 % additional cash flow was calculated for the project which has an active continuous improvement component. About 12.8% of the increase was due to income increase and 1.6% was due to cost reductions in this example, **Figure 25**.

The owner-operator will need to evaluate their operation to evaluate the additional income generated for the specific project. Note that a continuous improvement project is an active system. Simply repeating the same techniques on recalibration will not reduce the cost. Further, recalibrating only at the optimum recalibration point will not increase the income. The owner-operator must seek out these techniques to apply to the specific process to know the exact percentage increase for a continuous improvement program. In any case, it appears from the example that significant effort should be applied to the income side of the continuous improvement process.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

VIII.1. CONCLUSIONS

This section focuses on the conclusions from each of the specific aims.

VIII.1.1. Aim 1. Maintenance of the APC

In this I set out a common method by which the owner/operator can determine the optimum schedule for recalibration for and APC installation. This model encourages the owner/operator to track the performance (cash flow basis) and make the recalibration at the optimum time based on economic impact. Further, the model allows for different intervals based on the process involved. Each owner/user will need to develop its parameters through studies of the decline curves. These parameters can be developed even on the same process from one run to the next. It is expected that these decline curves would be more characteristic for the specific process/site and thus would not vary significantly; however, this needs to be proven. Accepting that the behavior is similar for all APC projects, regardless of industry or application, a manager can use industry/application-specific values for the rate of decline and time to zero benefits for each process or class of process (e.g., all crude units, all FCC units, etc.). The APC recalibration schedule needs to be decoupled from process turnaround maintenance. The optimum recalibration schedule had neither critical timing nor a critical dependence on the p-value of the decline curve.

The optimization of a stochastic model is demonstrated and reveals the importance of periodic recalibration of the MPC models within an APC application. As well, it reveals the relative insensitivity of the exact recalibration date. This application demonstrates the utility of Leapfrogging with a steady-state convergence criterion in optimizing a stochastic model, such as an economic forecast which includes uncertainty on future costs and events.

VIII.1.2. Aim 2. Capital Evaluation Process

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 of 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 periodic maintenance. These regular maintenance intervals can be estimated through Equation (2).

The optimum is fairly flat and thus 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 (i)The technology costs – This depends in part on the contract that is made with the technology provider, (ii) Labor hour cost – Different guidelines are available in the literature; but one guideline is given here, (iii) 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. Any equipment changes that are required to make sure the technology works need to be included. This is 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.

I 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.

VIII.1.3. Aim 3. Continuous Improvement

In this part, I show how to continuously improve the returns from an APC after it has been installed. The maximum throughput is achieved when the variability reaches the minimum. In considering a throughput a yield equation has been developed that combines the statistical probability defined by policy and the variability reduction demonstrated by the APC and the initial variability. The cost side of the profit equation can be reduced according to established learning curve rules.

The calculation techniques presented in this paper enable the owner-user to value efforts for developing and stewarding a continuous improvement program for their APC program. Further, the relative focus of the efforts can also be valued. Guidance is also included in what to include in the overall benefit calculations for standard comparison across the industry.

Finally, there is a calculation technique that shows that an effective continuous improvement program moves the recalibration intervals for APC in the opposite direction of turnaround intervals. The turnaround intervals and recalibration intervals should, therefore, be decoupled.

VIII.2. RECOMMENDATIONS

The next step in this area of research is validation in a formal statistical method for the parameters in the dimensionless equations. The parameters will be functions in the plant environment. These functions could be the "dirtiness of the process" or the maintenance of the control equipment.

The road map to get to the answers are getting to the information contained within operating plant data is laid out in the IRB application (APPENDIX A) and the question List (APPENDIX B). Execution of the single-blind Delphi Study is one way to gather the data from the plant environment and organize it so that it will satisfy all the barriers identified in the METHODS chapter. The single-blind feature would guarantee that the data are sufficiently independent to satisfy the Delphi parameters and also satisfy the collusion and proprietary knowledge criteria. These barriers are routinely circumvented in the fuels study by Solomon Associates for global refining operations [31].

The list of participants in any formal Delphi Study should contain nearly equal representation of both the providers of the technology (vendors) and the users of the technology (Owner-Operators). The numbers of the participants should be greater than 13 [15]. The best should be 13 owner-users and 13 vendors. Examples of the vendors would be representatives of companies (e.g., Honeywell, AspenTech, Emmerson, Yokogawa, etc.) or any of the well-recognized independent contracting firms that install the different technologies (e.g. Greenfern Dynamics, etc.). Examples of owner-user sample pool would That question list could be further supplemented with questions arising from the data contained in the Capital Chapter for regional differences. This study has identified some possible geographic variances in the price for the execution of APC projects [82, 83]. There may also be significant differences between industries [83, 96].

One aspect about APC is the number of APCs at a site and the number of manipulated variables within the APC, For example, if there are 100 manipulated variables (MV) at a site, the way that an APC can be configured is one APC with 100 MV, two APC's with 50 MVeach, 5 APC's with 20 MV each, etc.. There are several other combinations. Pulling together the data to ensure optimum segregation of APC among the various MV would be very valuable information. At this point, the art of putting together the APC MV combination is left up to the individual technology provider preference or failing a preference on the technology provider, some owner-operators have a preference. The clues to solving this problem are bound in the ways that sites are optimized. Discovering these clues may be found in the crowd knowledge techniques like a Delphi Study.

REFERENCES

[1] *Chapter 6 - Process Control and Automation of LNG Plants and Import Terminals*. Elsevier Inc., 2014, pp. 259-296.

[2] M. Bauer and I. K. Craig, "Economic assessment of advanced process control - A survey and framework," *Journal of Process Control*, vol. 18, no. 1, pp. 2-18, 2008.

[3] A. Taylor and A. Jamaludin, "Innovative APC boosts LNG train production," *Hydrocarbon Processing*, vol. 91(1), pp. 49-53, 2012.

[4] D. Fayruzov, Y. Bel'kov, D. Kneller, and A. Torgashov, "Advanced process control system for a crude distillation unit. A case study," *Automation and Remote Control*, vol. 78, no. 2, pp. 357-367, 2017.

[5] L. A. Richard and M. Spencer, "Austrian refiner benefits from advanced control," *Oil and Gas Journal*, vol. 93, no. 12, 1995.

