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Economic Auditing of Control Systems

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2.1 Chapter Outline

In this chapter, a method for integrating the use of the benchmarking and optimisation algorithms with economic process control auditing is discussed. The focus of the methodology is to selectively target process control loops with economic importance for benchmarking and optimisation. The method is a step by step approach to prioritising control loops according to economic importance and then benchmarking and optimising the necessary loops.

Section 2.2 discusses a framework for process control benchmarking at the different layers of the process hierarchy and reviews some of the properties and characteristics of performance assessment metrics at each layer. Section 2.3 discusses the motivation for integrating process control benchmarking and optimisation with process economic control auditing and provides an integrated control and process revenue and optimisation (ICPRO) framework as a template for conducting process control audits. In Section 2.4, the integrated control and process revenue and optimisation framework is used to evaluate an industrial case study example. The case study example involves three offshore oil production platforms. The results and recommendations from this industrial case study are presented. In Section 2.5, some of these results are used to optimise a sub-system on one of the oil production platforms. Conclusions are presented in Section 2.6.

2.2 Formal Framework for Process Control Benchmarking Metrics

In complex control systems, such that can be encountered in living organisms or in large international organizations, goals are typically arranged in a hierarchy, where the higher level goals control the settings for the subsidiary goals. Such hierarchical control can be represented in terms of the process control schemes above level 0, as in Figure 2.1. The goals at the lower levels of the hierarchy become the result of an action, taken to achieve the higher level goals. In general, in the presence of a stochastic disturbance, a control loop will reduce the variability of the loop output, but will not be able to eliminate all the variations. Adding a control loop on top of the original loop may eliminate the residual variety. Therefore, the required number of levels in the control hierarchy will depend on the regulatory ability of the individual control loops. On the other hand, increasing the number of levels has a negative effect on the overall regulatory ability, since the more levels the feedback and control action signals have to pass through, the more they are likely to suffer from noise, corruption, or delays. As each device in the control hierarchy impacts composite performance of the units below it in the hierarchy, the more layers of hierarchy in a control scheme the greater the possibility that a degradation in performance of a device at the top of the hierarchy will result in a substantial reduction in the performance of the process. Because of this, control professionals have always sought to maximize the regulatory ability of layers 1 and 2 and thus minimize the number of requisite layers required to achieve the overall process objective.

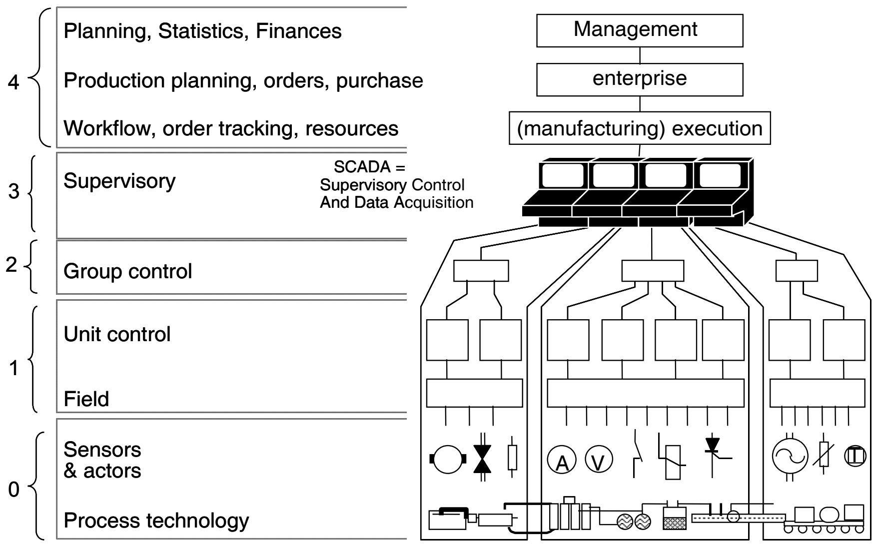

Figure 2.1. Hierarchy of Process Control

This may explain why predominantly the development and use of control performance assessment and benchmarking applications have centred around Levels 1 to 2 of the Process control hierarchy. The applications for use in Regulatory Loop Control (Level 1) assessments are by far the most commonly available commercially and have been the core of research and developments efforts over the decade. Because the characteristics of Levels 1 to 4 are different, some of the factors governing benchmarking and performance considerations at each of these levels are also different. Fundamental to the appropriate application of benchmarking applications and to effective utilisation of the results from any benchmarking exercise for process and product improvements, is to have an understanding of the different properties of benchmarking and performance assessment criteria required at each level in the control hierarchy and how these criteria relate to each other.

From Figure 2.1, the process control can be partitioned into a top level where process units are globally coordinated, a unit level where a complex process unit is operated seamlessly within the global process line and a sub-unit level where the intra-unit regulator operates autonomously. Overall process control itself can be represented as a combination of levels within the layers of an organisation's business process. The process control hierarchy in Table 2.1 describes the technical processes which intersect with the business processes at the lowest three levels (Process, Information and Economic) of the business organisation hierarchy.

Table 2.1. Business/Process Control intersection

Layers in Business Process/Organisation				
Cultural Level	The Company goal			
Strategic Level	The Company strategy			
Social Level	Staff relations, Teams	**The Industrial Control Hierarchy**		
Economic Level	Profitability, Resource usage	**Level 4**	Load management	Process line interface
		Level 3	Set-point optimization	Process unit top level management
Information Level	Information flow system	**Level 2**	Dynamic set-point changeover	Automated unit level procedures
Process Level	Process instrumentation, Technical system	**Level 1**	Regulator loop control	Low level control structure and controllers
		Level 0	Process	Actuators, process equipment, sensors

Table 2.2 shows a framework for classifying the benchmarking requirements at the different layers of the business process. At the “Process” and “Information” levels, the benchmark and optimisation process is dominated by the definition of local performance metrics, technical optimisation criteria and controller design and performance, and is less influenced by the social-psychological interactions of operators and/or team work groups. At the Economic level, the benchmarking and optimisation process is dominated by definitions of global performance metrics, process objectives, business operation strategies and optimisation procedures. Performance metrics are of two types:

- *Product Performance Metrics* : These are quality variables of the process product or output.
- *Process Performance Metrics*: Those variables which indicate if the process is operating in a desired way when manufacturing the product or output.

Table 2.2. Framework for control benchmarks

INDUSTRIAL CONTROL BENCHMARK FRAMEWORK	
LEVEL	FEATURES
Economic Level	1. Discrete event characteristics 2. Dependence on operator interaction 3. Social-psychological factors 4. Process unit interaction and inter-dependence 5. Qualitative/Quantitative performance 6. Global economics
Information Level	1. Quantitative performance 2. Some qualitative performance factors 3. Performance depends less on operator skills 4. Technical and design factors important 5. Market demand and supply and economic factors
Process Level	1. Quantitative performance dominates 2. Little operator dependence 3. Performance has a high dependence on technical and design factors

The key features of a performance metrics should be:

1. The performance metric should be physically and technically meaningful for the process being assessed.
   Thus the metric may capture and measure the presence of a desirable physical property or measure an economic dimension of the process.
2. The performance metric should preferably be amenable to an optimisation analysis to enable the full achievable optimised performance be computed.
   The extension of this is that the achievable optimised performance in the presence of structured design and implementation constraints should be calculated.

2.2.1 Goals of Benchmarking

The first thing in considering the application of benchmarking and the appropriate strategy for the potential optimisation of the system under test, is to set out the goals of the levels to which the system is associated. The goals of the most prominent of these levels can sufficiently be summarised as:

1. Company: To continuously generate a healthy and increasing profit from the production and sale of the range of products.

2. Engineering process: To realise the company goal, by creating a continually improving technical environment for the efficient manufacture of the required products.
3. Control system: To implement the company and engineering goals by ensuring a safe and optimal means of increasing /maintaining a consistent production rate and product quality while simultaneously decreasing operational costs, plant downtime and maintenance costs.

2.2.2 Principles of Benchmarking

Goldratt [1993] considered the problem of optimising the performance of the entire manufacturing process, which may be made up of numerous control loops. That work is useful in developing a summary of principles to ensure that in conducting any benchmarking exercise, the exercise is structured in such a way as to actually result in a routine for performance improvements. Some of these principles include:

1. In a multivariable process, where interaction exists between the process loops, optimising each loop independently of all others does not ensure that the overall process is optimal. ("*A system of local optimums does not necessarily translate to a globally optimal system*").
2. Benchmarking the performance of individual loops in the process gives a measure of how far from a local optimum an individual loop may be, it does not say anything about the overall performance of the process and how far the process is from a global optimum.
3. The global performance of the process will be predominantly determined by the performance of constrained loops. Constrained loops are loops that have some physical, environmental or user imposed limitations applied.
4. To reach a global optimum, the ideal working point for loops with bottlenecks identified as key to the process objectives will most likely be at the constraints, the operation and performance of all other loops must allow for these limitations.
5. For global process-wide optimisation to be achieved, the control objectives must be derived from the management and process objectives.

2.3 Framework for Integrated Control and Process Revenue Optimisation

The traditional literature on benchmarking [Codling 1992, Andersen and Pettersen, 1996], has been mainly concerned with business processes rather than the problems of operating and controlling physical/mechanical/chemical process lines or factories. On the other hand, the conventional literature on process optimisation [Huang and Shah, 1998; 1999, Desborough and Harris, 1993] has been more concerned with technical performance metrics and control loop performances but not with the financial and economic aspects of the physical process.

There is a link between the economic performance of a business and the control performance of the technical process related to this business. The existence of this link has been documented by Rolstadas [1995] and Ahmad and Benson [1999]. In trying to establish and understand what exactly the relationship between economic performance and the control performance is, and how it works, a high level analysis of how the performance of the control system in an oil production facility influences the financial returns of the business will be done. The analysis will be conducted with the aid of the Return on Net Assets (RONA) business benchmark model as documented in a review of integrated performance measurement systems [CSM, 1997] in Figure 2.2.

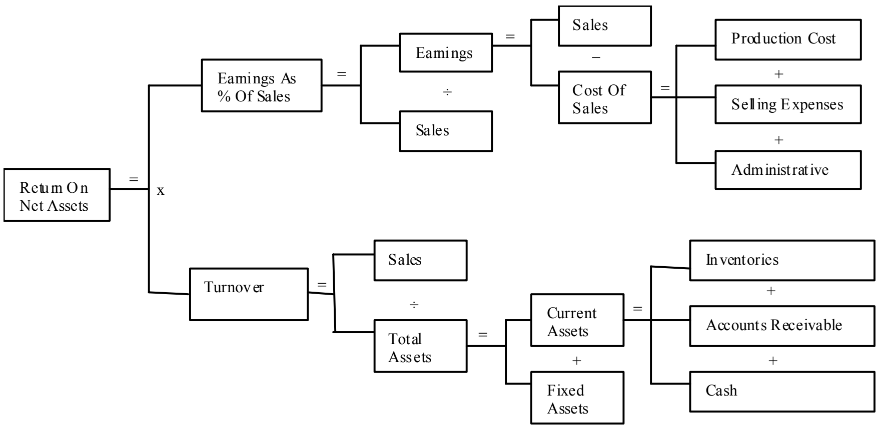

Figure 2.2. RONA performance benchmark

The oil production facility belongs to a hydrocarbon exploration and production petroleum company whose business process can broadly be defined as the production and sale of crude oil and associated products from recovered reservoir fluids. To achieve this goal the company has designed and built a number of reservoir fluid processing platforms, whose aim is to separate the commercial product in the reservoir fluid from the waste products. Each platform has a specific daily processing capacity.

