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North Sea FLOW Measurement Workshop

Paper 2.1

Equitability, Allocation and Game Theory

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1 INTRODUCTION

If not actually written into allocation agreements, equitability is often assumed to be one of their governing principles. The belief being that, if the system is equitable, then it should be free from bias and all participants treated equally.

But what exactly does equitability mean in this context and can it mean different things according to different viewpoints? This question has been addressed in detail, and at a fundamental level, by industries outside of oil and gas, in developing fair methods to allocate costs, resources and products.

Examples include:

- Civil engineering projects (Tennessee Valley Authority)
- Aircraft construction (McDonnell Douglas)
- Tree log allocation in the pulp and paper industry (several Finnish companies)
- Airport landing fees (Birmingham airport).

Many of these methods have been informed by the science of game theory.

This paper describes the application of these methods to hydrocarbon allocation in an effort to gain a deeper understanding of what is meant by the concept of equitability. The paper compares these methods with the more familiar proportional based approaches and explores instances when these traditional approaches may not appear equitable.

Three particular aspects of hydrocarbon allocation, fuel gas, the effects of commingling and access to restricted capacity, are used to illustrate the various approaches. These comparisons use data from real systems to assess how “fair” each appears.

In Section 2, the concept of equitability is examined, in particular the proportionality principle. A simple compression fuel gas allocation example is used to explore aspects of fairness. Section 3 describes alternative approaches to allocation borne out of co-operative game theory and describes their application to cost allocation in other industries. In Section 4 the alternative approaches are applied to the simplified example. Section 5 applies the various allocation approaches to data obtained from real allocation systems. Finally Section 6 provides a summary and some conclusions.

2 CONCEPTS OF EQUITABILITY

2.1 Proportionality

Proportionality is a deeply rooted concept in many areas such as law and business customs as a means of distributive justice. Examples include:

- When a firm goes bankrupt, creditors are repaid in proportion to the amounts they are owed
- If heirs to an estate are willed more than it is worth, they would normally inherit the estate in proportion to their bequests
- In 1987, the industrialised countries signed an accord to reduce their emissions of ozone damaging chemicals in proportion to their current emissions

- Metered oil and gas produced from a commingled process is frequently allocated in proportion to the amounts estimated to have been produced by each participant in the process.

The concept of proportionality dates back to the fourth century BC and the Greek philosopher, Aristotle who considered it to be a universal principle of distributive justice [1]. The dominance of the principle in Western culture owes much to Aristotle.

For it to be workable however, the quantity to be allocated needs to be divisible (e.g. oil or gas production, as opposed to the election of a member of parliament which is indivisible) and each claimant's entitlement should be expressible in some common metric (e.g. estimated oil production). When these two conditions are met proportionality appears the most reasonable method of allocation and is so deeply rooted in our ideas fairness that it is difficult to imagine any other method.

To gain some perspective however, it is useful to examine other cultures in which proportionality is not so prominent. A case in point is the Talmudic form of contracts which is almost as old as Aristotle's Ethics. The Babylonian Talmud is the collection of Jewish religious and legal decisions set down during the first five centuries A.D. The following problem was posed in the Talmud nearly 2,000 years ago (known as the "Contested Garment" problem):

"Two people have a claim on a garment; one claims it all and the other claims half, what is an equitable division of the garment?"

According to Aristotle's equity principle this would be split in the ratio of the claims, i.e. ⅔ to the first and ⅓ to the second claimant. According to the Talmud however, ¾ goes to the first and ¼ to the second. The reasoning for this is that only one half of the garment is contested and hence is split equally, the other half is uncontested and given to the one who claims it. In fact each claimant suffers an equal loss (i.e. ¼ of the garment).

The logic of the division in the Talmud is consistent with its precepts of fairness just as the Aristotle solution is in accordance with its precepts. The concept of what is fair is different in the two approaches and the example illustrates that what appears equitable can vary dependent on the properties a fair system is deemed to have.

A simple allocation example is used in the next section to illustrate some of the potential problems with the proportionality principle.

2.2 Simple Example: Compression Fuel Usage

Consider fuel gas allocation associated with a compressor on an offshore platform. In such allocation systems, various methods for the allocation of fuel gas can be observed; these include:

- In proportion to oil throughput
- In proportion to gas throughput
- In proportion to BOE production
- In proportion to estimated fuel usage.

Though it is acknowledged that fuel gas consumption on a platform may be allocated using any of the above metrics, some appear more equitable or fair than others. For example, allocation in proportion to oil production, when often compression fuel usage is the dominant fuel consumer on a platform, does appear to unfairly benefit high GOR fields at the expense of low GOR ones. Sometimes it appears a metric is selected upon which to base fuel allocation just because it is convenient rather than actually equitable.