[6] P. R. Latour, "Align HPI operations to economics," *Hydrocarbon Processing*, vol. 87, no. 12, pp. 103-111, 2008.

[7] H. Wang, Z. Wang, H. Mei, F. Qian, and Z. Tang, "DCS advanced control improves Chinese ethylene cracker operation," *Oil and Gas Journal*, vol. 109, no. 1, pp. 96-103, 2011.

[8] A. Taylor, "Advanced Control Upgrades - Part 1," *PACE*, no. August, p. 14, 2008.

[9] R. Salliss, "2014 Honeywell Users Group Europe, Middle East and Africa, Optimize your Process with Advanced Process Control," ed: Honeywell Users Group, 2014.

[10] L. Heavner, "Private Communication Between Lou Heavner and Stephen Mayo In 2018," S. Mayo, Ed., ed, 2018.

[11] A. G. Kern, "Summiting with multivariable predictive control," *Hydrocarbon Processing*, vol. 86, no. 6, pp. 63-64, 2007.

[12] "2019 Guide to the Business of Chemistry," American Chemistry Council2019, Available: https://www.americanchemistry.com/GBC2019.pdf, Accessed on: 11 April 2020.

[13] N. Dalkey and O. Helmer, "AN EXPERIMENTAL APPLICATION OF THE DELPHI METHOD TO THE USE OF EXPERTS," *Management Science (pre-1986)*, vol. 9, no. 3, p. 458, 1963.

[14] N. C. Dalkey, *Studies in the quality of lifeDelphi and decision-making*. Lexington, Mass.: Lexington, Mass., Lexington Books, 1972.

[15] J. A. Smith, "Core Components of a Doctoral Program in Agricultural Communications: A National Delphi Study," Master of Science, Agricultural Education, Communications & Leadership, Oklahoma State University, Stillwater, OK, 2012.
[16] K. Mattingly, "The wisdom of crowds," ed: TECxBrighton, 2014.
[17] D. Shook, "Best practices improve control system performance," *Oil & Gas Journal*, vol. 104, no. 38, pp. 52-54,56-58, 2006.
[18] S. M. Mayo, "Disscussion Notes with Dave Shook," 24 June 2019, 2019.
[19] T. Fiske, "Best Practices for Advanced Process Control," ed. Deham, MA: ARC Advisory Group, 2008, p. 32.
[20] P. Nordh, "Understand Advanced Process Control," *Chemical Engineering Progress*, vol. 112, no. 6, pp. 69-72, 2016.
[21] P. Nordh, "Meeting Notes - Perry Nordh 2019-08-30," S. Mayo, Ed., ed, 2019.
[22] J. G. J. Hadzima, "How much does an employee cost," *Boston Business Journal*, 2005.
[23] J. Anderson, T. Backx, J. Van Loon, and M. King, "Getting the most from advanced process control," *Cost Engineering*, vol. 38, no. 11, pp. 31-38, 1996.
[24] G. Lew, "Qualify an Advanced Control Project," *Control Engineering*, vol. 53, no. 11, pp. IP1-IP7, 2006.
[25] S. Mokhatab, *Handbook of liquefied natural gas*. Amsterdam: Elsevier/Gulf Professional Publishing, 2014.
[26] M. L. Darby, M. Harmse, and M. Nikolaou, "MPC: Current Practice and Challenges," *IFAC Proceedings Volumes*, vol. 42, no. 11, pp. 86-98, 2009.
[27] K. Lehman, "Implement Advanced Process Control," *Chemical Engineering Progress*, vol. 114, no. 10, pp. 60-66, 2018.
[28] P. Singh and K. Seto, "Analyzing APC performance," *Chemical Engineering Progress*, vol. 98, no. 8, p. 60, 2002.
[29] M. Kano and M. Ogawa, "The State of the Art in Advanced Chemical Process Control in Japan," *IFAC Proceedings Volumes*, vol. 42, no. 11, pp. 10-25, 2009.
[30] "Solomon Associates' advanced process control survey," *Hydrocarbon Processing*, p. 1, 2006.
[31] S. Associates. (Sept 30, 2019). *Solomon Benchmarking Fuels Study*. Available: https://www.solomononline.com/benchmarking/refining/fuels-study
[32] P. Celya, B. Tkatch, Y. Zhu, and R. Patwardhan, "Closed-loop identification at the Hovensa Refinery," presented at the NPRA Plant Automation & Decision Support Conference, September 19 - 22, 2004, 2004.
[33] L. Heavner, "APC Estimation," S. Mayo, Ed., ed, 2018.
[34] B. Cott, "Capital Calculations Exchange with Barry Cott," ed, 2019.
[35] S. M. Mayo, "Meeting Notes - Mark Darby 2019-09-19," 2019.
[36] S. M. Mayo, "Meeting Notes - Mark Darby 2019-10-02," 2019.
[37] W. contributors. (2010, 21 June). *Continual improvement process*. Available: https://en.wikipedia.org/w/index.php?title=Continual_improvement_process&oldid=940142678

[38] M. Reeves, G. Stalk, and F. S. Pasini. (2013, 25 Apr 2019). *BCG Classics Revisited: The Experience Curve*. Available: https://www.bcg.com/en-us/publications/2013/the-experience-curve-bcg-classics-revisited.aspx

[39] B. Henderson, "The application and misapplication of the experience curve," *The Journal of Business Strategy,* vol. 4, no. 3, p. 3, 1984.

[40] A. Kalafatis, "Meeting Alex Kalafatis 2018-11-09," S. Mayo, Ed., ed, 2018.

[41] K. Buscovich, "Adaptive Modeling for Shifting Process Conditions," ed. AspenTech Webinars, 2016.

[42] M. L. Darby and M. Nikolaou, "MPC: Current practice and challenges," *Control Engineering Practice,* vol. 20, no. 4, pp. 328-342, 2012.

[43] S. Mayo, "APC Life," R. Salliss and G. Jubien, Eds., ed, 2018.

[44] A. Taylor, "Private Communication On APC...Additional Income," ed, 2019.

[45] J. Ramsey, "Meeting Notes - Jon Ramsey - 2019-09-23," S. mayo, Ed., ed, 2019.

