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Review

Economic assessment of advanced process control – A survey and framework

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Abstract

A key objective of industrial advanced process control (APC) projects is to stabilize the process operation. In order to justify the cost associated with the introduction of new APC technologies to a process, the benefits have to be quantified in economic terms. In the past, economic assessment methods have been developed that link the variation of key controlled process variables to economic performance quantities. This paper reviews these methods and incorporates them in a framework for the economic evaluation of APC projects. A web-based survey on the economic assessment of process control has been completed by over 60 industrial APC experts. The results give information about the state-of-the-art assessment of economic benefits of advanced process control.

Keywords: Advanced process control; Process control benefits; Process monitoring; Economic performance assessment; Financial analysis; Survey

Contents

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1. Introduction

Economic assessment of APC projects facilitates the roll-out of a new APC technology and moves the technology from the development stage to wide-spread implementation. If a direct relationship between the economic benefits and the effect of process control systems can be identified then the control system investment cost can be weighed directly against the benefits to establish a business case. Financial analysis is therefore crucial to advance control technology developments and provides a basis for the main business drivers of process control. These business drivers include reduction in variability, thus moving process variables closer to their optimum, safety and environmental regulations, reliability and customer specifications [1]. In a recent industrial publication [2], the number of APC applications worldwide was estimated to be around 6000 and it has been growing steadily over the last few years.

At present, process control engineers struggle with the life-cycle of APC projects [3]: after thorough implementation, the system operates at its maximum efficiency. Changes in the operating conditions and process equipment cause the performance of the APC system to degrade over time and eventually the controller could even be switched off. APC projects are said to have a pay-back period of 3–9 months but often the maximum efficiency degrades after a shorter period of time and the investment does not yield the expected pay-back.

This paper introduces and discusses a framework for the economic performance assessment of APC projects, see Fig. 1. The basic version of the framework was presented and discussed at an industrial workshop [4]. The framework was subsequently expanded to capture the assessment steps throughout the life-cycle of APC projects by describing parallel engineering and managerial processes that are often conducted in manufacturing organizations. This paper is structured using the expanded framework. The steps for the economic assessment can be grouped into three main blocks as shown in Fig. 1. The first block covers the estimation of cost and benefits of a new project before implementation. The second block describes the calculation of performance and economic assessment after implementation and when operating data from the new system is available. The last block of the assessment looks at the performance after a period of time has elapsed. After this period, operating conditions will most likely have changed, which might affect the performance of the controller. APC system maintenance and the last assessment step might be repeated regularly to ensure that the controller is still achieving the desired performance.

A survey conducted among APC industry experts was designed as a web-based questionnaire covering benefit estimation, calculation and reporting. Sixty-six respondents reported on the economic assessment within their organizations. The most important results of the survey are compiled in this paper.

The paper is organized as follows. In the next section, a historical development of economic performance assessment of APC over the last five decades is given. Section 3 describes the survey design and research methodology. The results of the survey are discussed in Sections 4 and

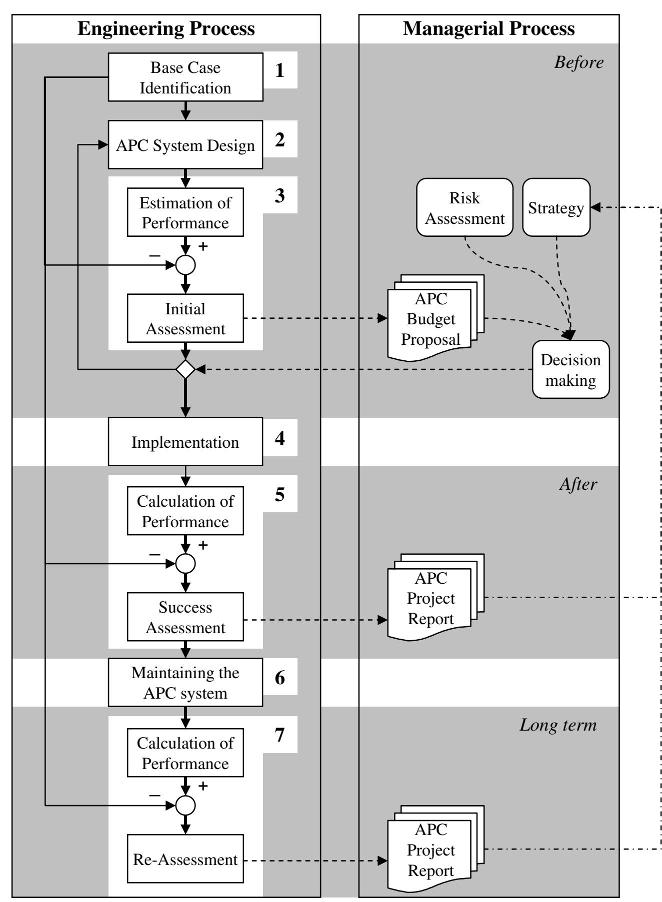

Fig. 1. Framework of the engineering and managerial process of the economic performance evaluation of APC.

5 according to the framework steps for both the engineering and managerial processes. Section 6 highlights future trends in APC technology development and the economic estimation thereof.

2. Historical development

Economic assessment of process control systems has been a concern of process control engineers since the first implementation of such systems. The first applications are therefore reported by industrial authors for whom the issue is part of their day-to-day business. Recent reviews indicate that the topic is still of great interest [2,5]. Although highly relevant and of practical value, many of the reported methods lack a theoretical basis and rely heavily on simplified assumptions.

A first major technology leap was the introduction of computers for process control in the early 1950s [6], triggering the discussion about economic performance: when is it worth investing in a computer control system? Several case studies reported successful installations and realized benefits of computer control, and also specified sizes and processes for which computer control could result in a significant economic benefit [7–11]. As a result, Williams [12] reported a linear growth in the number of applications of process control computers on chemical and petroleum plants in the 1960s.

It became evident in the 1970s that computer control could indeed result in increased profits, and most manufacturing companies switched to the new computer technology. In some cases, technology was installed for technology's sake [13,14]. Hidden or indirect benefits from computer control were discussed, including the availability of operating data, better information about the process and alarm management [15]. Steady-state design was now discussed in conjunction with dynamic control strategies [16–18]. The development of economic assessment during the 1970s and 1980s was mainly driven by control systems suppliers as a motivation and justification for their products such as Setpoint Inc. [19,20], Profimatics Inc [9,21–23], The Foxboro Company [13,24–26] and Honeywell [27,28].

At the beginning of the 1990s, globalization started to increase the pressure on manufacturing companies to lower their cost and increase productivity [29–31]. New generations of distributed control systems (DCS) also facilitated the easy implementation of new control strategies [32–35].

In 1987, the Warren Centre Case Study [36] appears to have focused the attention of academic research institutions on the economic side of process control. Since then, economic assessment has been taken up as an academic research topic. In particular, control for increased profit and a resulting economic estimate has been studied [37–40]. The economic impact of variance reduction measured by performance functions was put on a more solid theoretical base in the years that followed [41–44]. Recently, Xu et al. [45] developed an approach for the economic performance evaluation of MPC.