From the options in the above list the most equitable must surely be deemed to be in proportion to estimated usage as the others may bear little relation to the actual fuel consumed as a result of processing each field's hydrocarbons.

At first sight therefore, the fairest estimation method might appear to be in proportion to estimated usage. But will this approach necessarily always seem fair and are there alternative approaches which are fairer?

Some of these issues can be illustrated with a simple example. Consider two offshore fields, called Neumann and Fisher[1] (in preference to the more anonymous A and B, etc.) being produced on a platform. The gas associated with each field is compressed in a single stage and the compressor is the principal consumer of fuel gas on the platform.

Figure 1 is a plot of power consumption versus throughput for an idealised centrifugal compressor:

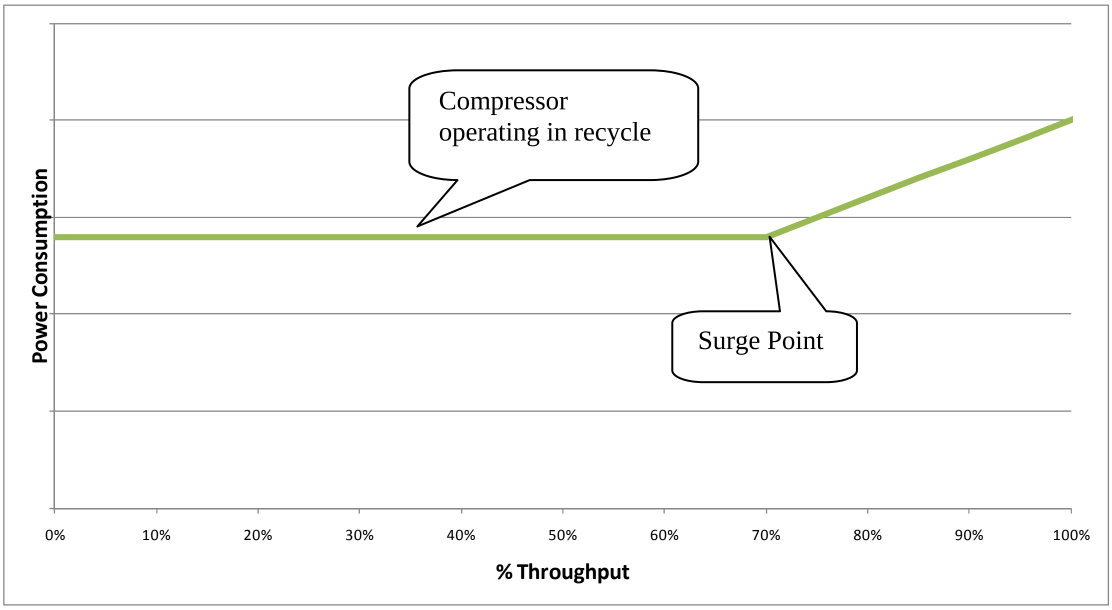

Figure 1 – Power Consumption as a Function of Compressor Throughput

Below approximately 70% of throughput the power consumption is constant. This is because the compressor has to operate in recycle mode below this point (surge point) and hence the actual compressor throughput is maintained at this minimum level.[2] This is illustrated schematically in Figure 2[3].

1 John von Neumann was one of the founding fathers of game theory. Ronald Fisher was credited with creating the foundations of modern statistics and also applied game theory to the study of animal behaviour.
2 Below this throughput the compressor experiences abnormal flows within its casing, loss of performance and possibly damage to the rotor blades.
3 In fact the flow rate dependent part of a real compressor power curve can be non-linear with power consumption actually falling as throughput increases towards the end of the curve. This is because the compressor efficiency normally improves with increasing flow towards some peak value.