[46] W. contributors. (2019, September 24, 2019). *Robin Hanson*. Available: https://en.wikipedia.org/w/index.php?title=Robin_Hanson&oldid=914031302

[47] R. Hanson, "Crowd Knowledge - Advanced Process Control," S. Mayo, Ed., ed, 2019.

[48] K. Mattingly, "Stephen Mayo Meeting with Karl Mattingly," ed, 2019.

[49] C. Riseling, "Meeting Notes Creyton Riseling," S. M. Mayo, Ed., ed, 2018.

[50] M. d. Sautoy, "BBC - The Code - The Wisdom of the Crowd," ed: BBC News, 2011.

[51] B. B. Brown, "DELPHI PROCESS: A METHODOLOGY USED FOR THE ELICITATION OF OPINIONS OF EXPERTS," C. A. Rand Corp Santa Monica, Ed., ed, 1968.

[52] S. R. Brady, "Utilizing and Adapting the Delphi Method for Use in Qualitative Research," *International Journal of Qualitative Methods,* vol. 14, no. 5, 2015.

[53] S. Sontag, *Blind man's bluff: the untold story of American submarine espionage*. New York: New York: Public Affairs, 1998.

[54] N. Johnson, P. Leighton, and J. Dias, "The use of the Delphi method for hand surgery research," *Journal of Hand Surgery (European Volume),* vol. 44, no. 5, pp. 547-550, 2019.

[55] B. J. Cott, "Private Communication Barry Cott 21 Feb 2019," ed: Stephen Mayo, 2019.

[56] S. M. Mayo, "Analysis of Presentation Panel," e-mail communication to Andrew Taylor on presentation of 15 Nov 2018 decline of LNG plant after 1-year ed, 2020.

[57] "Q4 2013 Aspen Technology Earnings Conference Call - Final," ed. Linthicum, 2013.

[58] B. Henderson. (1968, 25 Feb 2019). *The Experience Curve*. Available: https://www.bcg.com/publications/1968/business-unit-strategy-growth-experience-curve.aspx

[59] E. Jakubowski and J. Karlsson, "On turnarounds A service development investigation from a consultancy firm perspective," Master of Science, CHALMERS UNIVERSITY OF TECHNOLOGY, Göteborg, Sweden, 2010.

[60] R. B. Hey, *Performance management for the oil, gas, and process industries: a systems approach*. Cambridge, MA: Gulf Professional Publishing is an imprint of Elsevier, 2017.
[61] A. Hameed and F. Khan, "A framework to estimate the risk-based shutdown interval for a processing plant," *Journal of Loss Prevention in the Process Industries,* vol. 32, no. 1, pp. 18-29, 2014.
[62] A. Taylor, "Increasing LNG Production and Gas Plant Yields," ed. AspenTech Website: AspenTech, 2018.
[63] A. Taylor, "Have You Hugged Your APC Recently? " vol. pdf, ed. Australia, 2009.
[64] R. Coker, "Drive Continuous Improvement in APC Benefits with Performance KPIs," ed. AspenTech, 2018.
[65] S. M. Mayo, R. R. Rhinehart, and S. V. Madihally, "APC Maintenance Scheduling - Part 1," *Hydrocarbon Processing*, no. February, pp. 59-63, 2020.
[66] S. M. Mayo, R. R. Rhinehart, and S. V. Madihally, "APC Maintenance Scheduling – Part 2," *Hydrocarbon Processing,* no. March, pp. 51-55, 2020.
[67] R. R. Rhinehart, "Convergence criterion in the optimization of stochastic processes," *Computers and Chemical Engineering*, vol. 68, pp. 1-6, 2014.
[68] R. N. Ribeiro, E. S. Muniz, R. Metha, and S. W. Park, "Economic Evaluation of Advanced Process Control Projects," *O Papel,* Technical Article/Peer-reviewed Article vol. 74, no. 3, pp. 57-65, March 2013.
[69] R. R. Rhinehart, M. Su, and U. Manimegalai-Sridhar, "Leapfrogging and synoptic Leapfrogging: A new optimization approach," *Computers and Chemical Engineering,* vol. 40, no. C, pp. 67-81, 2012.
[70] S. Cao and R. R. Rhinehart, "An efficient method for on-line identification of steady-state," *Journal of Process Control,* vol. 5, no. 6, pp. 363-374, 1995.
[71] V. Yadav, P. Dube, H. Shah, and H. Debnath, "Optimize desulfurization of gasoline via advanced process control techniques," *Hydrocarbon Processing,* p. n/a, 2012.
[72] S. Kemaloğlu, E. Ö. Kuzu, D. Gökçe, and Ö. Çetin, "MODEL PREDICTIVE CONTROL OF A CRUDE DISTILLATION UNIT AN INDUSTRIAL APPLICATION," *IFAC Proceedings Volumes*, vol. 42, no. 11, pp. 880-885, 2009.
[73] E. L. Mohundro, D. R. Slim, and S. M. Mayo, "Arsine and phosphines as acetylene converter moderators," United States of America Patent 5,463,154, October 31, 1995, 1995.
[74] G. Parkinson, "NIR crude analysis saves Korean refinery $1.5 million/yr," *Chemical Engineering,* vol. 107, no. 3, p. 19, 2000.
[75] I. Sela, N. Fontjin, and I. Zilberman, "Software speeds implementation of the analyzer in crude unit," *Oil & Gas Journal,* vol. 98, no. 15, pp. 70-75, 2000.
[76] *Process safety management of highly hazardous chemicals.*, 1992.
[77] A. Taylor and A. Jamaludin, "Innovative APC boosts LNG train production," *Hydrocarbon Processing,* p. n/a, 2012.
[78] V. L. Trevathan, *Advanced Process Control*, 2nd Edition ed. ISA, 2006, pp. 1-1.
[79] O. P. C. Foundation. (3 Mar 2020). *What is OPC?* Available: https://opcfoundation.org/about/what-is-opc/