To demonstrate the effect of process control on the economics of the business, consider how the process control of the platform directly influences some of the elements on the RONA tree as described in Figure 2.2

1. Production Cost

The performance of the process control system on the oil platforms affects the efficiency of the overall process. The more efficient the production, the greater the ratio between the profit obtained from the products of the process and the production cost. In addition, in some cases, it can be shown that the efficiency of production has a direct impact on production costs.

2. Selling Expenses

Some of the expense involved in selling the derived crude oil and associated product come from the transportation and processing tariffs the company pays for sending the crude oil to export terminals through third party pipelines and for onshore processing of its gas products. The charges of these tariffs are calculated per km of pipeline used and per tonne of gas. The process control system ensures efficient separation of commercial products from waste products ensuring that additional transportation and processing charges / or penalties are not incurred for sending unwanted waste products down the pipelines to the processing facilities.

3. Sales

The amount of commercial product sold by the company is directly related to the production rate of its platforms. One of the functions of the process control system is to try and maintain the rate of production at a level specified by the design of the platforms. An optimal control system will ensure a rate of production that is close to the designed capacity.

4. Earnings

The revenue received by the company from the sale of its products depends on the quality and quantity of these products. The quality of the products depends on the process units on the platform operating to the specification to which they were designed. The efficiency at which these process units operate and hence the product quality depends, in some measure, on the process control system.

5. Current Assets

The major assets of the company are its reservoirs, oil wells and platforms. The task of maintaining these assets and ensuring maximum recovery of reservoir fluids from the wells, inherently rests on the process control and fault and condition monitoring systems.

Clearly the control system performance is interwoven with the economic performance of the business. Over the last 20 years there has been substantial progress in control system design and applications, some of which has great potential for improving process performance. However the capital expenditures required to implement these advanced technology solutions (installation, commissioning and support) are high. Therefore, what is required is a method/systematic procedure for selecting those processes where implementation of the new control technologies would have the greatest impact. This would limit the capital expense whilst maximising the revenue generated. An integrated approach to process revenue optimisation using advanced control or knowledge based expert systems can then be used to directly target specific areas in a production process where optimisation of the process unit will have substantial financial benefits in the revenue received.

2.3.1 Integrated Control and Process Revenue Optimisation (ICPRO) Method

The integrated control and process revenue optimisation approach is a means for identifying areas (bottlenecks) where advanced control and optimisation technology can have a marked effect on process revenue. This method requires that before any benchmarking analysis or control redesign is undertaken, either an in-depth plant auditing involving management, process and control objectives is carried out or information resulting from such an audit is available.

The approach identifies five steps as being critical to determining the sector of a process that not only has the necessary degrees of freedom for optimisation but also has direct impact on the financial returns from the process. These five steps can be defined as:

Step 1: Profile and Operations Assessment

The control engineer who wants to practise benchmarking must have a thorough understanding of:

- The critical business processes and products.
- The critical engineering factors for product objectives.
- The best measurements that will provide information on key performance indicators.

The linkage of the business process to the engineering process is critical to effective benchmarking. The process of control performance benchmarking must fit into an economic revenue improvement framework. The idea is that by using information about financial impact it is possible to detect the critical engineering processes and related control loops that are worth investigating. The results from the Profile and Operation Assessment should be used to design the scope and requirements for the actual benchmarking project.

Considering the multifaceted set of skills required to conduct a successful top down benchmarking and optimisation project, it is best to approach the benchmarking as a team effort. Team members need access to sensitive information on company production and operational targets and it is sometimes useful for the project to have a sponsor with a high level of seniority within the company and involve the staff with substantial knowledge of financial, engineering and the process dynamics. The benchmarking team needs to:

- Understand the critical processes and how they are measured.
- Decide what kind of data is needed and how this data will be collected.

The Profile and Operations Assessment provides insight into key company financial objectives and the engineering processes in the organization that address those objectives. At the Profile and Operations Assessment stage, the procedure involves understanding the company's business strategy. Next, it should be decided what measurements are required from those areas of company's operation from which financial benefits of the process accrue and capital expenditure or losses occur. Prime factors are:

- Product quality
- Production rate
- Raw material acquisition
- Plant operability
- Plant availability
- Power consumption
- Maintenance cost

Global benchmarks should be created and analysed for the entire process. A set of metrics for each of the objectives that the entire process aims to achieve (quality, economics and security) should be defined. Using present business and operating conditions, a set of values for the global metrics should be stored. The type of measurements (or metrics) chosen have to be useful and easily calculated e.g. production rates, hours of continuous operation, quality specifications.

Step 2: Process and System Assessment

The Process and System Assessment stage is where the benchmarking team profiles the underlying engineering process. A key step in the Process and System Assessment stage is using process and instrumentation diagrams so that the benchmarking team understands the processes and how they can be controlled and performance measured, both in the control terms and in management terms.

The purpose of Process and System Assessment is to:

- Identify processes as candidates for benchmarking.
- Establish the metrics to be used.
- For the chosen metric collect baseline data of the process variables that can be used as a calibration point for comparing the performance of the system before and after any retuning.

Identifying potential processes for optimisation is another step in the Process and System Assessment stage. It is always best to develop a list of three to five potential process units for benchmarking. Some of the potential process units may not be feasible for benchmarking on closer inspection, or may not fit within the allotted time-frame, others might not have the right sensors and instrumentation to gather data about the necessary variables.

This stage involves the identification of the important sub-processes, process goals, major control loops and control objectives. The bottlenecks existing within the process units that limit efficiency and productivity should be clearly identified and where possible, the sub-processes and control loops involved should be noted for measurement and data analyses. It is essential to obtain substantial knowledge about the company's process and control model, objective and strategies. This information can be acquired directly from staff with substantial knowledge of process and control operations and dynamics. A review of plant piping and instrumentation diagrams, operations chart and reports and maintenance reports can also help to provide a very clear picture of the physical process.

Before collecting a lot of data for an extensive benchmarking and analysis exercise, the benchmarking team needs to collect baseline data about the processes. This data can be current or archived records that show an extended period of normal plant operation with acceptable performance limits. Collecting this data will refine the measurement process and help develop the final set of metrics and application to be used in the benchmarking effort. The kinds of benchmark application and metrics chosen have to be compatible with the dynamics of the process and the performance to be assessed. For instance, there is no point in choosing a benchmarking application which relies on variance in a process to compute performance indicators if the process is relatively noise-free.

These local baseline benchmarks may sometimes be obtained by analysing the levels/units inside the process and finding a set of metrics that measure the performance of each level/unit. Using current operating conditions, a set of values for local metrics should be recorded. Also control loops within sub-processes that are either problematic, inefficient or that could be optimised should be noted.

Step 3: Correlation of Financial Benefits and Control Strategy

The Financial Benefit and Control Strategy Correlation stage is where the benchmarking team begins the process of linking control objectives and controller tuning to the organization's strategic goals. The benchmarking effort should be focused on those control loops that are most important. At this stage the correlation between subsets from which revenue accrues and sub-processes or groups of sub-processes within the system should be established. One way to determine the relative importance of loops in process units is to develop a list using the information already obtained from the previous stages:

Correlation List

1. State the mission, purpose or goal of the process or manufacturing operation.
2. List the process units associated with each of the above.
3. Identify major process units by the value or volume of their outputs.
4. Identify which processes add the most value and which add the most cost.
5. List the major enablers, bottlenecks and constraints for: production, quality and availability.
6. Identify which control loops affect these enablers, bottlenecks and constraints.

When an opportunity to enhance a company's financial objectives is identified, the engineering processes that can directly fulfil that objective can be considered as critical processes. The idea is to only benchmark critical processes, identifying weak critical processes that can give the most leverage when improved. Once this correlation exercise is done, a mapping between the related control loop and process groups should be produced. It is essential to analyse the control loops within these sub-processes, to determine if the provided control structure or algorithm is suitable.

Step 4: Optimality Assessment

At the Optimality Assessment stage the focus is on checking the process variables to determine if there exist any additional degrees of freedom by which the control action can be improved. An evaluation of the optimisation potentials at the regulatory, multivariable and supervisory levels of control hierarchy should highlight the optimisation strategy required.

Clearly defining how the evaluation process will be done, helps to define the data required and using lessons learned during collection of data for the baseline should help to refine the measurement process and develop the final set of metrics to be used in the benchmarking effort. There are measurement pitfalls to avoid as well. The benchmark team needs to have consistent collection methods (sampling rates, quantisation and compression methods for similar types of loops). The proper aggregation levels for data must be specified and the data units and intervals should also be specified to make comparison easier during analysis.

Although benchmarking stresses the use of the "best in class", often this has to be tempered with other factors, such as process dynamics, obtainable data, costs (interruption of normal process operation, model development, etc), time, and multidimensional process relationships. Analysing the benchmark performance for each identified loop or group of loops can be done as an isolated event or as an event trended over a period of time. Either method (or both) may be appropriate for the process being studied. When cost, productivity or quality is the metric under study, sometimes it is useful to look at the historical trend as well as the current performance. The benchmark metrics obtained should be used to determine if improving control action will influence/improve revenue. Note that benchmarking and optimisation criteria may be mathematical or intuitive in nature.

Step 5: Control System Adaptation

Benchmarking is about improving processes, and as such it requires a structured approach to discussing, assessing and implementing any change to the system that may be necessary as a result of the benchmarking analysis. The benchmarking team must be aware of this, before the adaptation phase is commenced, the following change management techniques should be employed:

- Communicate the benchmark findings widely.
- Involve a broad cross-functional team of employees (production, process, control and management).
- Translate the findings into a few core principles.
- Work down from principles to strategies and to action plan.

Each process has a process "owner," and process owners and other stakeholders need to have a voice in the changes recommended. Before developing control strategies, it is important to communicate with all who might be involved in the change. Communication can follow the following change management pattern [McNamee, 1994]:

- Identifying the need for change.
- Getting stakeholders to voice their opinions about the change.
- Providing a forum for all to discuss the methodology, the facts, and the findings from the benchmarking effort.
- Communicating the expectations about the changes.
- Building commitment for the change.
- Getting closure; celebrating the change.

In reaching a recommendation for a change of control strategy or design, the analysis of the collected benchmark data should expose the gap between the process performance level and the optimal level as suggested by the benchmark metric, and predict where the future gaps, constraints, and bottlenecks are likely to be. From the analysis of the benchmark results a decision on the need for retuning or redesign of the control strategy must be reached. The benchmark application used will determine the optimisation criteria that will enable full achievement of any benchmarking objective.