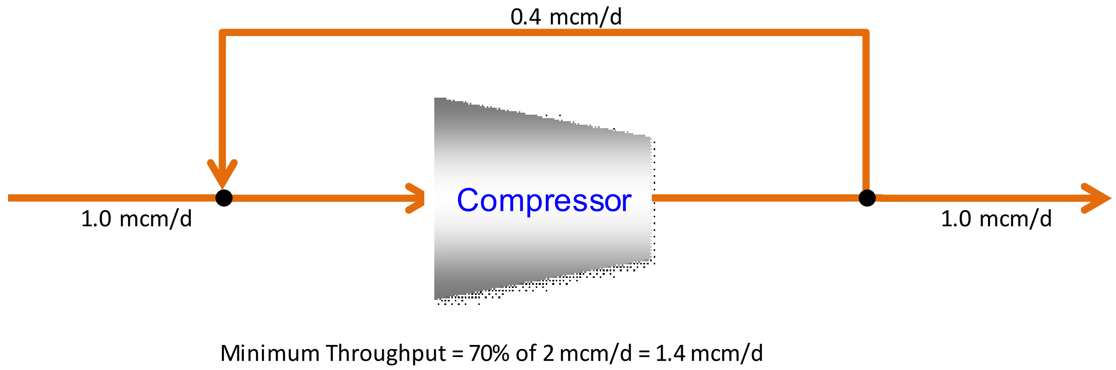

Figure 2 – Schematic of a Centrifugal Compressor Operating in Recycle Mode

The compressor capacity is deemed nominally equivalent to 2.0 mcm/d and hence the minimum flow is 70% of this, i.e. 1.4 mcm/d. In Figure 2 the gas production is only 1.0 mcm/d from the upstream process and hence the compressor has to recycle 0.4 mcm/d of gas. The fuel gas consumed by the compressor will be directly proportional to its power usage[4], so a plot of fuel consumed versus throughput has a similar shape to Figure 1. In this example, it is assumed that the compressor consumes 0.01 mcm/d of fuel for every 1 mcm/d of gas passing through it (i.e. 1% of throughput).

Say for example, Neumann is producing 0.8 mcm/d gas and Fisher 0.4 mcm/d. Since the production is only 1.2 mcm/d in total, the compressor would be recycling 0.2 mcm/d to maintain its minimum throughput of 1.4 mcm/d and hence consuming 0.014 mcm/d fuel gas. How should this be allocated between the two fields? Allocating in proportion to throughput, (0.00933 mcm/d to Neumann and 0.00467 mcm/d to Fisher), does not seem appropriate since the compressor fuel consumption at these throughputs is not dependent on field production. Indeed if either field was being produced alone it would incur an allocation of 0.014 mcm/d irrespective of its flowrate up to 1.4 mcm/d. Hence, since the fuel consumption is not flowrate dependent it seems more appropriate that fuel allocation should be equal, i.e. 0.007 mcm/d each.

Hence under this circumstance, the instinctive propensity to allocate proportionately does not seem as fair as allocating equally. This is because the chosen metric, gas production, does not have an impact on the fuel consumption at these rates and hence is an arbitrary basis.

However, consider what happens if Fisher production remains constant and Neumann increases. There will be no change in fuel consumption until Neumann's production exceeds 1.0 mcm/d, when the compression will no longer recycle and compressor fuel consumption will be directly proportional to total throughput. How should the fuel be allocated now? In proportion does not seem appropriate as the majority of the fuel consumption is due to maintenance of the minimum throughput. Perhaps 70% of the fuel should be divided equally and the remaining fuel divided pro rata to throughput. However, it could still be claimed by Neumann that if it was processed alone then the compressor would be in recycle and it is only the presence of Fisher that is rendering it beyond the surge point. Then there is the issue of what happens if Neumann's throughput increases above 1.6 mcm/d and a second compressor is started up in parallel. Both compressors would be in recycle and then should the second compressor's fuel be split?

Figure 3 plots the proportional allocation of fuel as a function of Neumann throughput:

4 Whether the compressor is driven directly by its own turbine or has an electric motor which is supplied power from an electrical generator, fuel gas will be consumed to power the compressor, at the generator or the turbine, and the consumption will be in proportion to the compressor throughput including any recycle.