[80] Anonymous, "2019 AIChE SALARY SURVEY," *Chemical Engineering Progress*, vol. 115, no. 6, pp. 24-33, 2019.
[81] P. R. Latour, "LinkedIn reply to a query on an article entitled "Align HPI operations to economics"," 21 Feb 2019.
[82] R. N. Ribeiro, "Private Communication Ronaldo Ribeiro," 2020.
[83] L. Heavner, "Meeting Notes with Lou Heavner 16 Apr 2020," S. Mayo, Ed., ed, 2020.
[84] P. Kesseler, "Advanced process control: quick and easy energy savings," *Hydrocarbon Processing*, pp. 55-57, 2010.
[85] E. F. Brigham, *Financial management: theory and practice*, 9th ed.. ed. Fort Worth: Fort Worth: Dryden Press, 1999.
[86] T. E. Marlin, J. D. Perkins, G. W. Barton, and M. L. Brisk, "Benefits from process control: results of a joint industry-university study," *Journal of Process Control*, vol. 1, no. 2, pp. 68-83, 1991.
[87] P. Rambalee, "Power Control: Advanced Process Control," *Control Engineering*, p. n/a, 2011.
[88] W. contributors. (5 April 2020 12:54 UTC). *Brix (page version id: 911546058 ed.)*. Available: https://en.wikipedia.org/w/index.php?title=Brix&oldid=911546058
[89] T. Hurlburt, W. Rossow, R. McDaniel, and R. Dollar, "Control strategies improve Louisiana NGL plant operations," ed. Tulsa, 2002, pp. 74-79.
[90] "Letters To The Editor," *Hydrocarbon Processing*, p. 1, 2006.
[91] K. Chin, "Make Your Plant the Model of Efficiency," *Chemical Engineering*, vol. 107, no. 7, pp. 119-120,124, 2000.
[92] D. Kannan, "Materials Use Reduction via Advanced Process Control," *Control Engineering*, vol. 55, no. 11, pp. S.14-SS15, 2008.
[93] "Model predictive control for liquefied natural gas processing plants," *Hydrocarbon Processing*, pp. 1-90, 2007.
[94] C. H. By Thomas, "Bruce Henderson, 77, Consultant And Writer on Business Strategy," ed. New York, N.Y., 1992, p. D16.
[95] A. C. H. a. N. S. Majluf, "Competitive Cost Dynamics: The Experience Curve," *Interfaces*, vol. Vol. 12, No. 5 (Oct. 1982), pp. 50-61, 1982.
[96] K. Praprost, "Meeting Notes with Ken Praprost 27 Mar 2020," S. Mayo, Ed., ed, 2020.

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APPENDIX A

INSTITUTIONAL REVIEW BOARD APPLICATION

Following is the institutional review board application to do a detailed Delphi Study. This application was approved by e-mail on 30 Jan 2020 (attached at the end of this Appendix).

View xForm - Application for Review of Human Subjects Research (Revised Common Rule)

Complete this form to apply for IRB Review of Human Subjects Research. This form is also used to determine if your study qualifies as human subjects research under 45 CFR 46. This is version 4 to comply with the Revised Common Rule.

Application Data Entry

Part 1: Administrative Information

Application for Review of Human Subjects Research

Pursuant to 45CFR46

For Assistance in completing this form:

~~ Download - Researchers Help Guide to IRBManager ~~

Version 4

xForm Owner:

If you want to give access to this xForm to other individuals prior to approval of this IRB, please click on the Collaborators link to the right of the OSU logo at the top left of this page in order to grant access.

Mayo, Steve

Email: stephen.m.mayo@okstate.edu

Date

1/15/2020

Administrative Information:

Title of Project:
The title of each project needs to be unique.

Advanced Process Control Delphi Study

Proposed Start Date

Click Here to see IRB Application Review Procedures
2/14/2020

Principal Investigator (PI):
Type in the e-mail address of the principal investigator.

Mayo, Steve

Email:	stephen.m.mayo@okstate.edu

Preferred Contact Phone Number:

4057620952

Please indicate your position/rank.

Graduate Student

Note: In order to add a contact, that individual will need to have logged into IRBManager at least once prior to adding them to the study in this section.

Faculty Adviser:
Type in the e-mail address of the adviser.
This is required for all student PIs.

Madihally, Sundar

Email:	sundar.madihally@okstate.edu

Co-Principal Investigator (Co-PI):
Please click add contact for each Co-PI that should be listed on the study. Faculty Advisers do not need to be added as Co-PIs.

No answer provided.

Project Coordinator (PC):
Please click add contact for each Project Coordinator that should be listed on the study.

No answer provided.

Research Assistant (RA):
Please click add contact for each Research Assistant that should be listed on the study. Use this if you know the research assistant on your study will be stable over the course of the study. If you think they will be changing each semester, please list them under unnamed personnel instead.

No answer provided.

Unnamed Personnel Table:

Position	Affiliation	Human Subject Training	Other Training Description

It is helpful to add individuals to your study as "Unnamed Personnel" when you know that this study staff will be changing on a frequent basis. An example would be Undergraduate/Graduate Research Assistant or Translators. You will need to keep records of the training listed in your IRB records.

Graduate Students will need to be listed as a PI, Co-PI, Project Coordinator, or Research Assistant if the project is for a thesis or dissertation to meet Graduate College requirements. Do not include CVs for unnamed personnel.

College:

Note: Graduate College should only be selected for the 5 interdisciplinary degrees that the Graduate College oversees directly. For departments not housed within a college, such as the Seretean Wellness Center or Admissions, please select General University.

College of Engineering, Architecture & Technology

Department:

Chemical Engineering

Please select your campus.

OSU Stillwater

Please select the primary location in which your study will take place.

You can only select one option. Online only studies, please select Off Campus.

Site: OSU Stillwater
Location: Other

Please provide specific details about the location of your study.
Include all secondary and additional locations where your study will occur.
Such As: school systems, businesses, buildings, hospitals, services/servers for web surveys, etc.
Examples: Classroom at Will Rogers Elementary School, Stillwater Medical Center, etc.
The study will be conducted with questionnaires sent out electronically. Questionnaires will either be with Excel spreadsheets or with the software tools available through Qualtrics. Questionnaires will be sent to industry experts. These experts will complete the questionnaires at their locations.

Will all necessary permissions be obtained prior to recruiting and/or completing study procedures at these locations?
Note: You should keep verification of these permissions in your study records.
Yes

Will you be working with any other collaborating institutions or organizations as part of this project?