This means that, because of technical or business constraints, it is possible that a re-tune of the existing controllers might not result in the performance desired and more advanced solution involving process re-design might be required. Note that the decision to use an advanced control design involves the use of process models which involves additional costs. Where possible the use of simulations to compute the improvement in performance between present control strategy and the proposed strategy is most desirable. The results for the simulated global and local metrics obtained using the proposed strategy should be compared against the stored baseline metrics. The benefit of the proposed strategy must be clearly visible before any decision to change the current system setup is implemented.

The five steps in the ICPRO audit process should be considered adaptable and are intended to act as a guideline only. When applying this or any other the performance auditing /improvement method it is important to remember that the benefits are only obtained if the procedure is repeated at regular intervals.

2.4 Case Study: Oil Production Platform

To illustrate the above concepts and to place the controller performance assessment within the framework of plant wide productivity audit, the results and analysis from an industrial feasibility study conducted by Strathclyde University on the financial benefits of implementing advanced control on an oil platform [Grimble and Uduehi, 2001] are utilised. The company at the centre the study is involved in oil and gas exploration and production. The aim of the project was to examine the operation of the company offshore production platforms and determine if implementing some form of advanced control system would improve production, and therefore result in a significant revenue increase.

The feasibility study was divided into two stages. Stage one comprised an economic control audit and benchmarking exercise to include:

- Reviewing the company financial strategies as regards the offshore oil production platforms and their products,
- Reviewing the production platform process and control operation from an economic perspective to determine if there exist any financial gain in introducing advanced control.
- Identifying areas within the process that can be optimised using advanced control to yield some financial benefit.

Depending on the results of economic control audit in stage one, stage two would be a quantification and implementation exercise that would include:

- Quantify any financial gain from the identified list of potential opportunities,
- Derive any change management strategy that might be required,
- Review the advanced control optimisation packages, and recommend those packages that are offering the best application fit for building advanced control systems.

The benchmarking team was sponsored by the Production Manager and included staff members from each of the following divisions in the company: Process, Control, Production and Finance. There were three additional members of the team with benchmarking and control optimisation expertise from a university and a consulting company in charge of the feasibility study. The economic control audit was performed and the information about the company and its engineering process and the resulting recommendations was obtained by using the ICPRO approach. Some additional insight was developed from meetings and briefings by various company staff members from the Reservoir Management, Production, Control, and Process and Forecasting departments.

2.4.1 ICPRO Step 1: Profile and Operations Assessment

The company's prime concern is the production and sale of crude oil and associated products. The company has three oil platforms called here: Platform A, Platform B and Platform C. These platforms manage the production of crude from sub-sea oil wells. The crude oil and associated products are then transported by pipeline to onshore terminals for processing before being sold. The company is charged a tariff per km for using other operator pipelines to export their products. The Raw products from the company platforms can be classified as:

1. Black oil
2. Natural gas liquids (NGL)
3. Condensate

4. Gas

The Company generates revenue by the sale of its products, the quantity and quality of the products thus influencing the amount of revenue received. The finished products are:

1. Stabilised crude oil
2. NGL
3. Sales Gas

(a) Stabilised Crude Oil

Black oil is produced on the company's platforms and processed at onshore processing facilities. It is sold by the barrel, as stabilised crude oil. The price of stabilised crude on the world market and the quality of the crude determines the price received for each barrel. Its base sediment and water (BS&W) content determine the quality of the stabilised crude. There is no regulation/restriction on the amount of stabilised crude the company can sell in any given month.

(b) Natural Gas Liquid

The Natural Gas Liquid produced by the company is sold by the tonne. The price received per tonne of NGL is determined by the price of its components on the world market and the quality (composition) of the NGL for the month. There is a regulatory procedure for the sale of Natural Gas Liquid. This procedure can be summarised as follows:

1. 100% of monthly production of NGL must be lifted (i.e. sold).
2. Lifting is based on forecast production of NGL.
3. If there is under lift (less than 100% of production lifted), then the excess is stored and sold based on next month's prices.
4. The forecast production and actual production may differ.
5. The NGL component prices are released on the first day of every month.
6. The NGL is sold/lifted on the 15th of every month.

(c) Sales Gas

The Sales Gas produced by the company is sold by the tonne. The price received per tonne of NGL is determined by the price of sales gas on the world market and its quality (Gross Calorific Value) for the month. There is a sales contract in place that regulates the sale of Sales Gas. This contract can be summarised as follows:

1. Carbon Dioxide content less than 1 mol %
2. Gross Calorific value: $36.9<GCV<42.9\ MJm^{-3}$

A substantial percentage of the monthly revenue comes from the sale of stabilised crude oil. This is produced in greater quantities and provides a higher financial return than the other company products. All three platforms A, B and C are designed to process crude oil, gas and liquids. Amongst the three platforms, A, B, C, Platform A produces the largest quantity of stabilised crude oil, and Platform B produces the largest quantity of Gas, NGL and condensate.

2.4.2 ICPRO Step 2: Process and System Assessment

The platforms are designed to produce and process reservoir fluids. Each of the platforms is uniquely associated with a number of wells /reservoirs from which reservoir fluids are recovered and processed into black oil, NGL, sales gas and condensate. The process system can be divided into two subsystems.

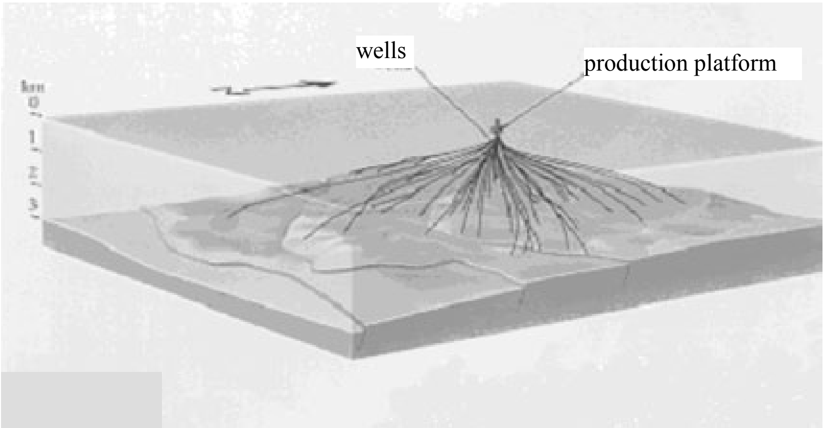

Figure 2.3. Production reservoir

1. <u>Reservoir system</u>

The reservoir system is depicted in Figure 2.3. It consists of the Reservoir, Production wells and re-injection wells. The reservoir system provides the raw materials (reservoir fluids) that are processed in the topsides system. Three reservoirs and their uniquely associated production wells and gas injection wells service the platforms. Although the reservoirs are distinct, there is a level of inter-connectivity between them provided by the underlying rock formation. This introduces a level of multivariable interaction into the reservoir system. The reservoir and the well characteristics depend not only on the temperatures and pressures existing within the wells and reservoirs but also on the nature and geological topography of the underlying rock formations that surround them. There is a level of interaction and recycling between the reservoir system and the topsides system. The result of this interaction/recycling is that disturbances or events in the reservoir system affect the dynamic operation of the topside system and *vice versa*.

2. <u>Topside system</u>

The topside process system provided on the platforms can be divided into four basic groups:

a) Wellhead system

b) Separation systems
c) NGL systems
d) Gas compression systems.

Figure 2.4. Production platform christmas tree and wellhead assembly

a) Wellhead System

The Wellhead system enables the management of the reservoir. It has associated with it a number of production wells and gas injection wells. The Wellhead system is designed to provide a safe means of producing reservoir fluids and re-injecting processed gas back into the reservoir. The 'Christmas tree' provides the facility for safe shut-off of the wells. It is an assembly of master valves and wing valves as shown in Figure 2.4. The master valves being used to shut in the wells and the wing valves to isolate the wellheads from the production manifold or gas injection manifold. On production wells, the reservoir fluids flow up the production tubing via the surface controlled sub-surface safety valve, to the wellhead and 'Christmas tree'. From the Christmas tree, the fluids flow through a choke valve which is used to control the rate of flow of reservoir fluid. From the choke valve the fluids flow through wellhead flow lines to the production manifold. Not all production wells associated with a given platform may be in operation at a particular time. The gas injection wells are used to maximise black-oil recovery by minimising reservoir pressure decay.

b) Separation System

The separation system is designed to process reservoir fluids. Black oil, flash gas and produced water are separated in a separation train comprising the following four stages

1. Feed and expansion system
2. High pressure (HP) separator
3. Medium pressure (MP) separator
4. Low pressure (LP) separator

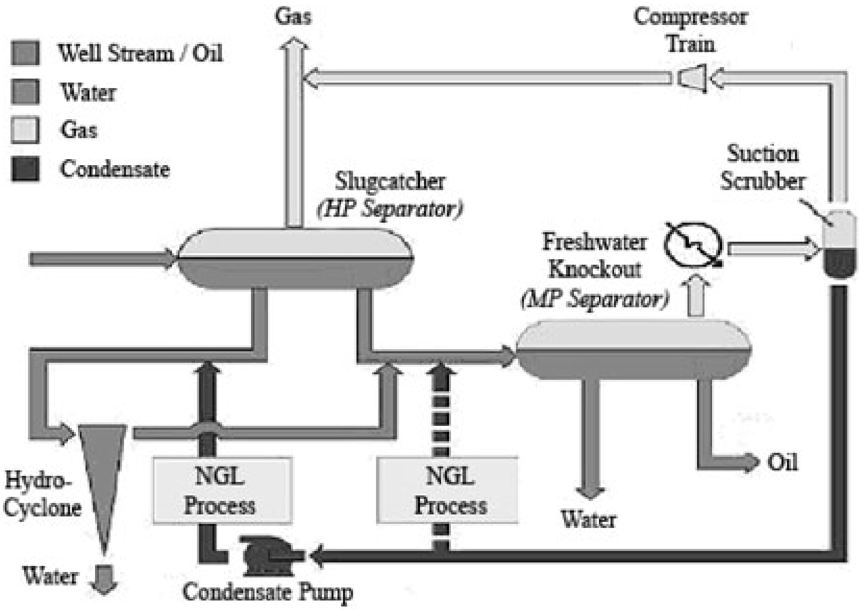

Figure 2.5. Simplified separation system

On the Platform A the operation and setup of the original system has been modified and the effective (simplified) view of the resulting system is show in the line diagram of Figure 2.5. The simplified separation process effectively consists of two tanks in series, the *High Pressure Separator* is setup as a *Slugcatcher* vessel and the *Medium Pressure Separator* is set-up as a *Free-Water Knock Out* vessel. The function of this plant is to remove gas and water from the crude oil flowing into the plant and pump this 'cleaned' crude oil to other plants down stream in the installation operation. The level of crude oil in both tanks has to be maintained between an upper and lower limit, for the Slugcatcher plant to function effectively. The level is also used as surge capacity to ensure a continuous and constant flow of crude oil downstream to other units.

c) NGL System

A typical NGL refrigeration process is depicted in Figure 2.6. Unstable condensate and gas from the HP separator are processed within the NGL system to recover those hydrocarbons which may be exported in liquid form through the main oil export system. The unstable condensate and gas streams enter the system separately and are cooled by heat exchangers and mixed. This mixture is further cooled using liquid refrigerant in the gas chillers. The cooled mixture is then routed to the cold condensate separator. NGL is recovered from the base of the column, cooled, metered and then introduced into the black oil export pipeline. Platform B uses an enhanced NGL recovery system. The system dehydrates and recovers NGL from the vapours of the inlet gas scrubber and HP separator in its separation system. The system returns the recovered NGL to the HP separator for subsequent export with the black oil.