3. Industrial survey on economic assessment of APC

A survey on the current practice of economic performance assessment of APC was conducted to capture industry guidelines and standards. The aim of the questionnaire was to estimate the influence of the economic performance on the managerial process and to identify methods for the estimation of the economic performance. Furthermore, questions on the current use of APC methods and tools formed part of the questionnaire to assess the impact that APC has on modern production processes. The questionnaire was aimed at APC experts employed by manufacturing companies or by APC solution providers. The design of the questionnaire as well as the research methodology will be addressed in the following. The results are discussed in Sections 4–6 of this paper.

3.1. Research methodology

The survey on economic assessment was conducted online as a web-based questionnaire. Two slightly different versions of the questionnaire were available, one version for experts within manufacturing companies, referred to as APC *users*, and a second version for experts at APC system vendors, referred to as APC *suppliers*. Included in the target group were process control engineers and managers as well as control technology developers.

In total, 66 APC experts, 38 APC users and 28 APC suppliers filled in the questionnaire.

The extensive search for respondents through advertisement at industrial conferences as well as on websites and in newsletters ensured that the respondents come from worldwide locations operating in various industries. Fig. 2 shows the distribution of respondents by industry and continent. The majority of the manufacturing companies operate in the petrochemical, chemical, petroleum refining and minerals processing industries while APC suppliers usually apply their product and services to a wide range of industries. Other industries include oilsands, steel, glass, cement and food processing.

On a note of caution, the relatively small sample size has to be taken into consideration throughout the discussion of the results, even though it is significantly larger than in similar studies [36,46]. Most of the results do not change significantly when considering only 40 answers compared to 66. All responses were verified as coming from APC experts in the field.

3.2. Questionnaire design

The content of the questionnaire was structured consistently with the framework introduced in Fig. 1. The questionnaire for APC users is attached to this paper in Appendix A and is organized as follows. The first two

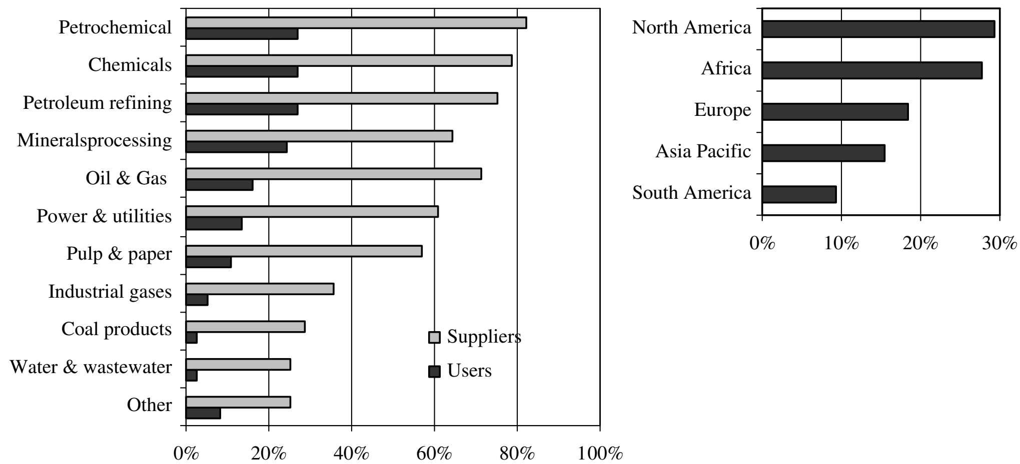

Fig. 2. Participants of APC survey by industry and by continent (total: 66 participants). Several answers were allowed for industry sectors.

sections identify the respondent and capture the size of the plant as well as the use of control technology within the organization. The third section queries the use of APC technology and tools. Sections four to six are key to the economic assessment process. While Section four covers the managerial process by asking about reporting, decision making and budgeting, Section five is concerned with the engineering process and the estimation of cost and benefits. Section six requests the respondents opinion about the accuracy, importance and satisfaction with the current estimation process in place as well as about future trends.

4. Framework – the engineering process

A good estimate of the performance that will result from improved process control requires process insight as well as an understanding of the control technology. Seven steps of assessing the performance before and after implementation are described in the left-hand column of Fig. 1. In this section, these steps will be discussed in detail.

The focus of the survey as well as of most APC projects is on continuous processes. In the survey, 90% of respondents work on continuous processes. Cost/benefit assessments of batch processes are conducted and reported less frequently since there are fewer batch processes in the chemical, petrochemical and refining industries. However, most of the methods described in the following can be applied to both batch and continuous processes for which the time trend is monitored.

4.1. Base case identification

The initial step when considering a new APC solution is to analyze the performance of the current system or the so-called base case. For the questionnaire, APC experts were asked how they determine the base case performance and benefits. The majority of APC suppliers (53%) and a large number of APC users (42%) estimate the variance before control using historical data. Other estimation categories include past experience with a similar project (25%) and the estimation of qualitative, non-monetary benefits (15%) as well as rules of thumb [47], such as that a new control scheme will increase the throughput by a fixed percentage (7%). For the water and waste-water industries, Lant and Steffens [48] provide a qualitative self-assessment form to establish how good the process control is. The disadvantage of such a table is that it is industry related and has to be updated with the development of new technologies.

The questionnaire results support the industry–university study by Marlin and co-workers [49], which highlighted the importance of determining the base case operation through in-depth analysis of historical plant data. An important consideration for the base case identification is then the selection of the appropriate process variables from which the variance is estimated. Latour [19] recommends the analysis of the following variables:

- Critical product qualities.
- Important manipulated variables.
- Material and energy balance parameters.
- Constraint variables.

In-depth process insight such as knowledge of the interrelationship between variables or the steady-state economic model of the process is indispensable information for the base case identification [50]. A careful preliminary data-driven analysis of the plant can provide further insight prior to any control upgrade [51].

4.1.1. Performance functions

In many cases, the variance of a process variable can be linked to a monetary value. Although this is not the only instance where economic benefit can be captured, it is the most commonly used. A performance function [22,52] defines either profit or loss as the process variable x moves away from an optimum operation point. The derivation of a performance function requires process insight and expert knowledge. General guidelines are difficult to establish, as the economic impact depends on the nature of the production facility and on the industry [53]. Performance functions reported in the literature are obtained from plant experiments [54], process knowledge combined with textbook relationships [55], the questioning of process experts [56], and from an analysis of the product value versus production costs [42]. There is a need for a systematic method to determine performance functions and for quantifying the impact that the choice of performance function has on the calculated profit.

The most frequently used performance functions θ are shown in Fig. 3, that is, a linear performance function with constraints, the CLIFFTENT and a quadratic performance function. These performance functions are the ones most commonly used in the literature, often without much theoretical justification.

Linear performance functions with constraints indicate that the economic benefit increases linearly until a certain threshold at which, if exceeded, the product turns out as waste and the profit is zero. This relationship was described for a fuel oil blending process [19]. An approach for controlling a process variable under economic constraints as described by a constraint performance function is the introduction of a back-off [37–39]. The true optimum, however, cannot be achieved owing to uncertainty in model parameters and measurements.