No

Generally, when one or more institutions work together equally on a research endeavor, it is a collaboration.

Is this research funded by an external funding agency?

No

Part 2: Determination of Research

Please select the project type: **Note: If you change your project type, please make sure you have unchecked all responses to follow-up questions from previous project type selected.**	
Research Project Thesis/Dissertation	*Oral History: The method of gathering, preserving, and interpreting the voices and memories of people, communities, and participants in past events.* *Classroom Assignment: This activity is primarily intended for education purposes, e.g., projects designed to provide practice of research methods. Only select this option if this research project is being assigned as part of a class you are taking.* *Assessment/Program Evaluation: Gathering data and information for purposes of institutional assessment, quality assurance, or quality improvement (e.g. surveys about student satisfaction with college services, analyses of the effectiveness of academic programs, etc.)* *Journalism: For example, investigations and interviews that focus on specific events, view, people, etc. and which lead to newspaper/news publication or documentary production.* *Public Health Surveillance: Activities conducted, supported, requested, ordered, required, or authorized by a "public health entity."* *Criminal Justice: Collection and analysis of information, biospecimens, or records by or for a criminal justice agency.* *National Security: Authorized operational activities in support of intelligence, homeland security, defense or other national security missions.*

Will the data be obtained in a systematic manner?	
Yes	*A systematic investigation is the gathering and analysis of information according to a fixed plan, system, or method. Generally most studies will meet this definition, even qualitative research.*

Will the intent of the data collection be for the purpose of contributing to generalizable knowledge (the results of the activity are intended to be extended beyond a single individual or an internal program to be widely applicable)?

Yes	*Generalizable knowledge is determined by whether results are published, presented to the public, or developed for others to build upon. This includes journal articles, oral or poster presentations, theses, dissertations, and some oral histories.* *For qualitative methodologies do you seek to have transferability of the results to other situations and experiences? If yes, please mark this question as a "yes".*

Part 3: Determination of Human Subjects

Does the research involve obtaining information about LIVING individuals?

No	*If the person is not living , please select no.*

Determination of Non-Human Subject Research

Your research project does NOT qualify as Human Subjects Research per 45 CFR 46.

How will the results of this project be used?
(e.g. Presentation? Publication? Report to Funding Agency?)

The results of this study will be used in research for a dissertation leading to a PhD degree in Chemical Engineering. The results will also be used for articles in academic and professional journals to publish the results.

Please describe the participant population you have chosen for this project, and any recruitment methods.

The population of individuals will be practitioners and customers of Advanced Process Control (APC). APC programs are control programs places on process plants (chemical, refinery, power, semiconductor, etc.) that optimize the process. This study will focus on aspects of implementation of these projects and the project performance decline after implementation. These individuals generally fall into two groups: providers of technology to industry and customers of the technology (industrial consumers). The body of information for determining decline rates for APC and recalibration methods, training methods, etc. is contained in the population. The responses of the providers of the technology and the consumers of the technology will provide different views of APC performance.

Do you need to request OSU system e-mail addresses for recruitment purposes for this project?

No

Please provide a brief summary of this project. Include the research question and a brief description of how data will be collected.

Advanced Process Control (APC) has a high failure rate for projects relative to the units they serve. Specifically, the failure rates are after 18-48 months over 65% of the APC projects are non-functional or turned off. The units they serve have planned lives of 20-30 years. There have been numerous articles written on the subject; however, these are largely qualitative. To solve the relatively high failure rates, industry needs to apply specific plans and be able to compare their operations with others in the industry. Specifically, quantitative equations that measure results and enables owner-operators to adjust their operations and show that the problem is solved.

To get at the information necessary to do the study, there will be extensive literature searches coupled with interviews of the authors followed by several mental experiments to develop the equations. This then will need to be followed by several rounds of Delphi study to apply crowd knowledge to the theories developed.

Substantial progress has been made toward the overall goals listed above. A series of dimensionless equations have been developed that give an overall structure for the a quantitative protocol. The framework of a Delphi study has been developed. The dimensionless equations form the Delphi backbone. The an initial list of questions developed from the research and interviews are starting to fill out the rest of the skeleton of the Delphi

Research Question

What are the set of equations that will enable the owner user to:

1. Quantitatively Measure cash flow from the APC
2. Determine optimum operation
3. Measure continuous improvement
4. And to measure the overall progress toward successful operation.

The set of equations must be on a common basis for comparison to other units of the same type and measure performance across the process industries.

Aims

These aims were summaries from the proposal document submitted to the research committee on 15 Jun 2019.

- Aim 1. Maintenance – Mathematical models for optimum maintenance intervals and optimum cash flow from an APC are developed. These models are dimensionless to apply to a wide variety of industries. Further testing is planned to ensure these models fit existing practice.
- Aim 2. Capital – Models for developing the installation costs have been developed. Further testing is required to understand the variabilities to these models. These models consider workforce costs, workforce requirements, size of the APC and steps required to implement the APC. Effects of the size of the APC and cash flow from the maintenance are explored on the overall return of the APC project.
- Aim 3. Continuous Improvement – This portion models the overall yield from an APC and potential follow-on increases due to organizational learning. The follow-on increases are bounded by maximum APC performance. This section explores the maximum APC

performance as well as organizational learning curves as applied to the recalibration costs and how those costs affect the optimum recalibration intervals and cash flow from the APC.

- Aim 4. Success Tree – The maintenance and management issues of running an APC are explored in this section. Rather than a fault tree, this section focuses on what systems need to be in place to ensure success of the APC operation. Systems explored are key process indicator (KPI) programs, available expertise, APC goals, maintenance, operator training on APC and human factors related to APC installation.

Will your project involve the use of existing data?

Yes

Does the secondary data set you are using have any identifiers in the data?

Yes

The following is considered identifiable if found in a data set.

Name
Date of Birth/Death
Date of Appointments, Hospitalization, etc.
Street Address, City, Zip Code
E-mail address
Phone or fax numbers
Social Security Numbers
CWIDs/Banner IDs
License, certificate, or other IDs
Medical Device Identifiers/Serial Numbers
Vehicle Identifiers (license plate numbers)
IP Address
Biometric Identifiers including voices and fingerprints
Full Face Photos/Video Images
Genomic Sequence Data
Website/Social Media User names/handles/avatars
Any other unique identifying number, characteristic or code

Please attach a copy of the survey/measures/demographics, if applicable.