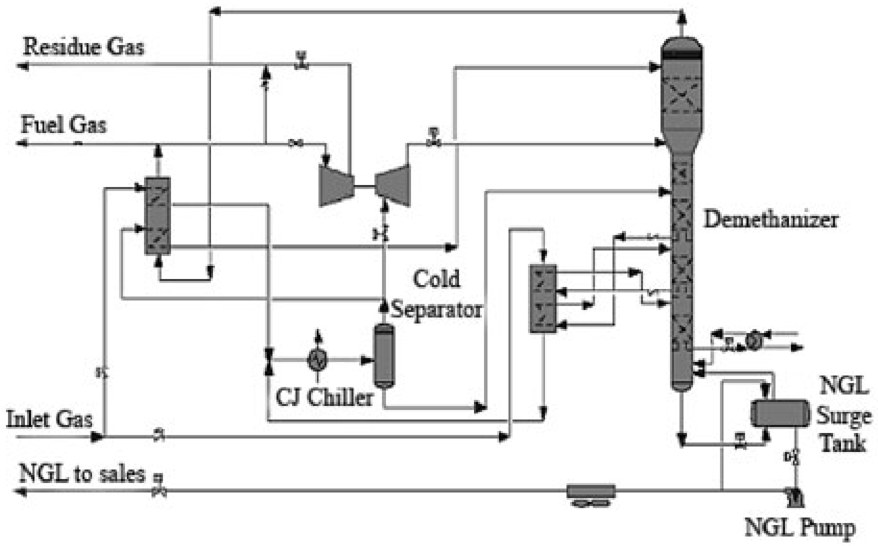

Figure 2.6. NGL refrigeration system

d) Gas Compression System

The Gas compression and re-injection system is shown in Figure 2.7**.** The purpose of this system is primarily to compress gas for export and sale or for re-injection into the reservoir. Separated gas is compressed through three parallel compression trains, each with an MP separator and Export Compressor. Compressed gas is exported via pipeline and gas for re-injection is taken directly from the export header upstream of gas metering and compressed. The re-injection compressor is a two-stage, gas-turbine driven machine with dedicated anti-surge and performance control. Gas re-injection is important for increasing gas throughput. It enables more liquids to be produced from the gas.

Remarks on Platform Processes

The topside process is very interactive because it contains a number of recycle loops. There is full inter-connectivity between all the sub-systems on the platforms. This results in a highly interactive multivariable system. The critical process parameters are: pressure, temperature and level. Although the process is in general a slow one, disturbances to any part of the system can produce fast acting ripple effects (transients) that are typically amplified as they move downstream from the source. This occurs because of the interactions within the process and its multivariable nature.

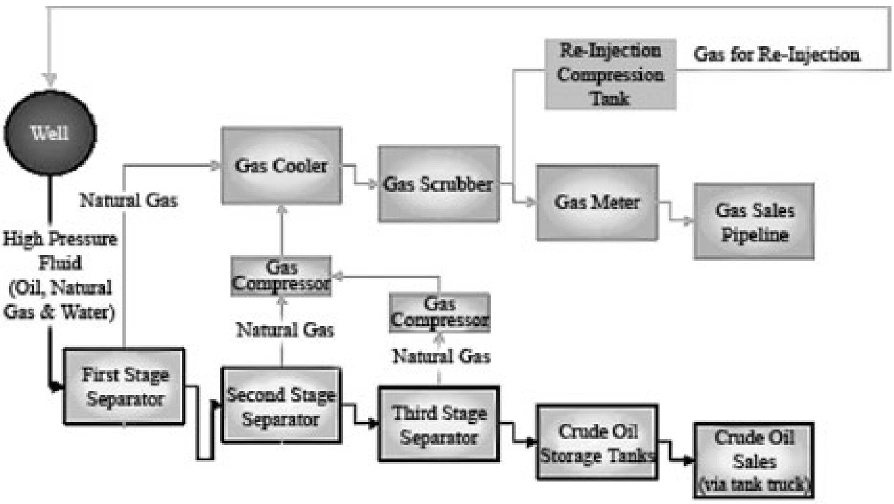

Figure 2.7. Gas compression and re-injection system

Process Control Overview

The control systems on the platforms serve two main purposes:

1. To provide a safe and efficient means of control for the production process and associated support services.
2. To provide a means for monitoring platform/system status and to initiate the necessary (shutdown) actions to preserve platform/system integrity and safety of personnel

All the primary control loops associated with the process system are controlled using PID controllers. There are three basic control loops:

1. Level Control
2. Pressure Control
3. Temperature Control

Although the process is highly interactive and contains a number of recycle loops, each control loop is tuned independently with limited consideration of the interaction with other loops or recycle effects. The platforms use the Honeywell TDC 2000 and 3000 (Total Distributed Control) system as the main platform control and data acquisition system. No supervisory control strategy or set-point optimisation is implemented, except in Platform A where the TDC 2000 is used to provide supervisory control for the gas compression system. On Platform B and Platform C, the export/re-injection gas compressors are controlled using Compressor Control Corporation (CCC) designed controllers. All the other PID controllers are located within the platform DCS system. There are no other local controllers on the platform.

2.4.3 ICPRO Step 3: Financial Benefits and Control Strategy Correlation

The information and product data obtained by the benchmark team from the first two stages of the ICPRO procedure was analysed using the correlation list discussed in Section 2.3. The objective was to determine the relative importance of loops in process units as well as the importance of the process units themselves, and to create a rational hierarchy of the various optimisation potentials that might exist. A summary of the results is presented according to correlation list.

1. State the mission, purpose or goal

Continuous production, transportation and sale of crude oil, natural gas liquids, gas and condensates in line with established environmental policy and limits of the production facilities.

2. List the process units associated with each of the above

The major system components that together facilitate the goals of the company are:

a) Reservoir system
b) Wellhead system
c) Separation systems
d) NGL systems
e) Gas compression systems.

3. From all the process units identify the major units by operations

From the analysis of the operations data the following units were identified as the major operating units:

a) Separation systems
b) NGL systems
c) Gas compression systems
d) Reservoir system

4. From the shortlist of key units, identify which processes add the most value or cost

Analysis of the production, maintenance and cost data showed that the following units contributed either the highest percentage of revenues or losses from the platform operations:

a) Separation systems
b) NGL systems
c) Gas compression systems.

5. List the major production, quality and availability, enablers, bottlenecks and constraints

For this feasibility study the benchmark team were able to identify a number of candidate cases which could be either potential enablers or bottlenecks. These cases are presented below.

- ***Analysis of Present Reservoir and Well Management Strategy***

The Company employs gas lifting, gas (re-) injection and water and gas injection (WAG) on certain wells to boost well pressures and increase reservoir fluid recovery. These techniques are used to manage the wells and limit their decline. The company also employs well scheduling. It has a detailed and accurate simulation model for their reservoirs. These models are used to simulate reservoir and well behaviour under varying circumstances. These reservoir models are however stand alone models, as they do not include either the production flow-line or the topsides process models. At present the analyses for WAG injection and the amount of gas to be injected and the rate of injection are being done as open loop calculations with no direct feedback information and without the interaction of the flow-line and platform processes. These calculations are not done online and there is a substantial time delay between analyses. This approach does not ensure optimal results and as such the resultant benefit of the whole operation is not maximised.

- ***Increase In Raw Material Financial Yield***

There are two issues involved in increasing the financial yield of the raw material (reservoir fluid). One aspect of this is to increase the amount of finished product extracted per tonne of reservoir fluid processed on the platforms. The other aspect is increasing the revenue received from the finished products; this essentially involves the quality or composition of the products, since the prices per tonne/barrel of the products depend on their quality or composition.

Black-Oil Yield: measured against the company standard, black oil extraction from reservoir fluids seems to be efficient. The base sediment and water (BS&W) content determines the quality of Black oil. The efficiency of the separation process, reservoir fluid residence times in separators, interface level and the efficiency of the chemical injections affect this index. The lower the BS&W content of the black-oil, the higher its market value and the less amount of water being exported down the pipeline. Since the company is charged a transportation tariff for exporting the black-oil from the platform, reducing the BS&W should improve market value of the product and maximise returns on transportation tariff. At present company targets for BS&W are set at 0.25%. This projected target is being achieved at the Platform B, and Platform C. On the Platform A hardware problems (problems with the electrostatic coalescer) and chemical formation and injection problems (problems with the formation of solid calcium napthanate) are currently affecting the BS&W target. However, company representatives believe that they have determined the source of the problem and can bring it under control.

NGL Yield: the efficiency of product extraction or recovery from reservoir fluids cannot be claimed to be optimal in the case of NGLs. The quality of the NGL is determined by its chemical composition (the proportion of propane, butane, dry gas, etc., and waste carbon dioxide). The fractions of each of these NGL components recovered from the gas stream are influenced by the temperature and pressure conditions on the platform (particularly in the NGL / Refrigeration systems). The NGL recovered on the platforms is exported by pipeline to onshore processing plants. There is a transportation tariff per km of pipeline as well as a processing tariff per tonne of NGL sent to the processing plant. There is also a penalty charge for carbon dioxide contents exceeding a certain level. Each of these NGL fractions has a unit price that may vary from month to month. These prices become known at the 1st of each month and the NGL produced for a given month is sold on the 15th of each month.

The composition of gas re-injected into the reservoir also influences the composition of the NGL stream leaving the reservoir and entering the platform. There is about a 30-day delay (approximate) before the effects become apparent. The Company's economic department at present produces forecasts for likely prices for various NGL components in the near future and then appropriate steps are taken by the reservoir engineers to try and influence the composition of the NGL in the reservoir. There might be room for an expert system with predictive forecasting and filtering ability to improve this aspect of the operation.

- ***Reduction Of Losses Due to Plant Downtime***

A significant portion of the Company's loss of revenue from operations is due to non-availability of different platforms. Some of these losses are also due to process or control problems. The data from the monthly production report was analysed and the loss in production due to process problems trended. Figure 2.8 to Figure 2.11, show the most prominent causes of losses in production due to process problems for all three platforms over the eight month evaluation period. These process problems shown in the chart have affected the production quota more than six times. Some areas have been identified as recurring problems with a substantial contribution to losses.