The CLIFFTENT performance function was introduced and named by Latour [57] and has been discussed subsequently for applications and multivariate optimization [41,58].

The control strategy can be adjusted to the economically optimal point and the economic efficiency of the process can be monitored online. The performance function thus provides a powerful tool for estimating the economic benefit of process control throughout the implementation and commissioning of a new system. The performance function, however, has to be updated with changing economic conditions.

4.1.2. Average performance

The economic performance of a process is often summarized in a single monetary value using historical data and the performance function of one or several process variables [42,59]. The average performance gives an indication of the loss or profit of the current process operation, and can be calculated in various ways.

The most common way is to multiply the estimated probability density function of the process variable by the performance function. The average performance P_{av} is computed as the integral of the product. The probability density function is usually assumed to be Gaussian to make it easy to estimate from historical process data. Although industrial process data does not necessarily follow a Gaussian distribution it usually provides a good enough estimate of the economic benefit [42].

Zhou and Forbes [42] determine the base case for several dependent process variables and compute the average performance of the process operation for varying process variables and specifications. The average performance is compared to the maximal achievable performance at the optimal operating point of the performance function.

4.2. APC system design

Once the base case has been established the next step is the design of the new control system as described in Fig. 1. Arguably the most important choice for the APC system design is the selection of the control method. In the web-based survey, the respondents were asked how frequently APC methods are used in industry. The results are shown in Fig. 4. Further APC methods reported by some respondents are inferential control, lambda control of combustion, and robust MPC technology. The results show the advance of model predictive control in the process industries, which is used as a standard tool or frequently by more than two thirds of the respondents. Constraint control as well as split-range control are also frequently used in the continuous processing industries. Computational intelligence techniques, such as neural networks and fuzzy logic, that some expected to bring considerable profits [60], are among the less popular methods.

4.3. Estimation of performance and initial economic assessment

An estimate of the new system's benefit will tell whether the benefit gained from better control will exceed the cost of the investment. In Step 3 of the framework described in Fig. 1 the performance of the new APC system is estimated and compared to the base case. It is possible to estimate the average performance of the new controller using performance functions as described in Section 4.1.1.

In the case of a constraint performance function, a reduction of variability allows shifting of the operating

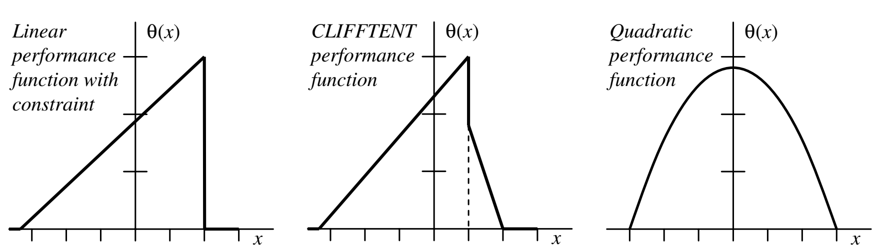

Fig. 3. Frequently used performance functions: linear performance function with constraints [19], CLIFFTENT [57] and quadratic [22] performance functions; x: process variable; θ: performance function.

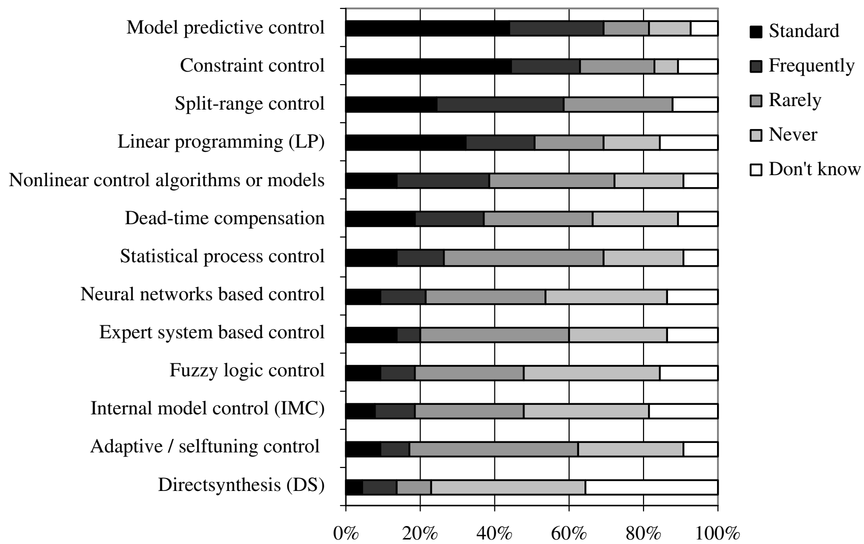

Fig. 4. Industrial use of APC methods: survey results.

point closer to a limit x_L by $\Delta\mu$, see Fig. 5, [43]. The reduction in variance is often assumed to be a fixed percentage. Several industrial and academic authors assume a reduction of the standard deviation by 50% [19,61–63] or by 35% [64]. More optimistic estimates even propose a reduction by 85–90% [20,27,65].

The assumption of a fixed rate of reduction as applied by many industrial authors is practical but in many cases somewhat arbitrary. To achieve a more objective measure, an upper bound for the economic benefit was proposed by Muske [44]. The minimum variance of the process variable can be estimated from historical data and process knowledge [66].

If an accurate process model along with the designed controller is available, then data for the new system can be simulated and used to estimate the average performance. This approach was pursued by Zhou and Forbes [42] as well as by others [56,67] to get a realistic picture of the performance of a new APC system. This approach, however, might not always be the best choice since it requires a detailed process model and significant computational effort.

The improvement resulting from the control system upgrade can be expressed in quantitative terms by comparing the average performance before the new system, that is, the base case $P_{\mathrm{av}}^{\mathrm{before}}$, and the estimated average performance that is expected from the new control strategy $\widehat{P}_{\mathrm{av}}^{\mathrm{after}}$. This improvement can be expressed as a profit index computed from the variance reduction achieved by the new system and a minimum achievable variance estimate [68].

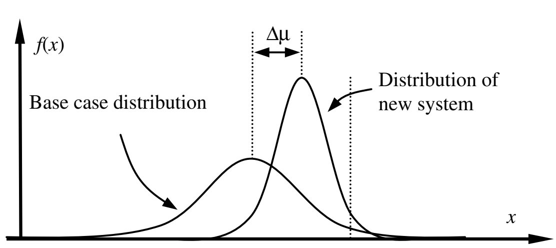

Fig. 5. Performance estimation through shifting of a process variable closer to limit x_L.

Several other profit and cost factors are not always easy to express in monetary terms but nevertheless make a considerable contribution to the assessment. In the following, several profit and cost factors are discussed.

4.3.1. *Profit factors*

Both APC users and suppliers were asked in the questionnaire to name the three most important contributors to the benefits that result from improved process control. Several authors [1,23,69,70] discuss the benefits of APC systems and their contribution, which formed the basis of the list in the questionnaire. Fig. 6 lists the most frequently named factors. Despite the small sample size a clear trend can be observed. In particular, throughput and quality, which are directly related, were two frequently named profit factors. A higher quality can be achieved by limiting the throughput as shown in Fig. 7. APC shifts the curve up, thus allowing higher throughput at the same quality or improved quality for the same throughput or a combination of the two.