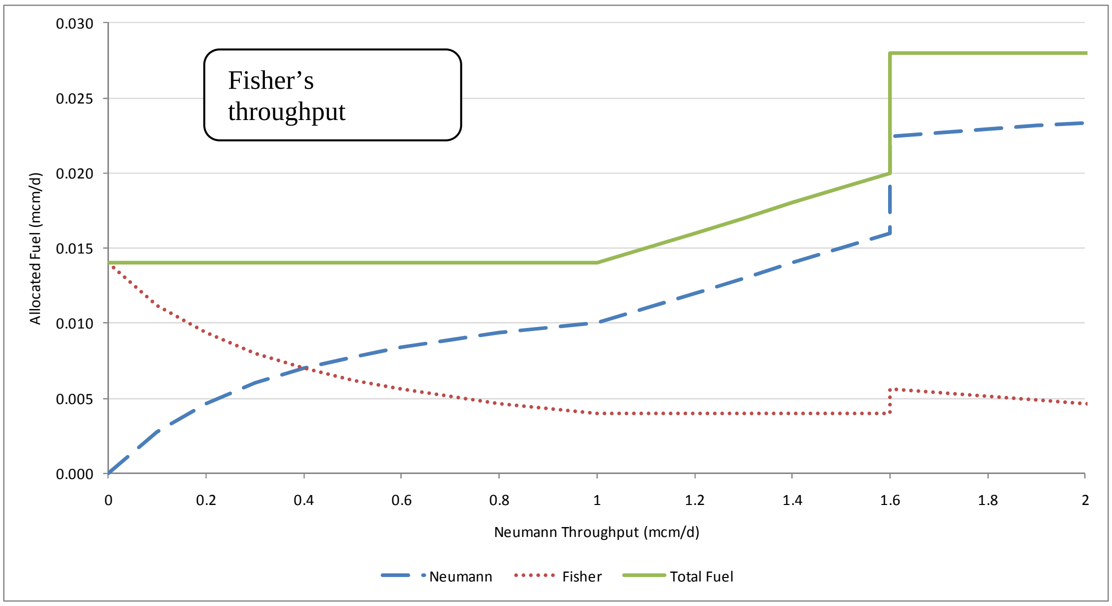

Figure 3 – Allocation of Fuel in Proportion to Field Throughput as a Function of Neumann Production

Two points appear incongruous from this plot:

- Despite the overall fuel usage remaining unchanged when the compressor is recycling Neumann's allocation increases and Fisher's falls.
- A rise in Neumann throughput above 1.6 mcm/d actually increases Fisher's fuel allocation due to the second compressor coming on stream.

Figure 4 is a reproduction of Figure 3, but also includes Neumann's fuel allocation if it alone had been compressed. Between 1.4 mcm/d and 1.6 mcm/d it is allocated the same fuel as when co-processed with Fisher. Between 1.6 mcm/d and 2.0 mcm/d it is allocated more fuel than it would have on a stand-alone basis. This is because in the comminlged case the second compressor is required. When the second compressor comes on stream, both fields may feel aggrieved at their fuel allocation for different reasons.

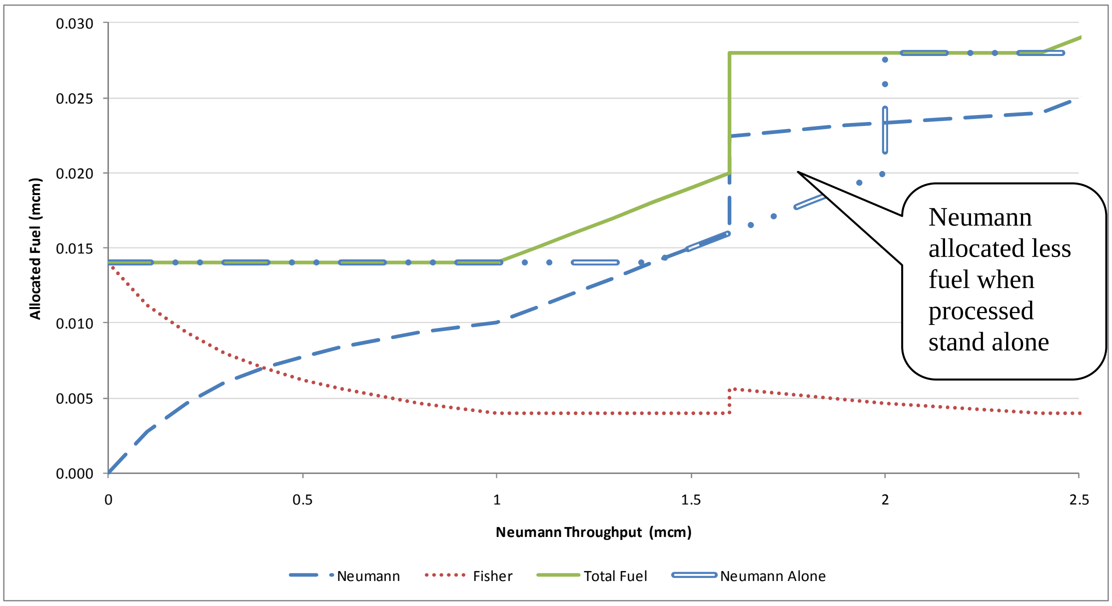

Figure 4 – Neumann Fuel Allocation Commingled versus Stand-Alone Production

The situation becomes more complicated when a third field, Nash[5], is brought on-line. Two scenarios serve to illustrate perceived problems with fairness. If the inclusion of Nash results in no increase in compressor fuel consumption, (i.e. the flowrates are such that the compressor(s) remains in recycle) then Neumann and Fisher will enjoy a reduction in fuel costs. Nash may claim that it should not pay any fuel costs as its introduction has not resulted in an increase in the consumption. This may appear unfair to Neumann and Fisher who might reasonably state that Nash should contribute to the costs.