Problem Areas on Platform A

1. Water treatment and handing facilities
2. Gas lift system
3. NGL system
4. LP and MP Separator control system on A and B train
5. Plant start up control system

Problem Areas on Platform A (Joint Development (J/D) Zone)

1. Slug-catcher control system
2. Booster pump control and monitoring system
3. Chemical injection and monitoring system
4. Plant start up control system
5. Water treatment and handing facilities
6. Riser pressure control system

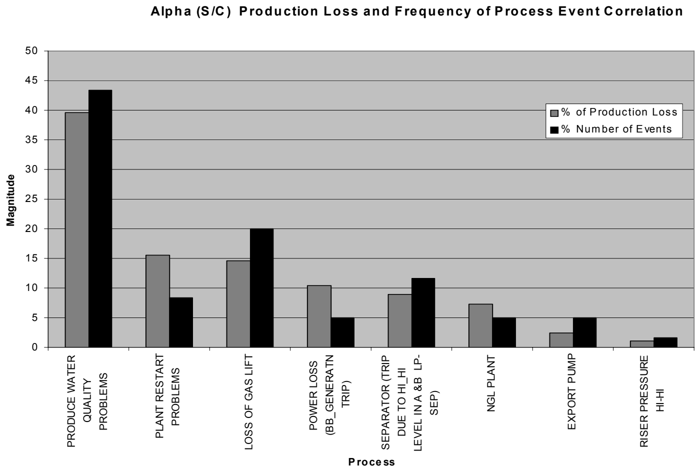

Figure 2.8. Platform A, production loss chart

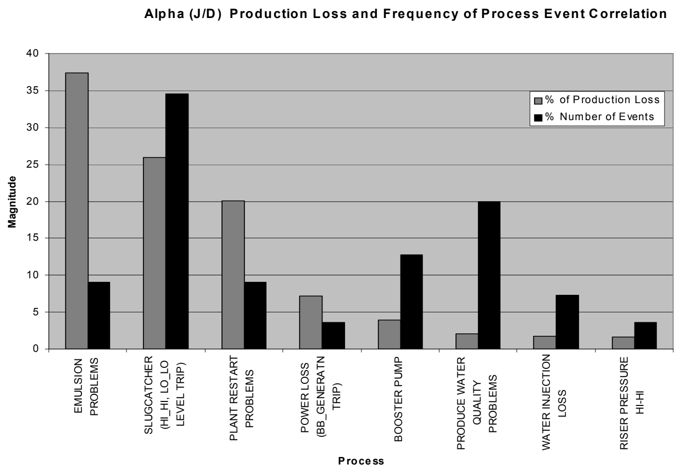

Figure 2.9. Platform A (Joint Development Zone), production loss chart

<u>Problem Areas on Platform B</u>

1. Refrigeration system
2. NGL plant
3. Power generation control and monitoring system

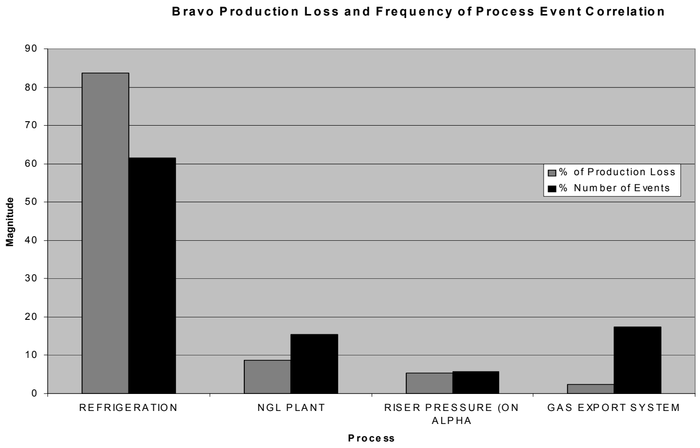

Figure 2.10. Platform B, production loss chart

Problem Areas on Platform C

1. HP Separator
2. LP and MP Separator control system on A and B train
3. Compressor control and monitoring system.

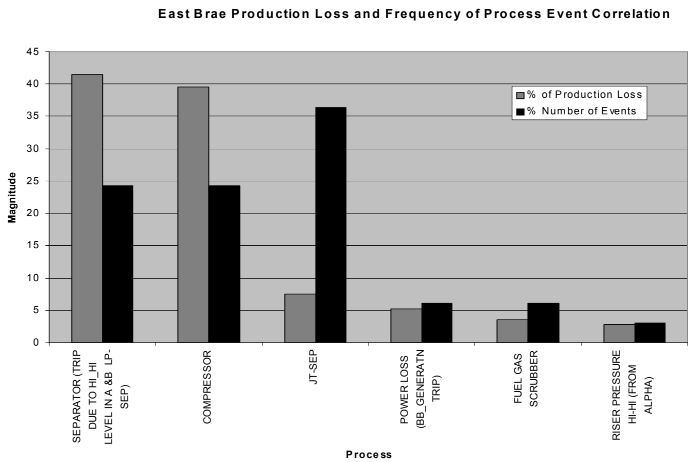

Figure 2.11. Platform C, production loss chart

- ***Analysis Of Present Control System and Strategy***

Although the present control strategy is adequate in providing a safe, and to some extent, efficient means for production of the required product, it cannot provide the kind of efficiency or optimisation that the Company is looking for. PID controllers are by nature corrective controllers, they do not act until the system has been disturbed and a deviation from set-point has occurred. Sometimes the controller performance can be improved by including feed-forward or cascade action. These performance improvement measures are not in place at present. Analysis of the process and disturbance dynamics, showed that implementing a feed-forward or cascaded PID control strategies will not improve the control performance to the level required.

The PID controllers are tuned quasi-independently. The process is interactive, multivariable and has recycles, therefore, once all the controllers are switched to automatic, there will be some interaction between control loops. Independent tuning of PID controllers may limit the effectiveness of the required control actions and reduce the consistency of operation. As it is well known, these difficulties could be overcome by implementing an advanced (multivariable) control strategy. However, the motivation for implementation of advanced control is financially based. Therefore, changes to the existing system, where required, must be justified not only by the improved consistency of operation but, mainly, by the economics.

2.4.4 ICPRO Step 4: Optimality Assessment

The results from the audit make it possible to conclude that:

- Present control strategy is adequate but not optimal.
- Present strategy is purely based on classical control and cannot be easily adapted to meet and respond to future company process goals and operational efficiency.
- Present PID controllers are too sluggish in responding to disturbances to platform operating points.

Research on the application of model predictive control to industrial processes has shown that advanced process control techniques can enhance the performance of complex processes in petrochemical and process plants as found on the production platforms [Clarke, 1988 and 1991; Cutler and Ramaker, 1980; Richalet 1993; Schley *et al.* 2000]. Given the dynamics of the processes on the platform, then to improve platform operation and optimise revenue flow, a new supervisory level of integrated control structure is needed.

An advanced controller can be designed to continuously optimise plant operation on an economic basis according to operating conditions that prevail at any point in time. An advanced controller will reduce trips through improved disturbance rejection. From analysis and evaluation of the Company's economic targets and platform operation, a number of process areas can be targeted for an enhancement in control operation. This enhancement in the form of an upgrade from the present control strategy to an advanced one will provide positive financial benefits.

- ***<u>Recommendation For Enhanced Reservoir Management and Improved Reservoir Fluid Recovery</u>***

With advanced control strategies and modelling techniques, the reservoir models can be integrated with the flow-line and topside models. Once an integrated model is obtained, a mathematical representation of the full multivariate system can be deduced. Using this mathematical representation, the aim would be to develop a criterion for optimising well scheduling, WAG injection, gas lift and gas re-injection such that the reservoir fluid recovery is maximised while minimising well decline. From this criterion an integrated predictive control system plus an expert decision making system can be designed. Such a control system will ensure that at any time the re-injection rates and well schedules will be optimal and recovery of reservoir fluids and input flow rates maximised. There exist a number of reservoir and well process parameters that are being monitored in real-time at present. These parameters can be used for control feedback, and other required parameters that cannot be measured directly can be inferred. Although such an advanced control and decision making system would provide large financial benefits, designing and implementing it would require a substantial amount of time, engineering and research effort plus many hours of input from the Company's personnel. Therefore it is not a strategy that can be implemented in the short term, but can be considered as a long term control development strategy.

- ***<u>Recommendations For Enhancing Black Oil and NGL Financial Yield</u>***

There might be some advantages in introducing some form of advanced control and monitoring into the crude oil separation process. Using advanced control strategies, the efficiency of the separation process can be improved by optimising control set points and improving the control action to ensure constant production efficiency. The Company spends a substantial amount of money each year in procuring the chemicals needed for the chemical injection process. Chemical injection is necessary to deal with the situation that arises due to the nature of the process. Some of these chemicals and the situations that necessitate their use include:

- Emulsifiers: used to help with the de-emulsification process. The formation of emulsion during the separation process affects black oil quality,
- Scale Inhibitors: used to prevent scaling in separators and pipelines. Scale formation can partially/completely block pipelines hindering the flow of black oil and possibly causing plant shutdown,
- Acetic acid: on Platform C, acetic acid is used to counter the effect of sodium napthanate.

Monitoring targeted variables or indicators and setting up a control procedure to handle the rate and amount of chemical injection could significantly enhance the chemical condition monitoring and injection process. The incremental revenue that would accrue from implementing such strategies would be gained from improved product quality and reduction of lost production time. Lost production time occurs due to faults associated with the problem. Additionally, revenue would be saved through reduced chemical acquisition costs. However, since the company targets for the BS&W are already very low and are mostly being met, the amount of revenue generated by optimising these processes with advanced control will not be substantial. For the NGL using advanced control strategies, the 15 day window between price determination, production, extraction and sale can be used to optimise temperature and pressure control set-points (once the individual NGL component prices are known) to recover the optimal proportion of NGL components that maximise the revenue.

A spin-off from such a set-point optimisation strategy will be more efficient NGL recovery that should result in minimal carbon dioxide content; this should:

- Maximise returns on transportation tariff
- Maximise returns on processing tariffs
- Reduce the amount paid out as carbon dioxide penalty charges.

An example of the optimisation strategy is given below. The revenue can be calculated from the equation:

$$R = I \times a + J \times b + K \times c - C \tag{2.1}$$

where:
a = unit price of Propane per tonne
b = unit price of Butane per tonne
c = unit price of C_5 per tonne
I = % proportion of Propane in recovered NGL
J = % proportion of Butane in recovered NGL
K = % proportion of C_5 in recovered NGL
C = Cost of operating the refrigeration system.
R = Total revenue received per tonne of NGL

I, J and K depend on the temperature (T) and the pressure (P). To obtain a formula that can be used in deriving the optimal set points for the process controllers I, J and K should be expressed in terms of T and P and substituted into Equation (2.1). Given a, b and c and the process constraints (not listed here), Equation (2.1) can be optimised for temperature and pressure set-point values that maximise R. Using such a simple optimisation criterion, an advanced controller can ensure that the recovery of NGL fractions is optimal at any time once the individual prices are known. This places the operating point of the NGL system in the optimal region.