Some factors contributing to the benefit of APC are difficult either to estimate or to express in monetary terms. Nevertheless, they contribute to the initial assessment and budget proposal, as shown in Fig. 1. An interesting result of the questionnaire is that the reduction of operating manpower is named as a profit by 14% of the APC suppliers while it is not regarded to have an impact on the profit improvement by the manufacturing companies. A reasoning that manpower reduction results from advanced process control is that operator attention necessary for problem loops or alarm conditions can be reduced [71]. A reduction of operating manpower as a result of APC was reported for an Austrian refinery [72].

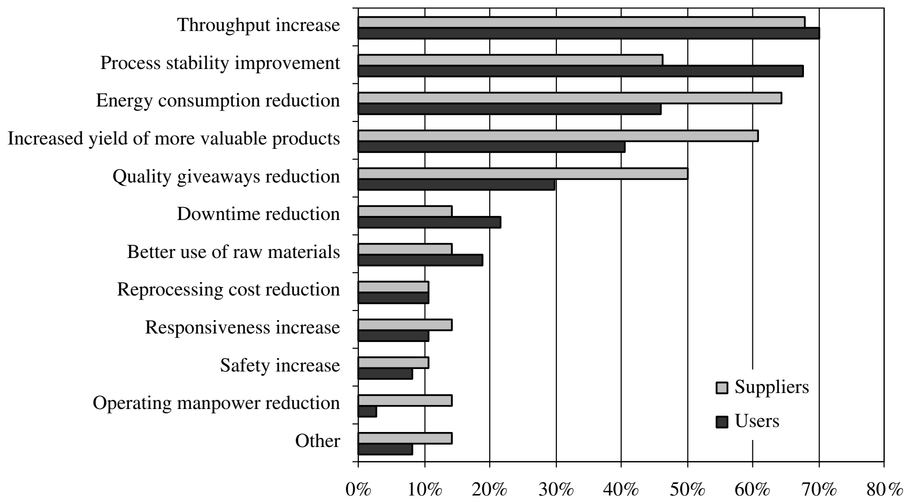

Fig. 6. Main profit contributors: survey results.

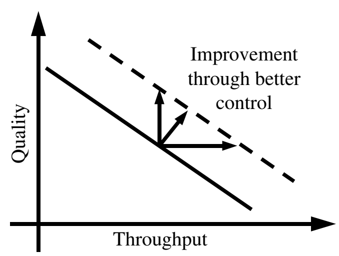

Fig. 7. Relationship between quality and throughput.

4.3.1.1. Throughput increase. An increase in throughput can be beneficial if additional quantities of the product can be sold at the same price. This is, if the quality remains unchanged. Canney [3,73] estimates that the APC increases throughput by approximately 3–5%. Both suppliers and users regard an increase in throughput and therefore production as the main profit contributor of process control. Several respondents estimate that the throughput increase lies between 5% and 10%.

4.3.1.2. Process stability improvement. Process stability ensures that the product meets customer specifications consistently and that operations run smoothly. Probably for this reason, process stability is given by two thirds of the APC users as a main profit factor but only by less than 50% of the APC suppliers.

4.3.1.3. Energy consumption reduction. Process control can significantly reduce the energy consumption of a process by adjusting and controlling appropriate process variables. The importance of energy savings depends on the process [1], for example, specialty chemicals typically use less energy than refining processes. Energy reduction also depends strongly on the energy price that is charged at the location of the production facility.

4.3.1.4. Increased yield of more valuable products and quality giveaway reduction. An increase in more valuable products and the reduction of quality giveaways are flipsides of the same coin. Significantly more APC suppliers than users regard quality as a main contributor for the profit resulting from improved process control. A reason for this might be that a market position achieved through consistently producing high-quality products is a long-term strategic trend that does not reflect in the day-to-day business. A further possible explanation is that suppliers tend to overrate energy consumption while users are more concerned about the operational criteria.

4.3.2. Cost types

While the benefits of process control have been studied in detail, less information is available on the cost encountered when implementing a new process control system. The cost is certainly related to the number of loops and process units involved in the APC project. A functional dependency is however difficult to derive [49].

Several cost factors and their importance are listed in Fig. 8. The most important cost factor is the manpower required for the installation from both the APC user and the supplier. Since the main part of the APC solutions is software based, the control software upgrade has a larger impact on the implementation cost than the control hardware upgrade. Control system upgrades tend to be more complex and costly than the basic control system instrumentation [74]. Only 30% of the respondents identified maintenance as one of the three most important cost factors. This may suggest that insufficient attention is paid to system maintenance.

4.4. Implementation

Implementation of a new control system requires considerable resources and time [75]. Such implementations are either done inhouse or outsourced to vendors that offer integrated APC solutions.

Fig. 9 shows a list of APC solutions arranged according to the knowledge that survey respondents have of them.

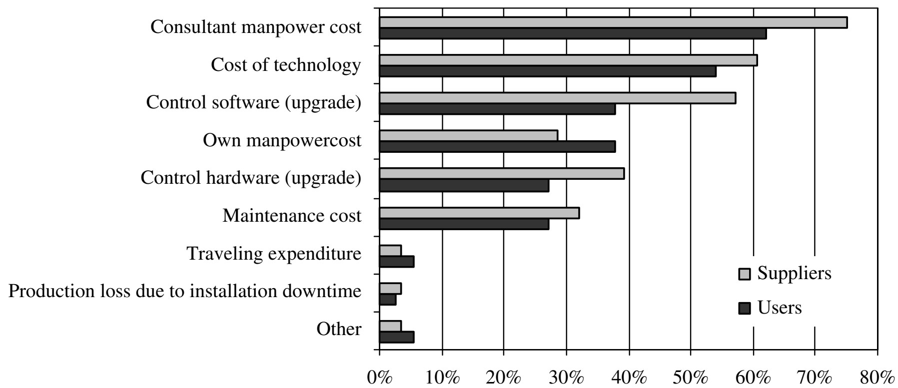

Fig. 8. Main cost contributors: survey results.