Delphi Question List.docx Surveys/Measures/Demographics

As Principal Investigator, I certify the following:

I certify I have reviewed this protocol submission and acknowledge my responsibilities as Principal Investigator.
I certify that all information provided in this application is complete and correct.

My signature indicates that I have read, understand, and agree to conduct this research in accordance with the assurances listed above.

By entering my password in the space provided, I am electronically signing this form and confirming the above attestations.

Not signed

To submit your application, please click "Next." Click "Submit" on the next page.

ORANGE MAIL

Mayo, Steve <stephmm@ostatemail.okstate.edu>

Approval of Not Human Subjects IRB Application IRB-20-58

irb@okstate.edu <irb@okstate.edu> Thu, Jan 30, 2020 at 3:36 PM
To: Steve Mayo <stephen.m.mayo@okstate.edu>, Sundar Madihally <sundar.madihally@okstate.edu>

Dear Steve Mayo,

The Oklahoma State University Institutional Review Board (IRB) has reviewed the following application:

Number: IRB-20-58
PI: Steve Mayo
Title: Advanced Process Control Delphi Study
Review Level: Not Human Subjects

The IRB has determined that your study does not qualify as human subjects research. You will find a copy of your Determination Letter in the generated documents section on IRBManager.
Click IRB - Initial Submission to go directly to the event page. Please click attachments in the upper left of the screen to access the letter.

If you make modifications that could change the determination, please contact the IRB prior to implementation.

If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB office at 405-744-3377 or irb@okstate.edu.

Best of luck with your research,

Sincerely,

Dawnett Watkins, CIP
Whitney McAllister, MS

Oklahoma State University
Institutional Review Board
Office of University Research Compliance
223 Scott Hall, Stillwater, OK 74078
Website: https://irb.okstate.edu/
Ph: 405-744-3377 | Fax: 405-744-4335| irb@okstate.edu

APPENDIX B

DELPHI QUESTION LIST

This is the list of questions submitted for the continuation of the Delphi Study.

Delphi Question List

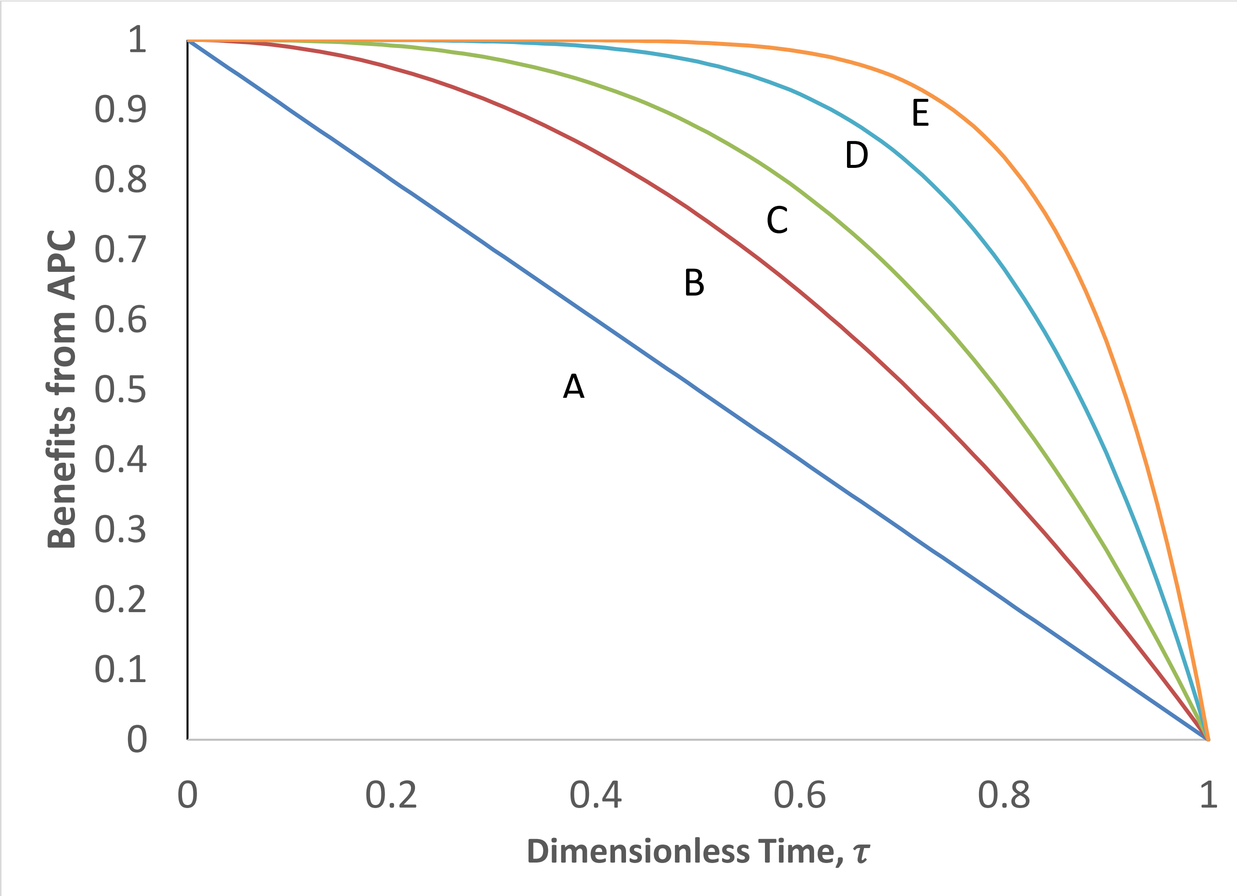
16 Jan 2019

Stephen Mayo

This list of questions is only meant as an exemplar of those questions that would be asked, participants. The questions will change with the different rounds of the Delphi study to achieve a consistent result across all experts.

Performance Decline Questions

the shape question could be put together like this. Which curve best represents the decline curves that have been seen



Other decline questions could include the following

What are base data around doing recalibrations: This section would require an introduction to the dimensionless equation. This would be the experts' best guess at theses parameter for a variety of installations. There would likely be a difference of opinion between the vendors and the owner-operators.