- ***Recommendation on reducing plant downtime***

The process control audit showed that production platform trips due to separator control were responsible for over 60% of the combined production loss due to down time. A review of the PID control set-up for the level control of the separators indicated that a re-tune was necessary. Further evaluation of the separator systems showed that the process trips could be attributed to the level controller in the separator. Because the audit highlighted the Separator's level PID control loop as a key target for reducing production losses, the loop was chosen as candidate for performance benchmarking analysis. The results of the analysis on the crude oil separation system are presented in the rest of this section.

2.4.5 ICPRO Step 5: Control System Adaptation

As discussed earlier, simulation is used to assess effects of improved control action. Firstly, this example highlights the consequences and problems that result when a proper plant audit is NOT carried out before benchmarking and optimising plant control loops (snapshot optimisation). Secondly, the function of plant auditing in prioritising the control loops for optimisation, in order to attain management level objectives is recalled, and the exercise is repeated, this time leading to performance improvement

2.4.6 Process Characteristics

The inflow of reservoir fluids into the separation train can be described as oscillatory with high amplitude and can be modelled as a sinusoidal disturbance. The PID control system associated with each separator is tasked with keeping the level in the vessel constant. However because of the sinusoidal nature of the input flow of reservoir fluid, an existing PID solution did not meet the requirements. The fluctuations in level and pressure within the first stage (HP) separator resulted in trips and shutdown of the entire platform. A MATLAB® / Simulink® model of the first two stages of the separation system (high pressure (HP) and medium pressure (MP) separators) was developed and validated with real plant data. A scaled down model from the process characteristics was obtained by linearizing this model around normal operating conditions and using balanced model reduction techniques.

Figure 2.12 shows a simplified schematic of the process, from which a simplified mathematical model can be developed using equations for conservation of mass and pressure balance. The generic process transfer function in Equations (2.2) to (2.5) were developed from that model on the basis of the relationship between the valve position (manipulated variable) and the level of crude oil in the vessel (controlled variable).

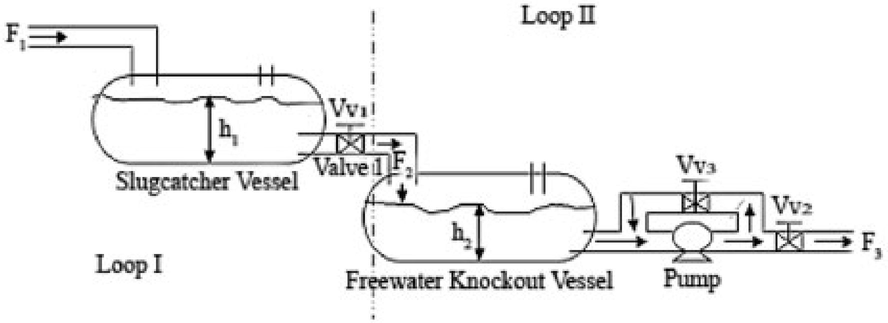

Figure 2.12. Schematic diagram for simplified 2 stage separation process

The key process assumptions, used in the model derivation are as follows:

- The gas entering the vessel along with the crude does not affect the equilibrium balance of the system.
- The vessel is rectangular with a flat base, it has a constant cross sectional area.
- Flow of crude from the vessel is laminar and the friction in the valve and pipes is negligible.
- The valves have linear characteristics.

Notation:

A_1 and A_2 = cross sectional area of vessel
F_1 = Input flow into vessel 1 (slugcatcher vessel)
F_2 = Output flow from the slugcatcher into freewater knockout
h_1 = height of crude in slugcatcher
F_3 = Output flow from the freewater knockout
h_2 = height of crude in the freewater knockout vessel
Vv_2 = hydraulic conductance of valve
M = pump characteristics
Vv_3 = constant valve position
Vv_1 = hydraulic conductance of valve
ρ = density of crude
g = acceleration due to gravity

- Open Loop Diagram for Loop 1

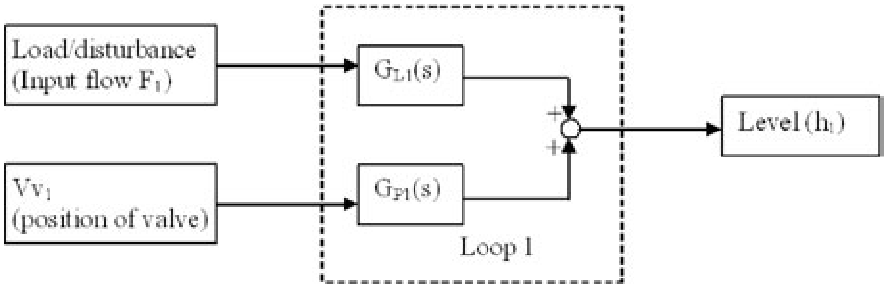

Figure 2.13. Block diagram for Loop 1: slugcatcher vessel

$$G_{P1} = \frac{\rho g h_1}{A_1 s + \rho g V v_1} \qquad (2.2)$$

The input flow to the system (F_1) appears as a load/disturbance variable to the system. The transfer function between inlet flow as input and the level of crude in the vessel as output is:

$$G_{L1} = \frac{1}{A_1 s + \rho g V v_1} \qquad (2.3)$$

- Open Loop Diagram for Loop 2

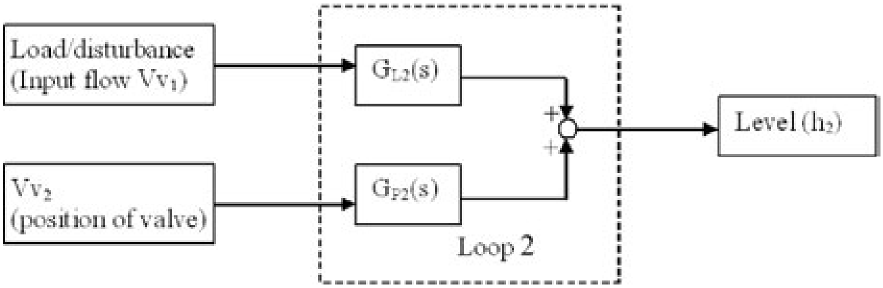

Figure 2.14. Block diagram for Loop 2: freewater knockout vessel

$$G_{P2} = -\frac{\rho g C h_2}{A_2 s + \rho g C V v_2} \tag{2.4}$$

The valve position (Vv_1) appears as a load/disturbance variable to the system .
The transfer function between inlet flow as input and the level of crude in the vessel as output is:

$$G_{L2} = -\frac{\rho g h_1}{A_2 s + \rho g C V v_2} \tag{2.5}$$

From the generic equations described above, a process model was built in Simulink® and optimised and calibrated using the peak input flows data collected from the real plant. The input flow disturbance to the separators is shown in Figure 2.15 and the response of the level loops in the separator is shown in Figure 2.16 and Figure 2.17. From Figure 2.16, it can be observed that the level in Loop 1 does not meet the high-level trip constraint (dotted line). This resulted in a number of plant shut downs and revenue loss.

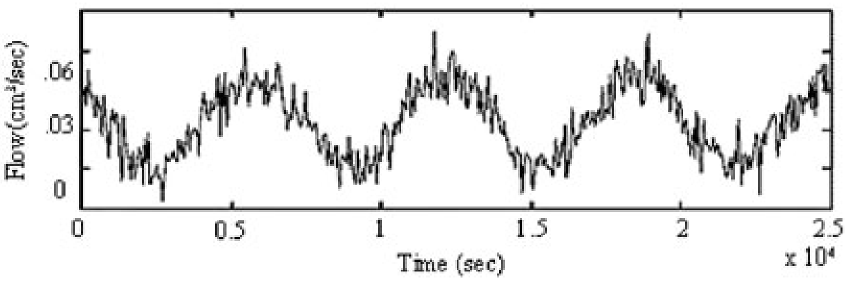

Figure 2.15. Crude oil input flow into separation system

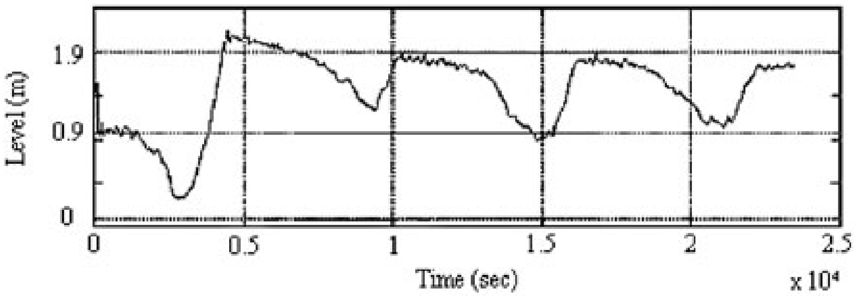

Figure 2.16. HP separator level

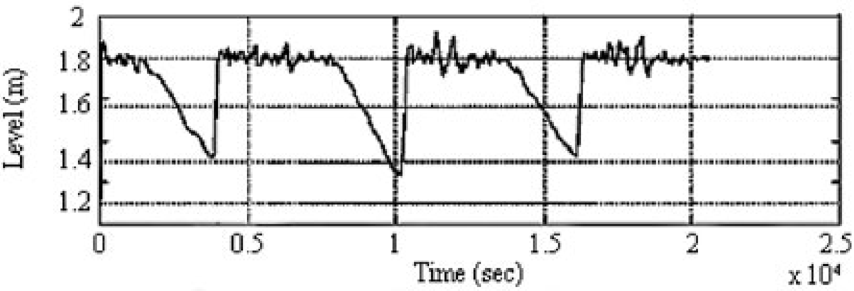

Figure 2.17. MP separator level

2.4.7 Snapshot Benchmarking and Optimisation

This approach is identical to taking a snapshot of the process at a given time. The performance of the control loops is then analysed independently, using a suitable benchmark index. In this approach no consideration is given to the overall process and management goals. Also, heuristic and knowledge based information about the process, acquired over time, is not considered.

Benchmark Analysis
A local loop performance analysis of the individual level control loops using 1000 samples was undertaken without taking the interaction between the loops and the overall process goals into account. This analysis was performed by using the normalised minimum variance control benchmark index [Desborough and Harris, 1993], to determine the performance of the control loops in the validated process model. The details of this performance index will be explained in Chapter 3. The minimum variance controller was used as a benchmark and for this, the plant performance index is given by:

$$J = \sigma_y^2 = J_0 + J_{\min} \qquad (2.6)$$

$$\sigma_y^2 = E[y^2(t)] \qquad (2.7)$$

where: J is the actual output variance, J_0 is the part of the output variance which could be affected by selection of control algorithm, and J_{min} is the minimum-variance obtainable for the given plant. The normalised minimum variance index:

$$\eta = \frac{J_0}{J} = 1 - \frac{J_{\min}}{J} \tag{2.8}$$

lies between 0 and 1, where 1 indicates minimum variance control (excellent control performance) and 0 indicates a very poor control. The graphical results for the two loops are shown in Figure 2.18 and Figure 2.19. From these graphs it can be deduced that Loop 1 is very far from minimum-variance (optimal) performance and therefore poorly tuned while Loop 2 is performing better.