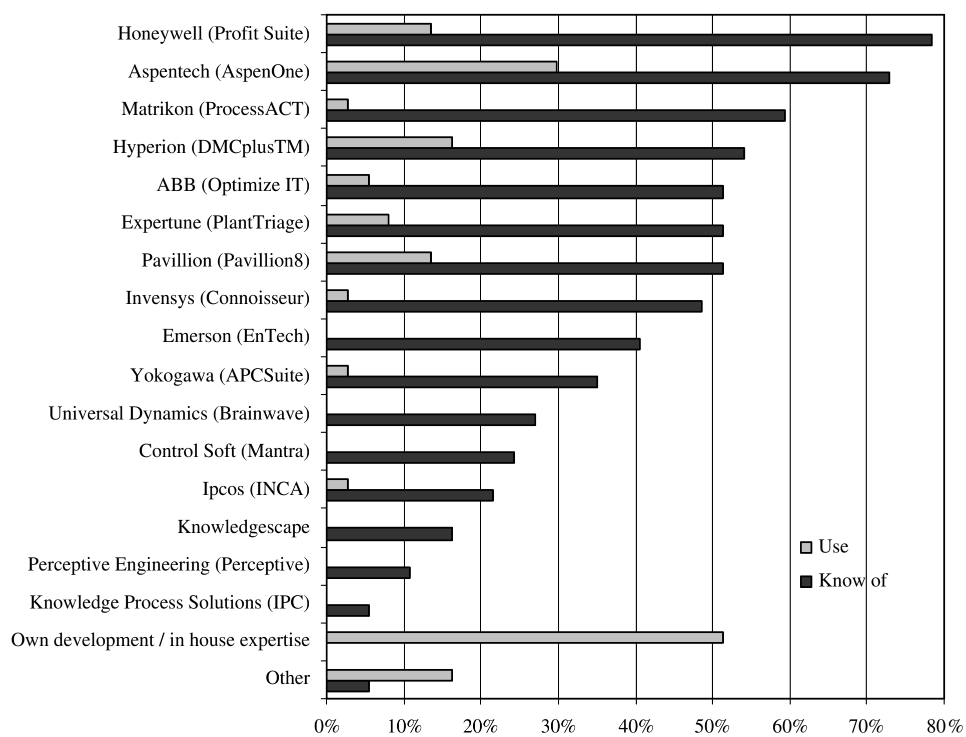

Fig. 9. APC solutions by popularity: survey results. DMCplusTM is an Aspentech solution distributed by Hyperion on a technology partner basis.

Honeywell's Profit Suite, Matrikon's ProcessACT and Aspentech's DMCplus are the three best known APC toolboxes.[1] The most frequently used standard APC solution, according to this survey with 37 APC user respondents, is AspenOne. It is noteworthy that more than 50% of the users have their own APC software and use inhouse expertise to implement new control technology. The survey indicated that almost all APC projects conducted by APC suppliers last between 4 months and 1 year. A third of the projects conducted by APC users with inhouse expertise, on the other hand, last longer than one year while 11% of the projects are completed in a period of less than three months.

[1] DMCplusTM is an Aspentech solution distributed by Hyperion on a technology partner basis.

4.5. Calculation of performance and success assessment

After implementation of the new APC system the performance can easily be assessed since operating data is now available. The next step in the framework in Fig. 1 is therefore the assessment of the current performance and the comparison to the base case. The comparison of the two controllers is more complex than it appears at first glance. The reason is that since the implementation and commissioning of the new system took place, time elapsed. During that time, process conditions might have changed, plant maintenance might have been carried out and instrumentation problems such as sticky valves or a dead sensor might have been removed.

If the old control system is still available, an objective comparison between the two systems can be achieved by switching between the two [55,76]. In the survey, APC experts were asked how the benefits of the new system after implementation are assessed. Eighty percent of the APC suppliers and more than 50% of the APC users stated that switching between the old and new control system is carried out to estimate the success or failure of the new APC system. Correct switching between the old and new system should result in a confidence level that says how reliable the result of better control is.

4.6. Maintaining the APC system

A technical shortcoming of almost all APC systems is that if left unsupervised the performance will deteriorate over time [2]. Deterioration is inevitable since a number of factors can change and affect the operability of the process.

Maintenance of the APC system is therefore essential to ensure continued performance. Fiske [77] anticipates that the maintenance is more challenging than the implementation, in particular if the maintenance is carried out proactively rather than reactively. In a recently conducted survey [78], 11% of the respondents stated that the reason for not using process automation to its full capacity is inability to cope with the maintenance.

Some processing companies have therefore shifted their focus from implementation of new projects to maintenance of existing applications [79,80].

An important aspect of proactive maintenance is the monitoring of individual control loops, operational performance and equipment [81]. Control loop performance assessment has evolved in the last two decades to focus maintenance efforts on the worst performing loops. The respondents of the web-based survey were asked on what basis they conduct loop performance assessment. About 70% of the users conduct an assessment of their loops frequently: either online (22%), daily (19%), weekly (11%) or monthly (19%). Loop monitoring is an important and popular step in monitoring and maintaining the APC system.

4.7. Calculation of benefits and re-assessment

A survey on APC in the Japanese industry [46] found that a large number of APC controllers are not operating after some time. The most cited reason for this are changes in the operating conditions on which the controller is unable to act. It is therefore advisable to conduct a re-assessment of the benefits resulting from the APC controller, e.g. after a number of months or years. The procedure is similar to the assessment after implementation as described in Section 4.5. In case the old control system is still available after a period of time, experiments can be conducted by switching between the old and new system. Alternatively, the performance can be calculated as before while taking the changes in process operation into account.

5. Framework – the managerial process

Profitability is a key objective of the processing industries [1]. The role of the plant management is to maximize the profit through asset management while monitoring specifications, safety and environmental requirements as well as other business drivers. Asset management is the operational management of equipment, including control hard- and software, to manufacture products as efficiently as possible [82].

Regarding the APC system as an asset, managerial mechanisms and tools are in place, as shown in the framework in Fig. 1. Reports are required to monitor and assess the APC system throughout the engineering stages, that is, before and after implementation reports as well as a long-term report. The positive or negative reports will affect the decision and strategy on investing in a new control technology. A risk assessment is usually conducted to support the decision.

At any time, the plant supervision has to ensure the integration between control and planning and scheduling [83]. Planning and scheduling also aim at maximizing profitability though on different time scales. Planning systems provide production plans over a period of several weeks or months while scheduling systems operate on a daily basis. Process control systems, on the other hand, execute over time-horizons of several minutes or seconds. The bridge between scheduling and process control can be overcome by real-time optimization (RTO) systems, which operate every few minutes or hours. The integration of planning and scheduling, as well as RTO and APC solutions, remains a focus of current research [84].

5.1. Reporting

The framework of economic performance assessment introduced in Fig. 1 takes three reports into account that are usually conducted in an industrial environment to report the success or failure of an APC project. Firstly, a budget proposal is compiled before implementation to justify the expenditure. Project reports are submitted after the implementation and after a period of time, as follow-up reports ensure that the performance is monitored and the success or failure of the APC project is assessed.

In the survey, APC experts were questioned about the standards for APC reporting within their organization.

Around 80% of the survey respondents indicated that a quantitative report is required before the implementation to justify the investment, either in monetary terms or as a process quantity such as throughput or a quality variable. Of the respondents, around 75% stated that no investment is made without management approval while the remaining 25% of respondents stated that control investments below a threshold did not require any approval. This threshold lies between US\$ 5,000 and US\$ 100,000. Half of the respondents indicated that the expenditure is budgeted over a period of 2–3 years while the other half budgets the expenditure over only one year. This corresponds to the pay-back periods as reported in [46] for the capital spent on advanced process control.

A quantitative report after the APC system is implemented is required by approximately 75% of the respondents to assess the success or failure of the project. Several APC experts report a tendency to beautify the benefits of the new APC system because a positive outcome is beneficial while a failure will reflect negatively on everyone involved in the project [14]. The outcome of the assessment after completion will furthermore affect the strategy for future APC projects, for example, which APC methodology should be used and which supplier should be chosen.

