An investigation of deployment strategies of advanced process control systems

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Abstract

This research is intended for process control practitioners, plant decision-makers and process control technology leaders that are considering implementing Advanced Process Control (APC). An understanding of APC is developed from an introductory level a definition, its purpose and how APC relates to process control and the enterprise. Three types of APC techniques are adopted for elaboration on capabilities and applications. The applicability of the selected APC technologies is investigated based on the type of manufacturing industry. This investigation is conducted as there are varying approaches to the implementation of APC technologies in each of the selected manufacturing sectors. The key challenge is deciding on the best fit process control system. Various industry sectors are explored further to gain an understanding of the inconsistencies in the APC selection approach and to test the proposed decision framework. This research proposes a framework that guides the decision-making process that ranks the anticipated risks to be addressed for the considered APC technique to positively contribute towards the profitability of the enterprise. This framework forms the basis of the deployment strategy for APC. Hypothetical scenarios are defined to test the decision framework and validate its appropriateness. An impression on how various manufacturing sectors perceive process automation is given, together with a process that considers both qualitative and quantitative factors into the strategic decision-making process for the best APC technique.

Keywords

Advanced Process Control, Model-based Predictive Control, Intelligent control, Adaptive control

1. Introduction

The plant operation is faced with process constraints regardless of the manufacturing industry or type of manufacturing process. Conventional process control techniques alone do not have the capability to unlock further economic benefits that are caused by complex operational constraints.

Advanced Process Control (APC) has been identified as one of the technologies that can address these process constraints to improve profitability *(Eder, 2003).* Despite this, the decision-making process for the investment in expensive advanced process control systems and field instrumentation needs business justification *(Anderson, 1999).* Experts in the field of advanced control have proposed some pre-deployment techniques. These techniques evaluate the justification of APC deployment using qualitative or quantitative techniques.

Some authors have presented frameworks that consider both quantitative and qualitative techniques for the successful implementation of APC projects such as the General Controller Problem approach *(Craig, 2000)*.
Other authors have argued that qualitative aspects are critical to the success of APC implementation such as skills, technology and backing from all affected stakeholders *(Eder, 2003).* The literature has highlighted the risk introduced by negligence of qualitative factors in the pre-deployment phase such as user acceptance and management backing *(Craig, 2000).* The success of the organisation is related to its manufacturing strategy and overall business strategy. It is through such synergies that business decides on how to apply manufacturing technologies that will acquire a competitive edge and determine how well the business will perform *(Stephanopoulos, 1996).*

Considering APC technology is a business-driven decision, as most APC projects are motivated by economic returns. At the same time, there are multiple APC techniques and factors that the enterprise can choose from based on its manufacturing strategy. The selection and successful implementation of APC technology contributes to the success of the enterprise both financially and from a market competitive perspective.

A decision framework on how the enterprise can select the best suited APC technique based on both internal, external factors and quantitative and qualitative factors is investigated. This is achieved through the following research objectives:

- Identifying the factors that determine how advanced process control systems are decided upon and subsequently implemented.
    - Proposing a decision framework that could be adopted in prioritising the risks of APC projects based on the APC technique preferred to meet business requirements. This selection process considers both qualitative and quantitative factors, both internal and external to the enterprise.
    - The proposed decision framework is tested using various hypothetical scenarios and the results presented. The researcher provides evidence that both qualitative and quantitative aspects are critical to the successful deployment of APC, and that there is a way to incorporate both in the pre-deployment evaluation process.

The research questions addressed by the objectives are:

- What is the basis for manufacturing plants to choose or to implement advanced process control?
- Is there a decision framework for the selection of advanced process control techniques?

2. Literature Review

The literature review discusses the nature of process control systems with a specific attention on the sub-systems that make up a complete process control system. A history of control and its developmental highlights are presented with a focus towards process control. It shows the relevance and importance of process control systems. Most importantly, advanced process control is presented as a subsystem and how it integrates into the process control system and the purpose that it serves.