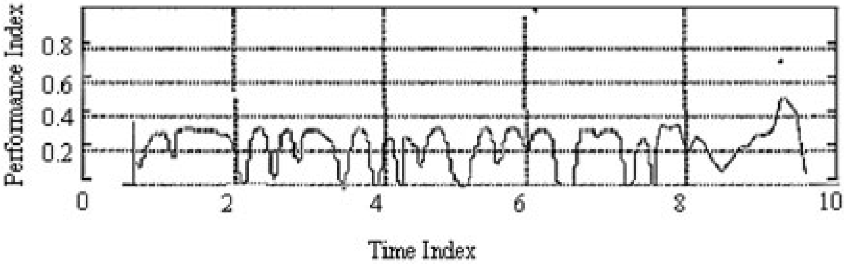

Figure 2.18. MV benchmark index for HP separator control (Loop 1)

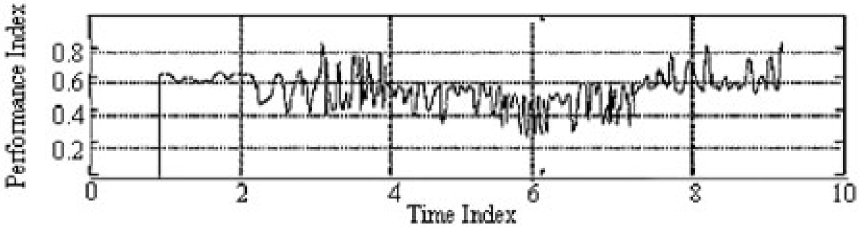

Figure 2.19. MV benchmark index for MP separator control (Loop 2)

Loop Tuning

Because both level loops are first order systems, an analytic solution to arrive at the proportional (Kc) and integral (Ti) PI controller parameters to meet the specification was used. The controller parameters were calculated using the following assumptions:

1. The damping coefficient to be used is $\zeta = 1$. The aim is to make the response of the system critically damped, so that the system response is not oscillatory and the disturbance introduces as little effect as possible during the transient period.

2. The expected maximum deviation in inlet flow is ΔF_{MAX} = 0.06 m^3/sec (3.6m^3/min).

3. For Loop 1, the steady state level is specified as 0.91m. A 10% deviation (conservative) from specified steady state operating points during transient disturbances is assumed, hence $\Delta h_{MAX} = \pm 0.091$ m

4. For Loop 2, the steady state level is specified as 1.71m. A 5% deviation (conservative) from specified steady state operating points during transient disturbances is assumed, hence $\Delta h_{MAX} = \pm 0.0855$ m

5. The cross section areas of the vessels are specified as $A_1 = 1.75$ and $A_2 = 3.4$

This resulted in the PID parameters,

$$\begin{array}{lcl} K_{C1} = 29.1165 & and & T_{I1} = 0.2335 \ \text{min} \\ K_{C2} = 15.4947 & and & T_{I2} = 0.8777 \, \text{min} \end{array} \tag{2.9}$$

Results of Re-tuning the System

Following the findings from the previous section, the system was retuned and the new benchmark results for the tuned system, as well as the levels in the vessels can be observed in Figure 2.20 to Figure 2.23.

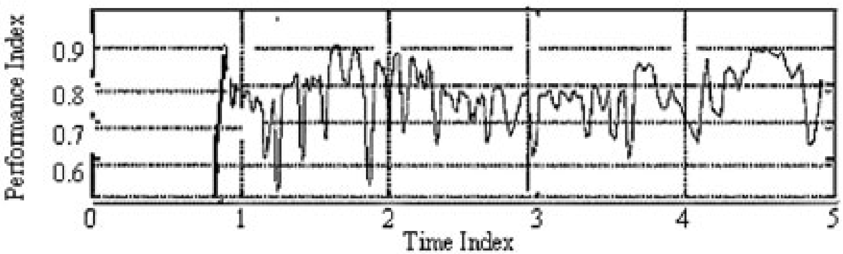

Figure 2.20. MV benchmark index for re-tuned HP separator (Loop 1)

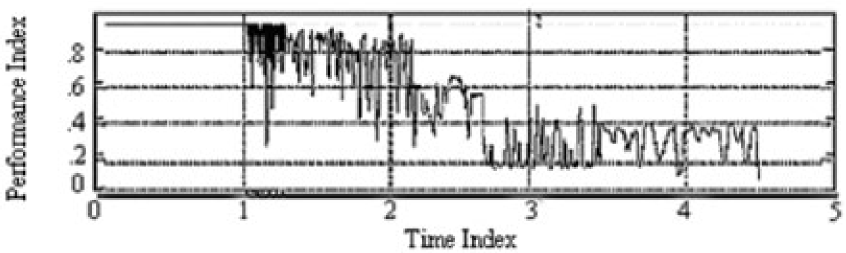

Figure 2.21. MV benchmark index for re-tuned MP separator (Loop 2)

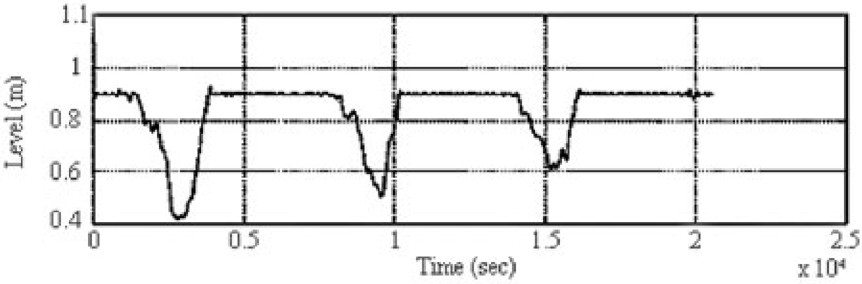

Figure 2.22. Re-tuned HP separator level (Loop 1)

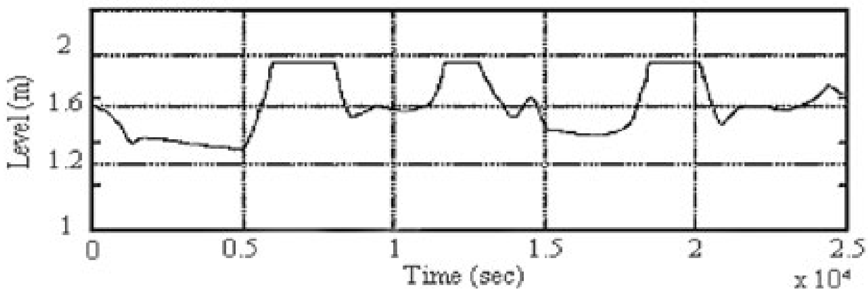

Figure 2.23. Re-tuned MP separator level (Loop 2)

From Figure 2.20 and Figure 2.21 which represent the performance index for the re-tuned loops, it can be observed that while the performance of Loop 1 has improved, the performance of Loop 2 has deteriorated. This is due to the fact that, since the control performance of Loop 1 is improved, the oscillatory dynamic disturbance of the input flow into the system is amplified and transmitted downstream to Loop 2. The effect of this can be seen from Figure 2.22 and Figure 2.23. It can be observed that Loop 1 is now meeting the high-level trip constraint while Loop 2 is breaking it. Thus the overall effect of the controller tuning effort was to shift the cause of the process trips from Loop 1 to Loop 2, with the net result that revenue will still be lost due to plant downtime in periods of peak disturbance.

2.4.8 Integrated Plant Auditing and Benchmarking

The integrated control and process revenue optimisation approach requires that before any benchmarking analysis, control design etc, is done, in-depth plant auditing involving management, process and control objectives should be carried out. The results of the audit presented earlier are now applied to the problem with the following observations:

- Management Objectives
  - The main management objective is to maximise production. The input flow oscillatory disturbance must be controlled and not transmitted downstream to other process units. A high process up time as well as the optimum separation conditions within the vessel is the target.
  - Reduction in plant down time.
    The problems caused by this sinusoidal disturbance are not only related to process control of the level, and pressure loops, but also to the platform revenue. These fluctuations in the level and pressure in the separation cause the entire plant to trip resulting in lost production and hence loss of revenue.
  - Increase in Production Rate.
    By improving set-point tracking of controlled variables (i.e. controller performance), set-points can be optimised and the process operating conditions moved closer to the constraints and production rates safely increased.
- Process and Control Objectives
  - Stabilise the flow of crude oil downstream of the HP separator.
  - Maintain the pressure and volume of crude oil in the separators at a level that ensures efficient separation.

In deciding on a criterion that will best achieve these goals, an analysis of the problem and process characteristics led to the following conclusions.

1. To stabilise the flow down stream of the separators, the volume of crude oil in the HP separator should be used as a buffer/surge control.
2. As long as the level in the HP separator is maintained within the constrained limits, adequate separation will be ensured. With the flow stabilising downstream of this vessel, the other separators will be able to perform better.

An obvious solution is to design two flow optimizing cascade controllers for the two individual loops. The cascade controllers will take measurements of the outlet flow from the loops and adjust the set points of the level controllers in the loops to compensate for any disturbance in the desired value of outlet flow. The level set points for both controllers will act, as the manipulated variables while the outlet flow from both loops will be the controlled variables. The level in both vessels will be used as surge capacity to compensate for periods of very low or very high flow rates. There are reasons however why such a design will not achieve the required performance objective and that necessitates a foray into the uses of more advanced control strategies.

Limitations of Standard PI Cascade Control Strategy.
In the cascade control structure the level loops will act as the secondary control system with the levels in both vessels serving as the measured secondary variable, while the primary system will be the flow loop.

Table 2.3 summarises the time and frequency domain characteristics for the primary and secondary systems.

Table 2.3. Loop characteristics

Time Domain Characteristics	Primary System		Secondary System	
	Loop 1	**Loop 2**	**Loop 1**	**Loop 2**
Rise time	120.46 sec	226.98 sec	12,455.28 sec	6455.28 sec
Settling time	205.67 sec	405.60 sec	17,850.47 sec	8000 sec
D.C. gain	0.426	0.0651	-1027	-872.30
Time constant	52 sec	114 sec		

Next, the standard design criteria for a cascade control system are examined:

a) There must be a causal relationship between the manipulated variable and the secondary variable.
There is a causal relationship between the measured levels in the tanks and the manipulated variables (which are the level set-points). Thus, this criterion is satisfied.

b) The secondary variable must indicate the occurrence of an important disturbance.
The measured secondary variables in the process are the levels in both vessels. The major disturbance to level Loop 1 is the sinusoidally changing input flow. Changes in the measured level in Loop 1 give an indication that the disturbance has changed value. While in Loop 2 the major disturbance is the valve position Vv_1. *Changes in this valve position cause oscillations in the magnitude of crude oil flow into Loop 2, resulting in changes in the level of the vessel in Loop 2. Thus, this criterion is satisfied.*

c) The secondary variable dynamics must be much faster than the primary variable dynamics.
From Table 2.3 it can be observed that the measured secondary variables fail to meet this condition. Since both vessels are effectively integrators at steady state, changes in the input flow to the system are almost immediately reflected in the output flow. The dynamics of these secondary variables are not much faster than of the primary variables.