Recalibration Cost for one recalibration	Are the recalibrations automated? Or Manual?	What is the undiscounted annualized benefit, b_0	Number of Manipulated Variables, MV	Number Controlled Variables, CV	Number of Disturbance Variables, DV

What is the Estimated time to Shut off the APC	What percent of benefit function at shutoff	Type of processing Unit				

Yield Equation Questions

1. What reduction in the standard deviation of the throughput have you seen by placing an APC on the unit? Nominal values seen in the literature are near 50%
2. What variability is the limit based on (note: ≤50% is not possible – 100% is not possible)
    a. 95% (1.64σ)
    b. 99% (2.33σ)
    c. 99.9% (~3σ)
    d. 99.99%(3.72σ)
    e. other
3. What was the initial coefficient of variation for throughput (standard deviation/mean throughput maximum) before application of an APC on the unit
4. What is the "best operator" coefficient of variation after the implementation of the APC?

Capital

1. Once an agreement is completed on a specific step for a capital project for the installation of an APC, what is the amount of work for that work step?
2. What is the amount of experience required for an engineer to lead the implementation of an APC project? Please note the amount of experience feeds into the total cost for an APC project.
3. How many engineers are associated with an APC Implementation?
4. Is the project step scalable by a parameter (manipulated variable, controlled variable, or disturbance variable) or constant?
5. For inferential variables, how much work is needed to develop each inferential variable?
6. Training required to bring an experienced operator up to speed on the APC being installed:
    a. Previous APC-experience

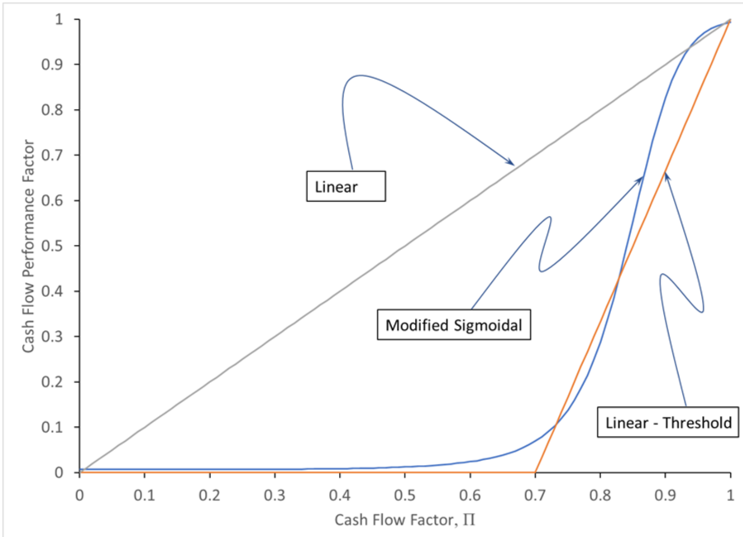
b. No APC-experience

Continuous Improvement

1. The Boston Consulting Group has proposed a model for a reduction in the cost to produce the next item. This incremental cost to produce the next item depends in part on the cumulative production that occurred before. For every doubling of the APC recalibrations, how much do you estimate that the incremental price for the recalibration will reduce(%)? Assume that the recalibration cost is for a unit of the same size
2. What is the best form of the equation for approaching the maximum yield?