2.1 What is advanced process control?

A process could be a series of events that form manufacturing activities. These manufacturing processes are usually unregulated and require continuous external regulation. The purpose of a process automation system is to ensure that the process is controlled to achieve the desired results through monitoring, evaluation and control. In the process control sequence, the measured variable is evaluated by the controller and compared against the desired set point to determine the required proportional corrective action. A process cannot operate in a steady-state indefinitely; upsets will continuously act on the process due to dynamic environmental changes such as feed quality, flow rate, temperatures amongst others. It is in such a case that a control system is required, to ensure that external upsets are negated and the process runs as close as possible to the desired operating conditions for as long as possible. Process control is required to meet the quality, consistency and competitiveness requirements of a manufacturing process of goods or services. Process control is attained by having a desired condition or value of a chosen parameter and implementing control measures to bring the parameter closer to the desired condition.

In defining Advanced Process Control (APC) a previous definition is been adopted: "*Advanced Control is the intelligent, well managed use of process control technology systems and tools, based on sound process knowledge, to enable and to benefit from operations improvements in a most cost and time effective way." and further expands on the two elements within the definition, well managed and intelligent (Eder, 2003):*

- *Well managed* – aspects of APC implementation are planned, monitored, aligned to plant operational objectives and governed by sound rules and standards.
- *Intelligent* – refers to the technologies available to achieve these goals and the knowledge and skill to deploy such systems.

This definition highlights the importance of technology, operational objectives, standards and expertise as success-critical aspects in successful APC deployment.

APC is not meant to replace every single control loop in the operation, but is rather intended for those control loops that are quality critical to the production process. Processes have certain constraint limits that if not adhered to can result in equipment failure, process upsets or downtime. Usually if a process is run at an optimum, meaning as close and as efficient as possible to its limits, this may result in maximum production rates which translate into increased profitability. Companies realise APC benefits by reducing the mean variability over time and at the same time shifting this mean closer to a constraint. In such applications, the operation needs to be run close to the constraint without violating it and operating away from it could be associated with costs.

2.2 APC techniques and applications

APC is ultimately about designing a high-performance controller that can deliver the required production related benefits. The selected controller is exposed to high order and multivariable processes that are constrained and not linear *(Dotoli, 2015).* These controllers perform control functions that can be largely categorised as the following.

- Model based control techniques

Model-based Predictive Control (MPC) is well-known in industrial processes and has become the standard. MPC has an advanced control technique applies a dynamic model, which represents the actual process. The process historical data together with the optimisation function is used to generate predictive outputs that generate control outputs that steer future process behaviour towards optimisation.

- Intelligent control techniques

Intelligent control approaches are based on reasoning from available data. These kinds of controllers make use of predictive methods that consider historical data to make decisions. This enables intelligent control systems to emulate human intelligence.

- Adaptive control techniques

Adaptive control techniques have been introduced to present time-varying parameters that can be manipulated to accommodate plant disturbance uncertainties.

These three APC techniques are chosen for this study; however, there are other techniques that are classified as belonging to the APC family.

Part of the literature review is to understand where these specific APC techniques is employed and for what purpose. The applications selected are categorised by industry type. Various industries is selected to have a view of the applicability of APC technology. The application of the nominated APC technologies is studied in each of the sectors to establish the industry-specific benefits and therefore the motivation to implement APC. A summary of each of the selected APC techniques and industry specific application are detailed in Table 1.

Table 1. APC application

	MPC Control	**Intelligent Control**	**Adaptive Control**
Coal Power Plant	Application: Decoupling Benefits: Efficiency *(Blaazer, 2011).*	Application: Pulverisation Preventative Benefits: Optimal combustion Reduced emissions *(Chai, 1999*)	Application: Turbine start-up Benefits: Improved response demand fluctuations. Efficiency *(Karashima, 1981) (Kamiya, 1997)*
Petrochemical Refining Plant	Application: Inconsistent raw material Benefits: Improved quality and yield of products *(Stephanopoulos, 1984)*	Application: Heat Energy inefficiencies Benefits: Reduced energy consumption Source: *(Szklo 2007)*	Application: Sulphur recovery Benefits: Reduced emissions *(Raimondi, 2012)*
Pharmaceutical Plant	Application: Continuous tablet compaction. Benefits: Throughput and Quality	Application: Continuous Wet Granulation Benefits: Throughput and Quality *(Faure, 2001)*	Application: Fermentation Benefits: Yield and Quality *(Rani 1999)*