A quantitative follow-up study is only conducted by about half of the respondents and a monetary estimate is only required by about a third. Several respondents remark that the resources are usually allocated to new projects. Once a project is implemented and running there is usually no time to assess the long-term benefit and whether the system is really performing as expected. Some APC suppliers explain that when a follow-up report is not required by the customer it is nevertheless compiled for their own interest.

5.2. Risk assessment

Risk factors for failure and excessive cost must be taken into account for all projects. Several aspects of the implementation of a new APC system are associated with a certain risk. For example, the estimated implementation cost might be exceeded owing to a longer project duration. Manpower cost is conceived as the main cost contributor, see Fig. 8, and is often coupled directly to the time spent. Also, the estimated benefits might not be obtained as expected.

Friedmann [50] differentiates between the risk in cost estimation and risk in benefit estimation. Two main risk factors of the cost are novelty and complexity. Both novelty and complexity are tied to the resources allocated to the projects. A newly developed technology can be associated with low risk if the control personnel is experienced, knowledgable and is committed fully to the project while a proven application might be destined to fail if not enough or unexperienced staff members are allocated to it. Most risks concerning the benefit are either technological or commercial risks. Technological risks include instrumentation failures, configuration problems and poor maintenance. Commercial risks are usually associated with market behavior. If the aim of an APC project was an increase in throughput and the market has become oversupplied since the beginning of the project, then the expected revenue increase will not arise.

From a managerial point of view, two important risk factors influencing the project outcome are management backing and user acceptance [85]. In this context, management backing means the support from the project sponsors for the allocation of resources. The user is defined here as the operator of the control system but could also include the first level of technical supervision such as the process or control engineer. Craig and Henning [85] allocate higher importance to user acceptance. This is supported by the results of the survey. While 57% of the respondents believed that user acceptance is more important only 16% thought that management backing is more important for the outcome of an APC project.

5.3. Decision making and strategy

Economic performance assessment of the new control system is only one, if crucial, aspect when deciding whether to implement a new control strategy. Several factors affect the decision whether to upgrade the existing technology. In particular, sustainability, reliability and robustness are among the most desired properties of a control technology [3].

Survey responses show that half of the APC experts choose a control technology that they are already familiar with, based on a favorable experience with that technology on similar processes. A further 25% indicate that they follow suggestions from APC vendors. This recommendation is often followed by a pilot implementation to verify the success and benefits. Collaborations with universities were said to be a factor for 6% of the respondents, particularly for the derivation of economic models and performance functions.

Other reasons for the decision were company-wide standards and a strategic focus. This applies particularly to large production companies with numerous plants but a centralized control and technology group. The advantage of using the same technology throughout the company is that expert knowledge is available to implement and maintain the control system. The economies of scale work to the advantage of a company-wide implementation of the same technology. Smaller production facilities often suffer from longer payout periods, capital and operating budget constraints and a lack of expert manpower [86].

6. Open issues and future trends

The area of economic assessment for process control presents a number of open research issues. In the web-based survey, APC experts were asked whether they are

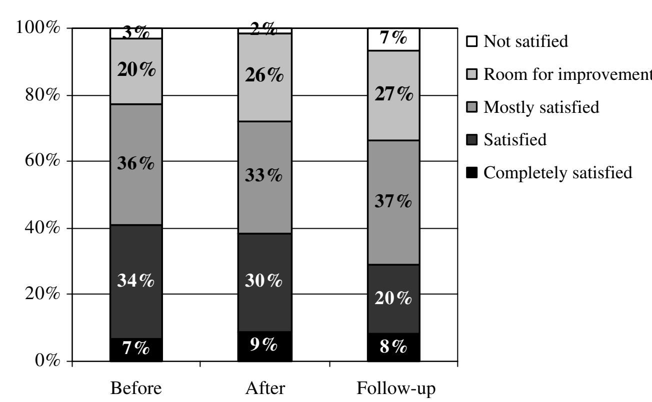

Fig. 10. Satisfaction with current methodologies for economic assessment: survey results.

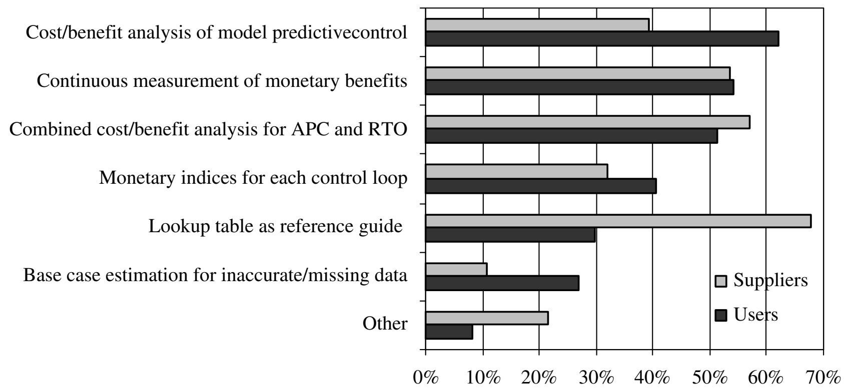

Fig. 11. Future trends: survey results.

satisfied with the current control benefit estimation methods. The results are shown in Fig. 10 for the estimation of the economic performance before and after implementation as well as after a period of time. About a third of the respondents are unsatisfied or see room for improvement when conducting a follow-up economic assessment. The reason could be that the processes within the organizations are not in place and that the resources allocated to long-term benefit estimation are limited.

APC experts were further asked what future trends they believe to be most important and the results are shown in Fig. 11. More than 60% of APC users would like to have a standard tool for the assessment of MPC, that is, whether it is economically viable to use an MPC controller on a process unit. Most APC suppliers, on the other hand, would find a look-up table useful which gives an estimate of the benefits to be gained from a new APC solution on, for example, a distillation unit or a grinding process. Further important and unsolved problems are continuous measures of economic benefit and the combined cost/benefit considerations for APC and RTO. Other suggested areas of future research include the lost opportunity cost from model degradation; benefits from an increased asset lifetime and calculation of expected performance without APC under the current operating scenario.

Tools and technology for sustaining the benefits and maintaining the control system will have an impact on future developments. The integration with higher level applications such as real-time optimization, planning and scheduling systems is a currently unsolved problem [83]. Incorporation of expert knowledge into advanced control solutions as well as the interface for operators and engineers plays an important role in current research directions [1].

In 1993, Jim Downs and Ernie Vogel at Eastman Chemical Company published an industrial case study of a chemical production plant with detailed information about the process model and disturbances [87]. The availability of this plant model triggered the development of both plant-wide control strategies and plant-wide disturbance analysis methods within academia. A similar detailed industrial case study that includes the economic parameter of a process could do the same for research concerned with the economic aspect of advanced process control. The benefit of a measure developed at a university or independent research institution is that it would be seen as an objective measure of success or failure that could be used by APC users and suppliers alike.