Implementing a cascade control structure under this conditions will not yield any really meaningful improvement in the process control performance and hence will not result in an optimized value of output flow. Since the standard cascade PI control structure is not suitable for this process, there was a need to explore more advanced control strategies. A better solution is to use a model predictive controller to implement the cascade solution since for cases when the dynamic response of the secondary system is not substantially faster than the primary, the predictive primary cascade controller offers a distinct advantage. The benefit of the predictive cascade arises because the feedback signal in a model predictive control system is the sum of the model error in the primary loop and the primary loop disturbances along with the fact that the secondary disturbances that cause deviations in the secondary measurement, appear in both the measured and predicted primary variable at about the same time and with the same magnitude (if the model is accurate), then as a result, the secondary disturbances have little or no effect on the feedback signal The model predictive controller chosen to design the cascade structure was the Internal Model Controller (Figure 2.24) developed by Morari and Garcia [1982]. The appealing feature of the IMC is that it provides a systematic approach for designing robust controllers that provide good control performance while compensating for modelling errors and usually involves only a single tuning parameter, which can be related to the desired closed loop time constant. The controllers are easy to design and are sometimes realizable in standard PID forms.

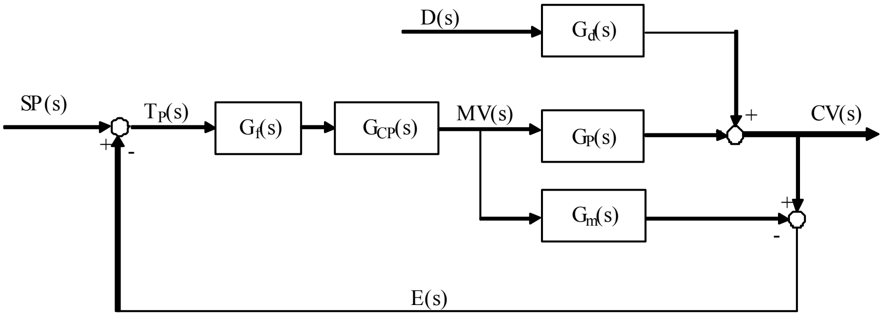

Figure 2.24. Structure of the IMC controller

Key:

SP(s)	Reference set-point	CV(s)	Controlled variable
D(s)	Disturbance variable	$T_P(s)$	Target Value
MV(s)	Manipulated variable	E(s)	Feedback signal
$G_{CP}(s)$	Predictive controller transfer function	$G_P(s)$	Process transfer function
$G_d(s)$	Disturbance transfer function		
$G_m(s)$	Process model	$G_f(s)$	Filter

The feedback signal E(s) is the difference between the measured and predicted controlled variable values. The variable E(s) is equal to the effect of the disturbance $G_d(s)D(s)$, since if the model is perfect $G_m(s) = G_p(s)$. This means that if the model is perfect then the predictive control would acts predominantly on the disturbance for feedback correction and not the combination of disturbance and errors due to model mismatch. In single loop IMC design, the convention is to use low pass filter of the form

$$G_f(s) = \left\{ \frac{1}{\tau_f s + 1} \right\}^N \tag{2.10}$$

The filter time constant, τ_f is the only parameter that has to be tuned to achieve any performance specification. Increasing the filter time constant modulates the manipulated variable fluctuations and increases robustness at the expense of larger deviations of the controlled variable from its set-point. From the given process transfer functions, the IMC filter time constants for Loops 1 and 2 can be calculated as:

$$\tau_{f1} \geq 10.4 \text{ secs}$$
$$\tau_{f2} \geq 22.8 \text{ secs}$$

Because inevitably there must be an error in the determined models, a safety margin is included in the realization of the filter time constant, so:

$$\tau_{f1} = 10.4 \times 2 = 20.8 \text{ sec}$$
$$\tau_{f2} = 22.8 \times 2 = 45.6 \text{ secs}$$

Analysis of IMC Controller Performance

The performance of the IMC controllers in a supervisory role was simulated and the data obtained used as a performance benchmark. It is usually a good practice to compare system performance benchmarks before and after process optimisation. However, this does not apply to this particular exercise. Because the high level objective is to ensure stable and nearly constant flow rate, benchmarking the performance of the separator level controllers will not provide a useful indicator. From the results and data obtained from the simulations, as shown in Figure 2.25 and Figure 2.26, the estimate is that, a 15-25 % reduction in the variation of crude oil flow rate downstream of the HP and MP separator units, can be achieved by using model based control systems in a supervisory mode.

The reduction in flow rate variations will decrease the amplitude of the disturbance experienced in the level loops of other separator units. The number of process trips caused by variations in flow rate should also be reduced. This is because the flow rate trip set-point has a value of 0.057 m^3/sec and as can be observed from Figure 2.25 and Figure 2.26, the IMC controller keeps the flow rate between the bounds of 0.03 ± 0.01 m^3/sec.

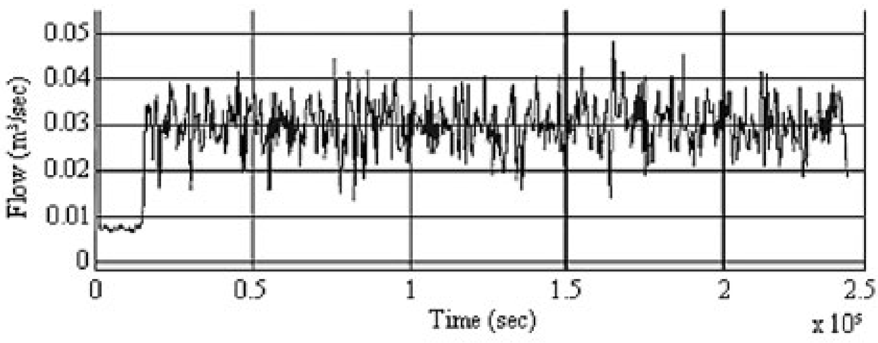

Figure 2.25. Crude oil output flow from HP separator

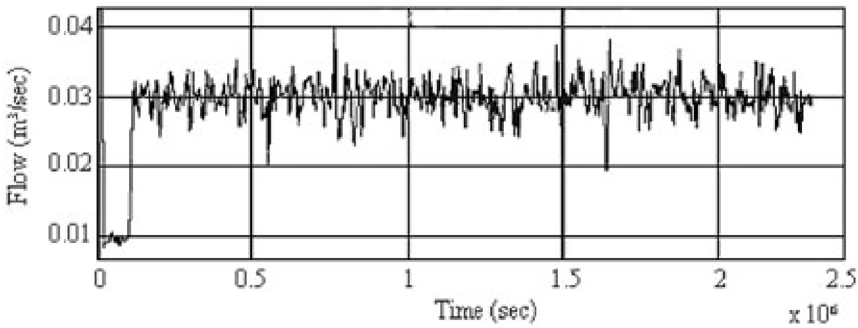

Figure 2.26. Crude oil output flow from MP separator

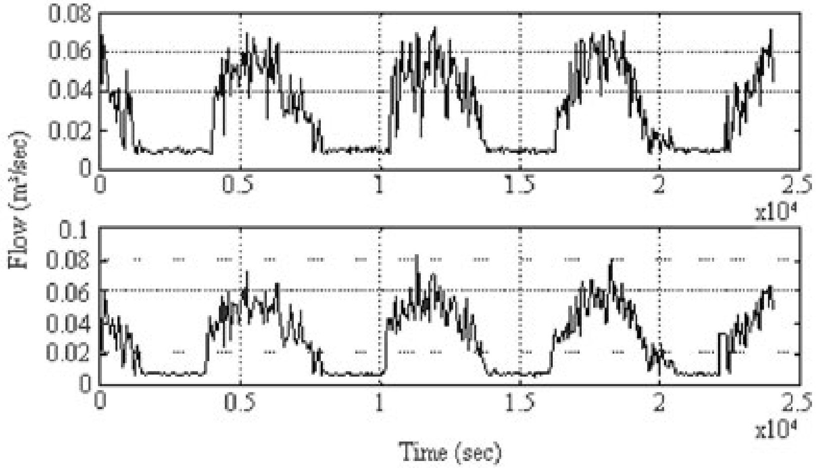

Figure 2.27. Initial crude oil output flow from HP and MP separators

For separator vessels downstream of the HP separator, a reduction in level control variations of about 10 % was recorded as shown in Figure 2.28. It is estimated that this reduction will not only reduce process shutdowns, due to the separator level trips, but also introduce the possibility of pushing the operating conditions of the separators closer to their physical constraints. This should have a significant impact in reducing the revenue lost due to plant downtime and should also enable production rates to be increased.

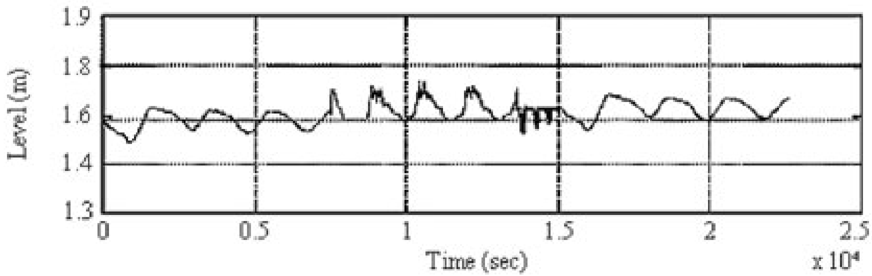

Figure 2.28. MP separator level

2.5 Conclusions

In this Chapter, the connection between process control performance and the revenue derived from industrial processes was highlighted. A method for integrating the use of process control benchmarking and optimisation algorithms with the optimisation of process revenue by means of an economic process control audit was developed. The goal of the method was to selectively benchmark and optimise process control loops in such a way as to derive maximum revenue from the process. The method was demonstrated by means of an industrial feasibility study. For large scale processes such as an integrated crude oil and gas production facility, it was possible to use this method to highlight potential areas where advanced control optimisation could be of substantial financial benefit. The method was also able to identify some process control loops which had substantial impact on process performance and revenue. For large scale processes and processes with interaction, it was shown that benchmarking and optimising individual loops without consideration for the wider objectives of the entire process can in some circumstances have a negative impact on overall process performance. As demonstrated the ICPRO approach can help focus process control optimisation and benchmarking, in conjunction with the aim of improving overall process performance for financial gain.

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