2.3 Approaches to APC deployment

Different approaches or pre-deployment methodologies are studied from various sources regarding APC systems and their benefit evaluation techniques. The aim of scrutinising these methods is to determine how various manufacturing industries perceive general process control and advanced process control. The second objective is to establish if there is a decision framework that is adopted to determine the priority risks associated with the selection of a specific APC technology in each of the nominated industries. Most reviewed approaches have proposed that the decision making of APC technology is based on qualitative factors that include technical aspects such as technology and the expertise to deploy and sustain the APC technology in consideration *(Eder, 2003) (Adler, 1995)(Marlin,1991).* The quantitative aspect is that of cost-benefit or economic analysis of the considered technology *(White, 2007)* (*Asawachatroj, 2012) (Craig, 2000).* The main factors of consideration that emerge throughout all reviewed approaches are quantitative even though authors have highlighted the importance of qualitative factors. The common theme in all the approaches is the economic benefit that would be realised through APC implementation and the technical ability to deploy and sustain the technology.

What is not articulated is how these qualitative and quantitative factors can be considered holistically as part of the decision-making process. It should be understood that the aspect of economic evaluation plays an important role and is a key business driver simply because the plant exists as a profit generating asset for the enterprise. The risks that have been highlighted are purely technical. Another observation is that the motivation to initiate APC projects are on the basis of economic gain. The external key business drivers are not used as part of the decision-making process towards the process automation strategy. Out of all the manufacturing sectors that employ process automation, three are chosen for scrutiny; Pharmaceutical and Food, Coal Power Generation and Chemical and Petrochemical refining. These have been selected due to their diverse production process characteristics and industries. The three selected manufacturing sectors are explored in more detail to develop an understanding of how process automation is perceived and implemented with a specific interest in APC technologies. The aim of this examination is to uncover (if any) factors that would influence the APC decision making process and the economic drivers.

3. Research Methodology

The factors that affect APC in decision making can be both qualitative and quantitative. Factors can be in a form of benefits, risks, opportunities and costs for the decision-making process from implementation through to maintenance. Quantitative aspects may include profit or economic factors such as throughput improvement and energy consumption reduction. Qualitative benefits such as ease of use or ease of integration reduction resulting from APC implementation and plant operability. The methodology applied is in the form of a decision-making framework which is depicted in Figure 1. The aim of the proposed framework is to incorporate external and internal factors and qualitative and quantitative factors that influence selection of an APC technology.

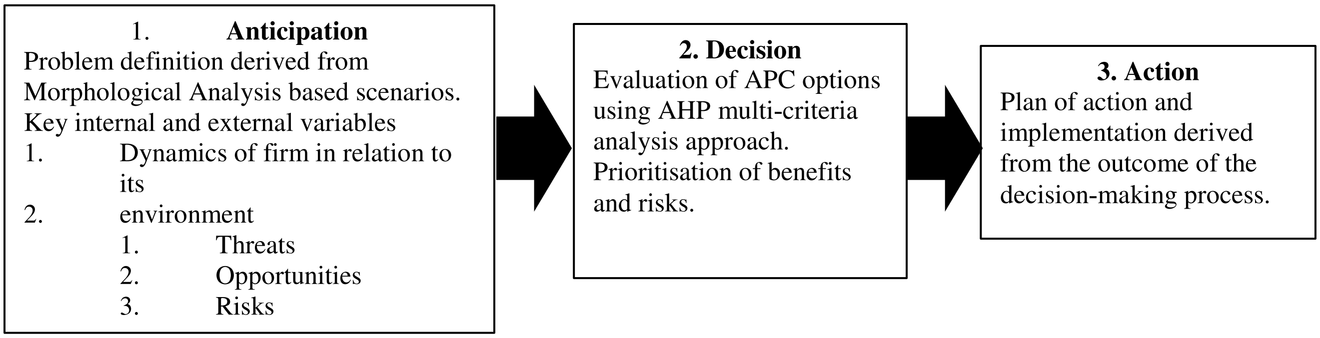

Figure 1. Decision making framework

3.1 Anticipation

This study presents hypothetical scenarios that a manufacturing business encounters that can be resolved using APC technology. The scenarios are based on the nature of each industry and industrial process applications as established in the literature review. The scenarios are there to test the appropriateness and effectiveness of AHP as a decision-making tool in this process. A form of determining or hypothesising various scenarios that an organisation can face is morphological analysis. Morphological analysis (MA) is defined as, "a method for rigorously structuring and investigating the total set of relationships in inherently non-quantifiable socio-technical problem complexes" *(Ritchtey 2009).*