7. Conclusions

While process control technology has evolved in the past decades, estimation techniques for the economic benefit that results from advanced control solutions appear to have remained static. Methods of benefit estimation from variance reduction that were introduced in the 1970s are still carried out and are reported today. This paper outlined the issues for economic assessment in the form of a framework comprising the evaluation steps through the life-cycle of an APC project. The results of a web-based survey on economic performance assessment of APC give a picture of the state-of-the-art assessment practices in industry. The results outline that most APC suppliers and users carry out cost/benefit analysis and are required to report the benefit to management. The estimation methods, however, are sometimes rudimentary and based on experience rather than on objective comparison.

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Appendix A

APPENDIX A – QUESTIONNAIRE FOR APC USERS

1 Identification of Respondent

This section establishes the identity of the respondent and the respondent's organization profile.

1.1 Contact details

Your contact information is for collation purposes only. It will *not* appear in any published results nor be provided to any person or organization.

Title (please delete as required): Mr / Ms / Miss / Mrs / Dr

Name: First ________ Surname ________
Organization ________
Department ________
Postal Address ________
Email Address ________

1.2 Position

Please select the position that best describes your responsibilities. Please select only one.

- ☐ Control systems engineer, hardware
- ☐ Maintenance manager
- ☐ Control systems engineer, software
- ☐ Quality engineer
- ☐ Process control engineer
- ☐ Technical sales engineer
- ☐ Process control manager
- ☐ Computer systems / IT suppor
- ☐ Process engineer
- ☐ Consultant
- ☐ Process manager
- ☐ Procurement engineer
- ☐ Operations manager
- ☐ Other

Other: ________

1.3 Industry sector

Please specify the industry sector(s) in which your organization operates.

- ☐ Chemicals
- ☐ Petrochemical
- ☐ Coal products
- ☐ Petroleum refining
- ☐ Industrial gases
- ☐ Pulp & paper
- ☐ Minerals processing
- ☐ Water & wastewater
- ☐ Mining
- ☐ Power & utilities
- ☐ Oil & Gas
- ☐ Other

Other: ________

1.4 Area of focus

Please specify which area of focus within your company you are knowledgeable of and will answer the questions in the next sections.

- ☐ Entire company
- ☐ Parts of site
- ☐ Entire site
- ☐ One plant

Comment: ________

2 Site/plant specifications

This section establishes the key parameters of plant size and type to put the remaining part of the questionnaire into context.

2.1 Number of APC experts

Please estimate the number of APC experts in your *area of focus* as specified in Section 1.4.

☐ <3 ☐ 3-10 ☐ 11-50 ☐ >50

Comment: ________

2.2 Number of operators

Please estimate the number of operators in your *area of focus* as specified in Section 1.4.

☐ <50 ☐ 50-100 ☐ 101-1000 ☐ >1000

Comment: ________

2.3 Number of products

Please estimate the number of products manufactured in your *area of focus* as specified in Section 1.4.

☐ <3 ☐ 3-50 ☐ 51-500 ☐ >500

Comment: ________

2.4 Number of control loops

Please estimate the number of control loops in your *area of focus* as specified in Section 1.4.

☐ <100 ☐ 100-1000 ☐ 1000-5000 ☐ >5000

Comment: ________

2.5 Number of advanced process controllers (APC)

Please estimate how many advanced process control projects are carried out in your *area of focus* **per year** (for a definition of APC please refer to the glossary).

☐ <10 ☐ 10-20 ☐ 21-50 ☐ >50

Comment: ________

2.6 Production type

Please specify the production type used in your *area of focus* as specified in Section 1.4. Please select only one.

- ☐ Continuous only
- ☐ Mainly continuous
- ☐ Batch only
- ☐ Mainly batch
- ☐ Continuous and batch equally
- ☐ Other ________)

Comment: ________

3 Control system & commercial tools

This section establishes the control systems and control technology in place.

3.1 Advanced process control (APC) methods

Please specify which and how often APC methods are used in your area of expertise (Please refer to the glossary for definition of the APC methods).

	Standard	Frequently	Rarely	Never	Don't know
Adaptive control	☐	☐	☐	☐	☐
Constraint control	☐	☐	☐	☐	☐
Dead-time comp.	☐	☐	☐	☐	☐
Direct synthesis (DS)	☐	☐	☐	☐	☐
Dynamic matrix	☐	☐	☐	☐	☐
Expert systems	☐	☐	☐	☐	☐
Fuzzy logic control	☐	☐	☐	☐	☐
Internal model control	☐	☐	☐	☐	☐
Linear programming	☐	☐	☐	☐	☐
Model pred. control	☐	☐	☐	☐	☐
Neural networks	☐	☐	☐	☐	☐
Nonlinear control	☐	☐	☐	☐	☐
Split-range control	☐	☐	☐	☐	☐
SPC	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

Comment: ________

3.2 Advanced process control (APC) – Commercial tools

Please specify which APC vendors you have heard of and which, if any, of them you use.

	Heard of	Use
ABB (Optimize IT)	☐	☐
Aspentech (AspenOne)	☐	☐
ControlSoft (Mantra)	☐	☐
Emerson (EnTech)	☐	☐
Expertune (PlantTriage)	☐	☐
Honeywell (Profit Suite)	☐	☐
Hyperion (DMCplusTM)	☐	☐
Invensys (Connoisseur)	☐	☐
Ipcos (INCA)	☐	☐
Knowledge Process Sol. (IPC)	☐	☐
Knowledgescape	☐	☐
Matrikon (ProcessACT)	☐	☐
Pavillion (Pavillion8)	☐	☐
Perceptive Eng. (Perceptive)	☐	☐
Universal Dynamics (Brainwave)	☐	☐
Yokogawa (APC Suite)	☐	☐
Own development / in house		☐
Other (Please specify)	☐	☐

Comment: ________________

3.3 Duration of APC projects

Please specify the average duration of APC projects from start (planning) to finish.

☐ < 4months
☐ 4-6 months
☐ 7-9 months
☐ 10-12 months
☐ >1 year

Comment: ________________

3.4 Control loop performance monitoring (CLPM)– Frequency

Please state on which basis you assess the performance of your control loops? (Please refer to the glossary for control loop performance monitoring).

☐ Online
☐ Daily
☐ Weekly
☐ Monthly
☐ Less frequent
☐ Never

Comment: ________________

4 <u>Decision making process</u>

This section investigates the management decision process of a new APC project.

4.1 Advanced process control technology decision

Please state how you decide on the APC technology for a new control project.

☐ Past experience with the technology
☐ Suggestion from APC system vendor
☐ New technology used by competitor
☐ University proposal and involvement
☐ Other (Please specify: ________________)

Comment: ________________

4.2 Management involvement – time

Please state at what point non-technical management is usually involved in the APC project.

☐ Never
☐ At beginning of project
☐ At end of project
☐ At beginning and end of project
☐ Throughout the project

Comment: ________________

4.3 Management involvement – levels

Please state how many management levels are usually involved in a new APC project.