Alternatively, the introduction of Nash may result in the start-up of another compressor and this may increase the allocation of fuel to Neumann and Fisher even though their operation remains unchanged. Under these circumstances, forcing Nash to pay its incremental costs may appeal to Neumann and Fisher. The problems posed by this example are not uncommon when a new field is tied back into an existing process. Addressing these increments in costs which seem to depend on the order in which fields join the process forms the basis of one of the alternative methods of allocation described later (in Section 3.4).

Two points may be concluded from the above analysis:

- Whatever fairness is in allocation it is not that easy to define and it can appear to depend on viewpoint.

- Allocating in proportion to throughput is not always equitable.

3 COST ALLOCATION AND CO-OPERATIVE GAME THEORY

Rather than assuming a method of allocation, co-operative game theory starts with the desirable properties an equitable method of allocation should have. It then mathematically derives methods based on these properties.

The following sections provide a high level discussion of the development of these methods and describe the properties they exhibit. More detailed analysis can be found in two books that address equitability and the application of game theory to cost allocation [6] and [7].

3.1 Game Theory

Game theory is the formal study of conflict and cooperation. Game theoretic concepts apply whenever the actions of several agents are interdependent. These agents may be individuals, groups, firms, or any combination of these. The concepts of game theory provide a language to formulate, structure, analyze, and understand strategic scenarios.

Though originally applied in the field of economics, game theory has been applied in sociology, as well as in biology (particularly evolutionary biology and ecology), engineering, political science, international relations, computer science, and philosophy. Game theory attempts to mathematically capture behaviour in strategic situations, or games, in which an individual's success in making choices depends on the choices of others.

Many of the concepts of game theory were developed by John Von Neumann and Oskar Morgernstern in their 1944 treatise “The Theory of Games and Economic Behaviour” [3].

The following sections describe some important concepts from game theory that have found applications in cost allocation in various industries. One of those concepts is the idea of the “The Core”. To illustrate the Core for three “players” in the game, it is convenient to introduce the triangular plot at this point.

5 John Nash developed many of the ideas of game theory and received a Nobel prize in 1994 for their application in the field of economic science.

3.2 Triangular Plot

The triangular plot (Figure 5) can be used to illustrate allocation among three fields.