By hypothesising various scenarios, the model determines which APC application best resolves the problem. The developed scenarios take into consideration the strategic business challenges that the company has to deal with, which are induced by its environment. Strategy and scenario should not be confused with each other. The second motivation of implementing this research style that encompasses two tools to achieve its objective is to address these questions *(Godet, 2000):*

- What can and might happen? Derived from scenario planning

In the business context, what environmental changes can negatively (threats) or positively benefit (opportunities) that would need to be exploited.

- What can be done? Presented by APC alternatives

In relation to its automation strategy what options are there that can achieve the strategic intent.
The MA based scenario would constitute both values and parameters.

3.2 Decision

The three identified APC technologies are subjected to the scenarios and the Analytic Hierarchical Process (AHP) is applied to determine the best suitable technology. AHP has been used because of its ability to handle both quantitative and qualitative methods in a single empirical enquiry *(Wedley, 1990).*

The hierarchy is presented in Figure 2, with the three levels of the decision-making process. Level 1 (top) is the ultimate objective that each of the plants is to meet, stated as profitability and sustainability. Level 2 (intermediate) consists of risks or criteria that would need to be fulfilled or addressed for the ultimate objective to be realised. At the lowest level are the types of advanced process control techniques, which are the alternatives.

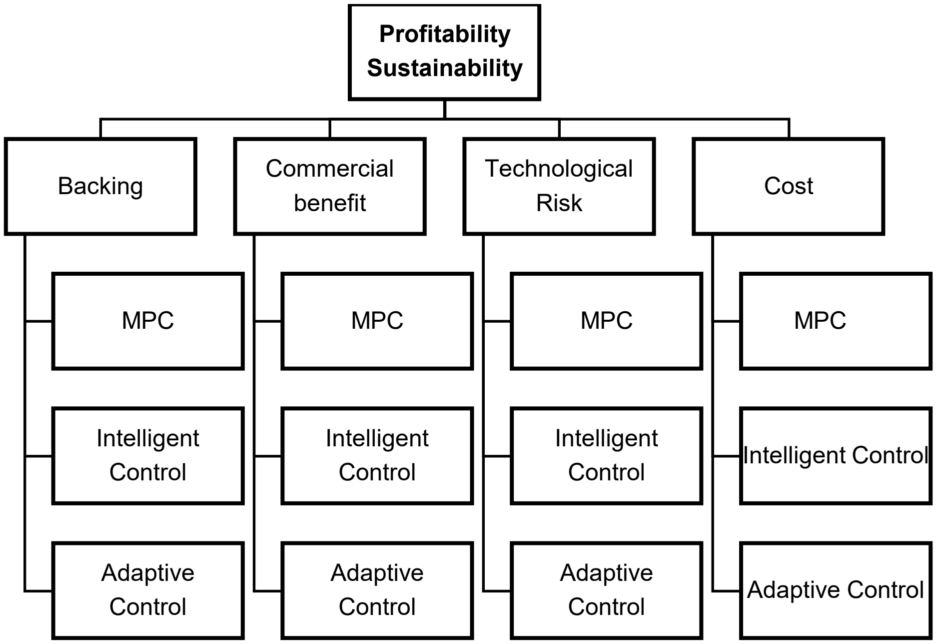

Figure 2. AHP hierarchy

The pairwise comparison is based on the identified AHP criteria that are posed as the following questions for all three scenarios.

i. Which APC technique would receive the most backing from all stakeholders, which includes engineering experts, operations staff and backing from sponsors in the form of senior management?
ii. Which APC technique would deliver the most return on investment considering the current affordability of the business at the time?
iii. Which APC technology would be most preferred without subjecting the firm to unmanageable risk that would deem the APC project unsuccessful from a technological perspective? Example, software, hardware and technical support capabilities (both internal and external).
iv. Which APC technique would provide the most competitive advantage for the business in the market place, through better responsiveness to market changes

3.3 Development of scenarios

The multi-dimensional matrices for all three chosen industries is used to develop scenarios that are subject to the AHP analysis. Each problem scenario is derived from the constraints that are specific to each manufacturing facility and its industry.