☐ 0 ☐ 1 ☐ 2-3 ☐ >3

Comment: ________________

4.4 Reporting - Before

Please state if in your organization it is required to prepare a proposal/motivation *at the beginning of an APC project*. If you select more than one reporting option, please indicate how often you use each method in the percentage (%) box.

	%
☐ Yes, with monetary value	☐
☐ Yes, with non-monetary value	☐
☐ Yes, only qualitative analysis	☐
☐ No	☐
☐ Other (Please specify: ________)	☐
Total	100%

Comment: ________________

4.5 Reporting – After project completion

Please state if in your organization it is required to prepare *a final report at the end of an APC project*. If you select more than one reporting option, please indicate how often you use each method in the percentage (%) box.

	%
☐ Yes, with monetary value	☐
☐ Yes, with non-monetary value	☐
☐ Yes, only qualitative analysis	☐
☐ No	☐
☐ Other (Please specify: ________)	☐
Total	100%

Comment: ________________

4.6 Reporting – Follow-up

Please state if in your organization it is required to conduct a *follow-up study* after a period of time of an APC project. If you select more than one reporting option, please indicate how often you use each method in the percentage (%) box.

	%
☐ Yes, with monetary value	☐
☐ Yes, with non-monetary value	☐
☐ Yes, only qualitative analysis	☐
☐ No	☐
☐ Other (Please specify: ________)	☐
Total	100%

Comment: ________________

4.7 Comparison of Reports

Please state if you usually make a comparison between the cost/benefit analysis made at the various stages of an APC project.

☐ Between proposal at beginning of APC project and final report at the end of the APC project

☐ Between proposal at beginning of APC project and follow-up study after completion of the APC project

☐ Between final report at the end of APC project and follow-up study after completion of the APC project

Comment: ____________________

4.8 Management backing and user acceptance

If you would have to balance between management backing and user acceptance, please state which you would consider as more important. 1 – Management backing most important; 5 – user acceptance most important.

	1	2	3	4	5	
M.B.	☐	☐	☐	☐	☐	U.A.

Comment: ____________________

4.9 Budgeting

a) Is there a fixed annual budget to be spent on new APC technology?

☐ Yes, the budget is _________ * ☐ No

Comment: ____________________

b) Is there a budget threshold above which an APC project requires management approval?

☐ Yes, the threshold is _________ * ☐ No

Comment: ____________________

c) Is the project success usually calculated and budgeted over more than one year?

☐ Yes, over _________ years ☐ No

Comment: ____________________

*Please give amount and currency. Alternatively, you can give the amount as a percentage of expenditure (please specify if expenditure is capital or operating).

5 Cost/benefit analysis for new APC project

This section investigates the cost/benefit analysis of APC technology carried out for new control projects to justify the investment.

5.1 Estimating the benefits – Benefit types

Please select **three** benefit types that you consider as the main contributors to the benefit of a new APC system (select three items).

☐ Better use of raw materials
☐ Downtime reduction
☐ Energy consumption reduction
☐ Increased yield of more valuable products
☐ Operating manpower reduction
☐ Process stability improvement
☐ Quality giveaways reduction
☐ Reprocessing cost reduction
☐ Responsiveness increase
☐ Safety increase
☐ Throughput increase
☐ Other (Please specify: ____________________)
☐ Other (Please specify: ____________________)
☐ Other (Please specify: ____________________)

Comment:

5.2 Estimating the benefits – Before

Please state how you estimate monetary benefits to justify a new APC control project (base case). If you select more than one estimation methods, please indicate how often you use each method in the percentage (%) box.

		%
☐	Past experience from similar project	☐
☐	Before control variance estimation	☐
☐	Rule of thumb	☐
☐	Estimate only qualitative benefits	☐
☐	Don't estimate	☐
☐	Other (Please specify: ___________)	☐
	Total	100%

Comment: ____________________

5.3 Calculating the benefits – After

Please state how you estimate monetary benefits to report the success/failure of a new APC project. If you select more than one estimation methods, please indicate how often you use each method in the percentage (%) box.

		%
☐	Experiments before/after control switch	☐
☐	Rule of thumb	☐
☐	Estimate only qualitative benefits	☐
☐	Don't estimate	☐
☐	Other (Please specify: ___________)	☐
	Total	100%

Comment: ____________________

5.4 Cost types

Please select the **three** cost types that you consider as the main contributors to the cost of a new APC system (select three items).

☐ Control hardware (upgrade)
☐ Control software (upgrade)
☐ Cost of technology
☐ Consultant manpower cost
☐ Maintenance cost
☐ Own manpower cost
☐ Production loss due to installation downtime
☐ Traveling expenditure
☐ Other (Please specify: ____________________)
☐ Other (Please specify: ____________________)
☐ Other (Please specify: ____________________)

Comment: ____________________

5.5 Estimating the cost

Please state how you estimate the cost of a new APC control project. If you select more than one estimation methods, please indicate how often you use each method in the percentage (%) box.

		%
☐	Past experience from similar project	☐
☐	Installation cost as quoted by vendor	☐
☐	Cost contributors weighed by percentage	☐
☐	Rule of thumb (please give example)	☐
☐	Don't estimate	☐
☐	Other (Please specify: ___________)	☐
	Total	100%

Comment: ____________________

6 Significance of economic assessment of control projects

This section investigates the importance, accuracy and current state-of-the art of the economic assessment as well as areas of development.

6.1 Importance of cost/benefit analysis

Please specify how important the conduction of a cost/benefit analysis is at various points in time.

	Before the project	After project completion	After a period of time
Indispensable	☐	☐	☐
Very important	☐	☐	☐
Important	☐	☐	☐
Sometimes important	☐	☐	☐
Not important	☐	☐	☐

Comment: ______________________

6.2 Accuracy of cost/benefit analysis

Please specify how accurate in your opinion the cost/benefit analysis should be at various points in time.

	Before the project	After project completion	After a period of time
As accurate as possible	☐	☐	☐
Accurate	☐	☐	☐
Only rough estimate	☐	☐	☐
Only qualitative	☐	☐	☐
Not accurate	☐	☐	☐

Comment: ______________________

6.3 Satisfaction

Please state how satisfied you are with your current process for cost/benefit analysis.

	Before the project	After project completion	After a period of time
Completely satisfied	☐	☐	☐
Satisfied	☐	☐	☐
Mostly satisfied	☐	☐	☐
Room for improvement	☐	☐	☐
Not satisfied	☐	☐	☐

Comment: ______________________

If you are not satisfied with the process in place or find that there is room for improvement, please state why:

Comment: ______________________

6.4 Areas of development

Please identify **three** areas of economic performance assessment which you consider as most important.

- ☐ Cost/benefit analysis of model predictive control
- ☐ Monetary indices for each control loop
- ☐ Lookup table for cost/benefit analysis
- ☐ Continuous measurement of monetary benefits
- ☐ Combined cost/benefit analysis for APC and RTO
- ☐ Benefit estimation for inaccurate/missing data
- ☐ Other (Please specify: ______________)
- ☐ Other (Please specify: ______________)
- ☐ Other (Please specify: ______________)

Comment: ______________________

You have reached the end of the survey.
Thank you very much for your time and contribution.

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