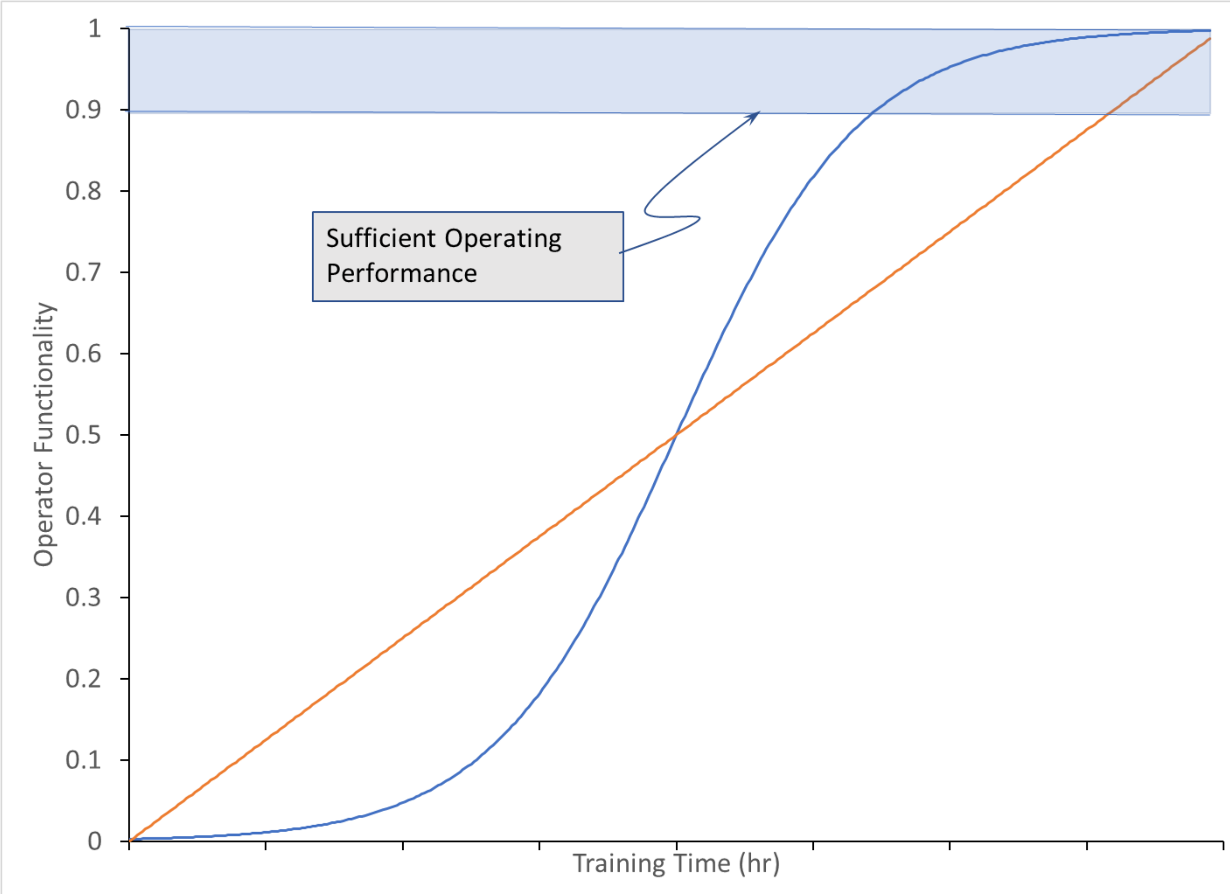
Success Equation

1. Key Process Indicators
    a. How often are key process indicators on APC reviewed site-wide or unit-wide
        i. Never
        ii. Daily
        iii. Weekly
        iv. Monthly
        v. Yearly
    b. Are there corporate goals for Advanced Process Control in terms of the key process indicators
2. Advanced Process Control Personnel Planning/Execution
    a. Is there a corporate plan to supply personnel trained in Advanced Process Control to each site?
    b. Is there a certification process for personnel trained in advanced process control
    c. Is there a corporate hierarchy for advanced process control?
3. What is the shape of a cash flow factor for the success equation? Some operators shut off an APC after the performance has dropped to a certain percentage of the original (SAT) performance.
    a. Linear – This would indicate the success of an APC is fully scalable with the cash flow from the
    b. Linear – Threshold – This would indicate that an APC success is scalable to the threshold and then shut off.
    c. Modified Sigmoidal – This would indicate that there is some other function that scales the cash flow to the success of the APC.



Operator Training

1. What is the shape of the training curve?



2. How much training is required of an experienced operator to come to sufficient operating capacity:
    a. That is experienced with APC on another unit?
    b. That has no prior APC experience?

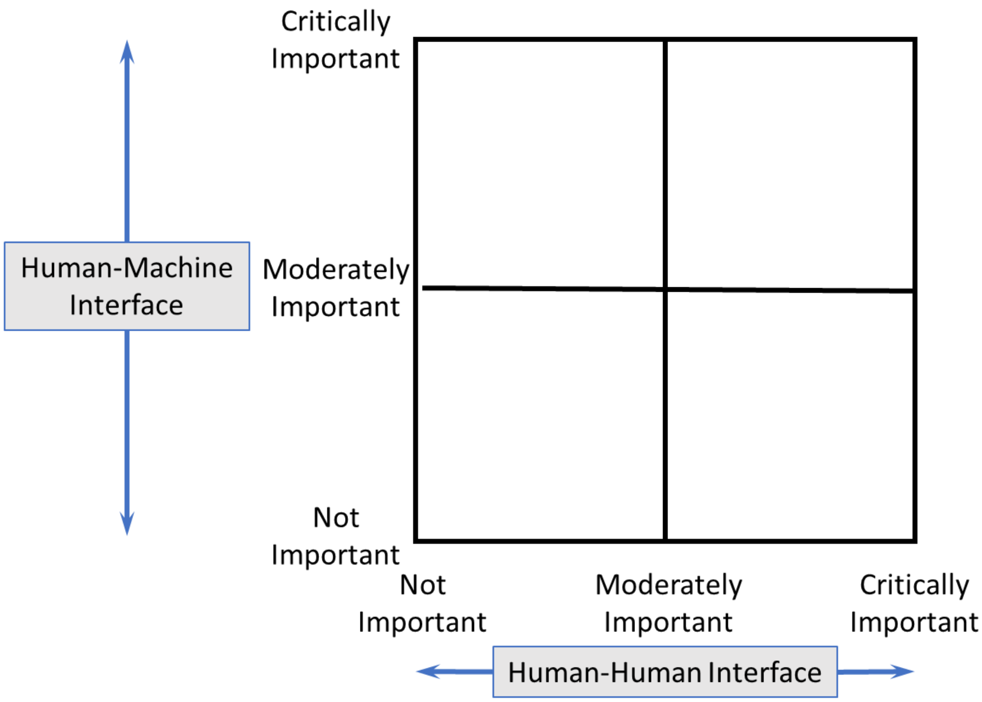
Note: Please assume the operator is experienced on the unit in which the APC is being placed

Human Factors

The following are notes to summarize the findings from the reading. There are few papers on the intersection of Human Factors and APC. There appear to be some common factors that characterize the human-machine interface and the human-human interaction that affect APC. It appears from the texts and experience that the variable for human factors may be a combination of the following parameters.

1. Workload –
    a. Based Work Load - Too high workload and that may adversely affect the capability of the operator to deal with issues on APCs
    b. Situation Management – There needs to be situation management that addresses showers of alarms during emergencies
2. Relationships – Relationships between the operators and the control engineering staff need to be good to ensure the full functioning of the APC. I have several examples of this affecting the overall performance of the APC
3. Ease of Operation of the Software – The NRC paper on human factors splits this into two factors: 1) Automation Complexity and the operator mental model and 2) Feedback from the Automation System and situational awareness. I have split these categories up across different aspects. Some of this is in Situation management under the workload and here. The software needs to do a few things well. Following is a list:
    a. Activate / Deactivate the APC easily
    b. Give a good status of the function of the APC
        i. Operators
        ii. Management
4. Management of Limits – There needs to be a clear expectation on the management of the individual manipulated variable on control of the limits. There is a wide variety of management philosophies on control of the limits. Some organizations have a high degree of control where others give complete control of the limits to the operator.

1. For human factors there are two aspects for consideration 1) human-human interface (the relationship between the operators and the APC professional) and 2) the human-machine interface: What is the relative importance of the human-human interface



2. Feedback from the Automated System and Situation Awareness…
    a. Has an evaluation been made of the program feedback to the operator on the status of the APC?
    b. How easy is it to remove the APC from the operation
    c. How easy is it to put the APC back on
3. Vigilance Workload and Skill
    a. What is the typical workload in terms of process units that the operator needs to keep track of?
    b. How many APC (MPC) does an operator need to operate
    c. What is the maximum APC that a successful operator operates?
    d. How quickly does performance degrade with increased APC input
    e. How many manipulated variables (MV) are contained in each APC

VITA

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