- **Scenario A: Power generation**

The defined scenario maps out all parameters and values which include regulatory, availability, throughput and environmental aspects.

Table 2. Power generation scenario

Regulatory	**Availability**	**Throughput**	**Environmental**
Electricity Price	Unplanned downtime	Poor Coal Quality	Diminishing Coal supply
Power Quality	Long MTTRs	Poor load tracking	Renewable Power emergence

The specific value is electricity pricing, the power plant needs to remain efficient to be profitable. The pricing is regulated because a power plant is deemed a public utility that may exploit its capabilities as a monopoly if not regulated. The value chosen under the availability parameter is unplanned downtime.

The cost of start-up that comes with every unplanned shut down has a negative impact on the ability to meet load demands.

A third phenomenon is the inability to closely track the load demands; this affects the longevity of the equipment within the steam circuit. The ability to regulate process temperature and pressure with respect to the load improves the life span of process steam infrastructure. Lastly, environmental regulations have been imposed on coal fired power plants to curb excessive emission of greenhouse gases. Furthermore, the renewable sources of generation have exerted more pressure on coal generation of electricity to remain relevant by controlling emissions. Another environmental aspect is that of diminishing sources particularly water and coal. These resources have required coal fired power plants to generate more power per ton of coal to preserve resource reserves.

- **Scenario B: Pharmaceutical**

The defined scenario maps out all parameters and values which include external regulatory quality requirements, throughput challenges and short product life expectancy brought about by generic manufacturers.

Table 3. Scenario B Tablet Manufacturing Plant

Quality Regulations	**Throughput**	**Process Type**	**Product Life Span**
Manufacturing process regulation	**Reprocessing**	**Batch**	**Short**
Product regulation	**Ability to scale up**	**Batch and Continuous**	**Long**

The defined problem scenario reflects an encounter where the enterprise is expected to adhere to strict product and process quality regulation for a product with a relatively short life expectancy. Due to the nature of the pharmaceutical industry, at times companies are challenged by products that experience a drop in demand, resulting in compromised profitability for the enterprise. The dual nature of the manufacturing process in a form of batch and continuous, presents the opportune manufacturing configuration for automation.

The reason for not adopting automation have been flexibility and lack of non-continuous manufacturing processes. This is an opportunity to employ automation to the continuous process, as it would deliver reduced production costs and improved product quality *(Schaber, 2011).*

- **Scenario C: Petrochemical**

The defined scenario maps out all parameters and values which include quality, throughput and efficiency aspects.

Table 4. Scenario C Petrochemical Refining Plant

Regulatory	**Quality**	**Throughput**	**Efficiency**
Emission/Waste Regulation	Inconsistent raw material	Poor Ramp up Rate	Poor Yield
Product Regulation	Inconsistent manufacturing	Inability to scale up	High Energy Consumption

The specific values are inconsistency of raw material supply, which negatively impacts the subsequent downstream processes and ultimately the quality of the final product. Due to inconsistent raw material, the ability to meet required demand is affected resulting in the inability to scale up. Fluctuations in energy demand impact the throughput expected of a refining facility. The increase in economic activity demand, drives refineries to produce more to meet the related energy demand. Thirdly, the problem is further exacerbated by poor yield, reduction in extractable valuable product. In refining one of the objectives is to increase the yield of the white products and a reduction of the less valuable material. This reduces the operating costs as more valuable product is extracted from the raw material.

These problem scenarios are subjected to the three APC techniques.

4. Results

Across all three chosen manufacturing sectors MPC is observed as the dominant APC technology. This is attributed to the number of documented applications that employ MPC. The power and pharmaceutical sectors have emerged with intelligent control as the second preferred APC technology. Both these manufacturing sectors vary from a petrochemical refinery in their nature of the manufacturing. Petrochemical manufacturing is considered a continuous process that can be modelled easily. The nature of a coal fired power plant constitutes of sequential control and processes that are coupled. A pharmaceutical manufacturing facility is made up of partial batch processing. Intelligent control is observed as the second most preferred technique in non-continuous manufacturing processes.

Table 5. APC Ranking

	Power		**Pharmaceutical**		**Petrochemical**	
	AHP Factor	*Ranking*	*AHP Factor*	*Ranking*	*AHP Factor*	*Ranking*
Model-Based Predictive Control	0.48	1	0.48	1	0.52	1
Intelligent	0.35	2	0.34	2	0.21	3
Adaptive Control	0.18	3	0.18	3	0.27	2

Table 6. Risk factors by industry

	Power	**Pharmaceutical**	**Petrochemical**
Buy-in	0.25	0.37	0.21
Cost	0.10	0.11	0.10
Technological risk	0.18	0.37	0.21
Commercial benefit	0.47	0.15	0.48

Table 6 details which risk factor has the most significant impact in selection of the APC technique in each of the selected industries. The effect of each risk factor is elaborated below.

- Buy-in

Buy-in represents the highest risk within pharmaceutical manufacturing because of the nature of the industry and manufacturing processes. The industry is considering continuous manufacturing to adopt process automation. This could be attributed to the sector's stringent regulatory requirements for product and process manufacturing licensing. The adoption of advanced process control would only be embraced once the industry has adopted continuous manufacturing techniques. The adoption of continuous manufacturing techniques will improve the implementation of process control. The results show buy-in in power generation as the second most critical factor in ensuring APC technology success when compared to other industries.

- Cost

The sector with the highest cost risk is pharmaceutical. This could be due to lack of expertise and products that are customized for this industry. The amount of funding could be substantial in creating or customizing solutions from other sectors. The other two sectors have similar cost risk magnitude which could be attributed to the low expertise level in the sectors

- Technological risk

In pharmaceutical and petrochemical industries, the technological risk is equal to the buy-in. It can be argued that this is so because technology depends on people for it to be a success. It can further be argued that by not having adequate support in a technology or system may negatively impact on its sustainability. The power sector results in relation to others show that buy-in risk is greater than technological. This could be interpreted as not having adequate understanding of the processes and not being able to effectively implement the available systems to power plant control problems.

- Commercial benefit

The petrochemical industry displays the highest commercial benefit when compared to power and pharmaceutical. The reason behind this could be because of a low investment relative to the other industries as the technology and expertise are readily available. The fact that MPC is synonymous with APC in petrochemical refining industry, means the technology is readily available and requires minimum spend to make further improvements that would improve profitability. This commercial benefit is followed by power generation being 2.1% lower than petrochemical refining. The magnitudes shown by the commercial benefit from both these sectors display a possible opportunity for APC to improve profitability. However, pharmaceutical is at the lower extreme of the scale with a 15% commercial benefits. It could be argued that the industry needs to reconsider regulations that govern the use of process control. This would increase the potential commercial benefit that lies therein. Currently 15% presents a risk to the firm that would consider the implementation of APC in resolving profitability challenges.

5. Conclusion

Literature reveals inconsistencies in how APC projects are decided upon and their subsequent implementation. Furthermore, the barriers that prevent deployment of process automation are explored as these impact the extent of implementation of APC.

This research investigates pre-deployment factors and proposes a decision making framework that could assist the implementation of an APC based project from a technology selection perspective. A decision framework is proposed that can be adopted in prioritizing the risks of APC projects using AHP to select the best suited APC technique. This investigation is based on documented literature pertaining to APC that is applied in various industrial sectors, specifically power generation, petrochemical refining and pharmaceutical industries. The business environment challenges are depicted through hypothetical scenarios that are formulated using morphological analysis. The presented decision framework is intended for use as a high-level tool that considers all stakeholders which are plant operations, management, engineering, maintenance and supplier.

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