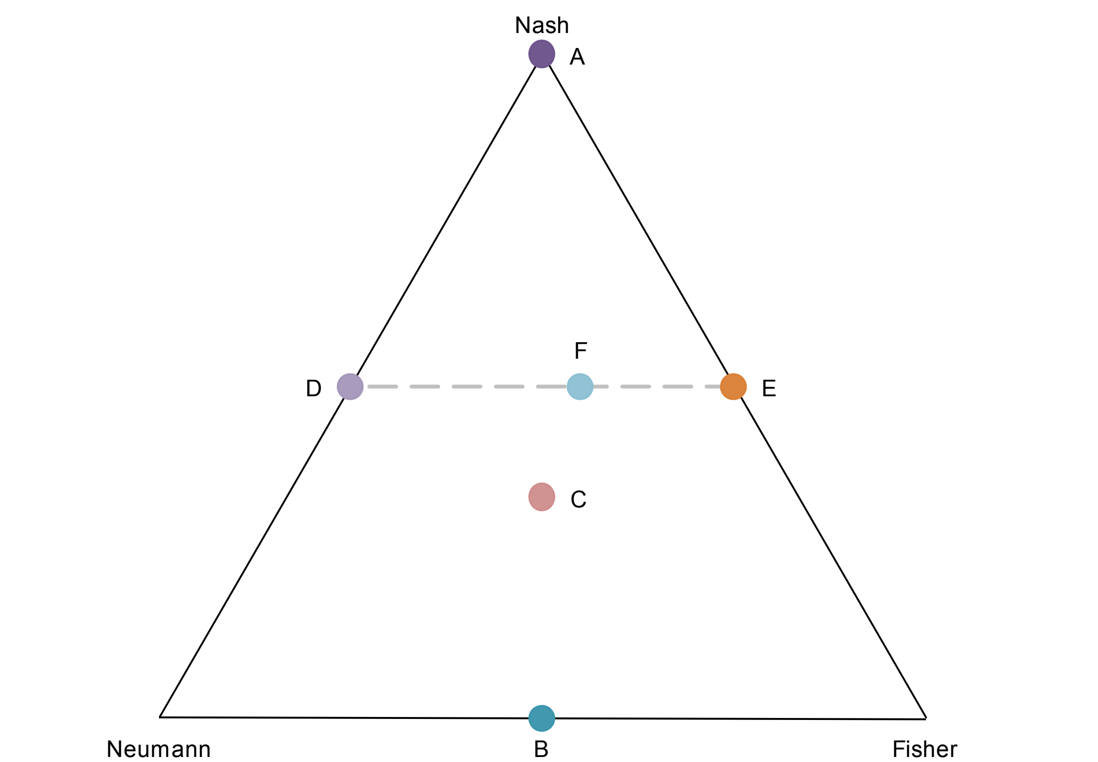

Figure 5 – Triangular Plot Illustration: Allocation to Neumann, Fisher and Nash

Each vertex of the triangle represents 100% of the fuel gas being allocated to one of the fields (as indicated by Point A where 100% is allocated to Nash). A point on the sides of the triangle represents allocation between two fields (as indicated by point B where half is allocated each to Neumann and Fisher and zero to Nash). Any point falling within the triangle represents allocation to all three fields as indicated by Point C where a third is allocated to all three fields. The closer the point is to a vertex the more is allocated to the associated field.

A line drawn parallel to the axis opposite the vertex represents a constant amount allocated to the associated field, for example any point on line D – E represents 50% being allocated to Nash. Points horizontally along the line represent how the remaining 50% is allocated to Neumann and Fisher. For example Point F represents 20% to Neumann, 30% to Fisher and 50% to Nash.

In summary, the closer a point is to the field's vertex, the more is allocated to that field.

3.3 The Core

In examining equitability it is important to identify properties an allocation method should have. Using the fuel gas allocation example, two such reasonable properties are:

1. Stand-Alone: No-one field shall be allocated more fuel than it would be if being processed alone.

2. Subsidy Free: The amount allocated to a field shall be greater than the incremental increase in fuel it causes when added to the other two fields being compressed. (If this is not true then the other two fields will be subsidizing the third field).

Satisfaction of these two conditions could reasonably be used to identify allocations as being fair and equitable. In essence, the economies of scale brought about by the sharing of facilities are enjoyed by all fields.

An allocation is said to be in the Core if it satisfies these two conditions and is illustrated on a triangular plot in Figure 6:

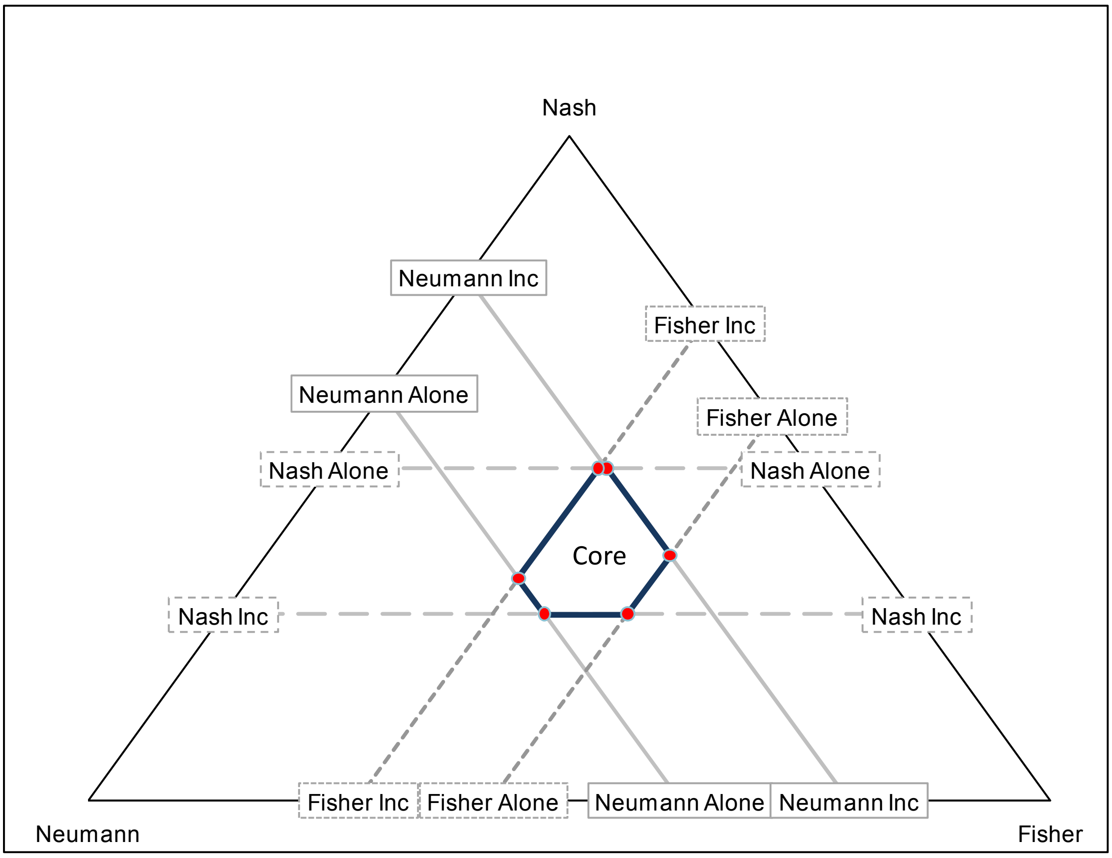

Figure 6 – Triangular Plot: The Core

The upper and lower fuel allocation lines are represented by the Alone (stand-alone) and Inc (incremental) lines respectively for each field. (The stand-alone fuel costs are greater and hence closer to the associated field's vertex than the incremental fuel costs). Points lying between these two limits for all three fields would satisfy the two conditions above. This bounded area (highlighted in the centre of the plot) is the Core.

Consider the simple example of Section 2.2, but now with three fields being processed. Field throughputs along with their stand-alone fuel costs and incremental fuel impacts are presented in Table 1.

Table 1 – Fuel Consumption and Allocation – Simplified 3 Field Example

		Neumann	Fisher	Nash	Total
Throughput	mcm/d	1.6	0.2	0.2	2.0
Stand-Alone Fuel	mcm/d	0.016	0.014	0.014	
Incremental Fuel	mcm/d	0.006	0.002	0.002	
Proportional Allocation	mcm/d	0.016	0.002	0.002	0.020

For the stand-alone fuel requirements, the compressor would be beyond the recycle point for Neumann whereas for Fisher and Nash the compressor would be recycling at 70% minimum flow.

The incremental fuel impact of 0.006 mcm/d for Neumann is calculated as the fuel consumed when all three are producing, i.e. 2.0 mcm/d throughput, compressor at full capacity consuming 0.020 mcm/d of fuel, less fuel consumption with just Fisher and Nash present, i.e. 0.4 mcm/d throughput, compressor recycling at 1.4 mcm/d and consuming 0.014 mcm/d fuel.

For both Fisher and Nash the incremental impact of 0.002 mcm/d is similarly calculated, i.e. 2.0 mcm/d, less the fuel consumption with just Neumann and either Fisher or Nash, which is at 1.8 mcm/d throughput, compressor consuming 0.018 mcm/d.

These upper and lower limits for each field are illustrated in Figure 7:

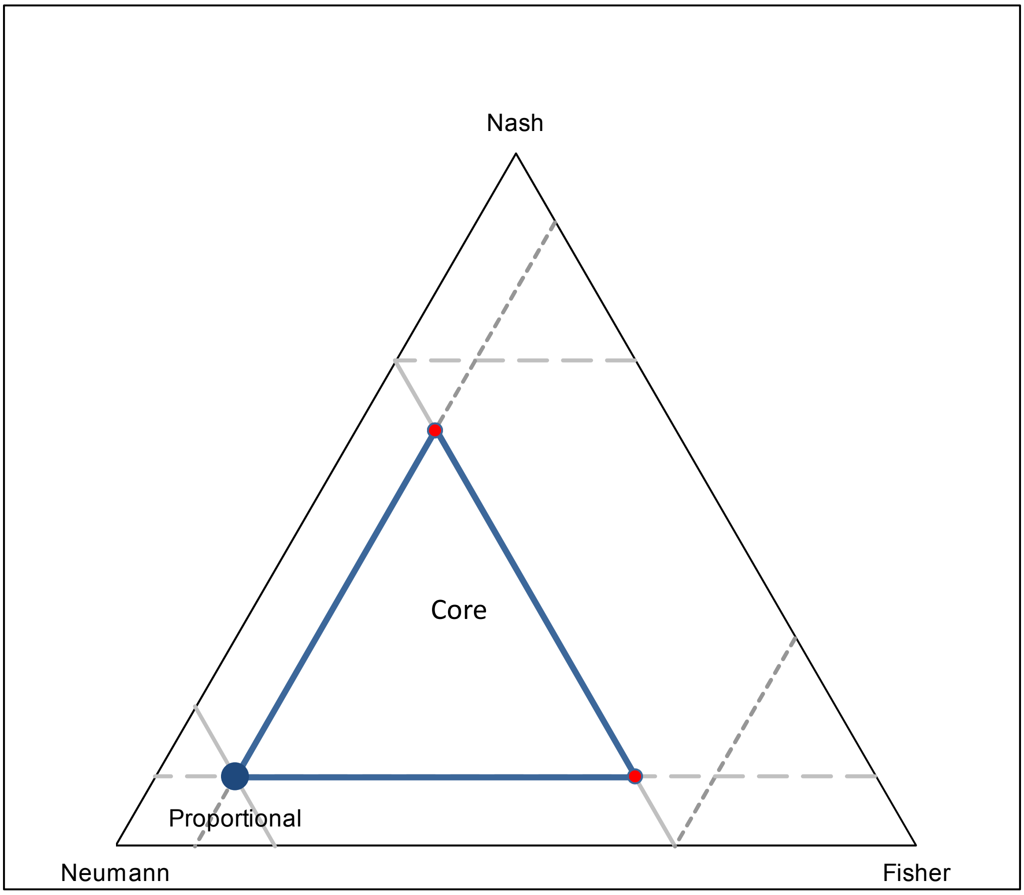

Figure 7 – Simplified 3 Field Example – Fuel Consumption Core and Proportional Allocation

As can be seen in this case the Core is delineated by Neumann's upper and lower limits and by Fisher and Nash's lower limits.

Also shown are the results of allocating the fuel in proportion to throughput located at the extreme vertex of the Core. The allocation is heavily weighted towards Neumann, i.e. favourable to both Fisher and Nash. The next two sections (3.4 and 3.5) discuss methods of allocation derived from co-operative game theory which result in allocations that appear more equitable in relation to the Core.

3.4 The Shapley Value

As discussed in the example in Section 2.2 above, the order in which fields join the problem has a bearing on how the participants view the impact of the new entrant. Two extremes were discussed: the first was when the introduction of Nash caused no increase in fuel consumption compared with the case when it caused a disproportionate increase due to the start up of a second compressor.

The order in which fields join and the incremental impact they have on the fuel loading appears to have a bearing on how equitable the allocation is viewed. The Shapley value (devised by Lloyd Shapley in 1953 [4]) provides a methodology to account for order dependent incremental impacts.

The Shapley value may be expressed as the average marginal increase in fuel a field causes if each field joins the process one at a time.

Imagine the case where only Neumann is being processed; its marginal fuel cost would be its stand-alone fuel consumption. Then Fisher is introduced, the fuel may increase and this increase represents Fisher's marginal impact. Similarly when Nash joins, its marginal impact is calculated as any further increase in fuel consumption. The Shapley value is the average of each field's marginal impact over all possible orderings.

In order to calculate the Shapley value the estimated consumption for the cases where each combination of fields flowing has to be calculated and this is presented in Table 2 for the simple example described in Section 3.3:

Table 2 Fuel Gas Consumption for Combinations of Fields Flowing

Fields Flowing	Fuel Gas Consumprion mcm/d
Neumann, Fisher, Nash	0.020
Neumann, Fisher	0.018
Neumann, Nash	0.018
Fisher, Nash	0.014
Neumann	0.016
Fisher	0.014
Nash	0.014

The incremental impact on compressor fuel demand for each field in each of the 6 possible orderings is presented in Table 3:

Table 3 Incremental Compression Power Demand

Order of Processing					Incremental Fuel Consumption (mcm/d)		
1		2		3	Neumann	Fisher	Nash
Neumann	->	Fisher	->	Nash	0.016	0.002	0.002
Neumann	->	Nash	->	Fisher	0.016	0.002	0.002
Fisher	->	Neumann	->	Nash	0.004	0.014	0.002
Fisher	->	Nash	->	Neumann	0.006	0.014	0.000
Nash	->	Neumann	->	Fisher	0.004	0.002	0.014
Nash	->	Fisher	->	Neumann	0.006	0.000	0.014
				Average	0.0087	0.0057	0.0057
				% Share	43%	28%	28%

For example, in the top row, first Neumann is processed alone and hence consumes 0.0016 mcm/d of fuel. Fisher comes on stream and its impact is the difference between Neumann plus Fisher versus Neumann alone (0.018 mcm/d minus 0.016 mcm/d). Finally Nash comes on stream and its impact is the difference between all three being compressed (compressor at maximum throughput) and Neumann plus Fisher (0.020 mcm/d minus 0.018 mcm/d).

These incremental impacts are calculated for all 6 possible orderings of the fields and the average calculated: this is the Shapley value and is presented in Figure 8.

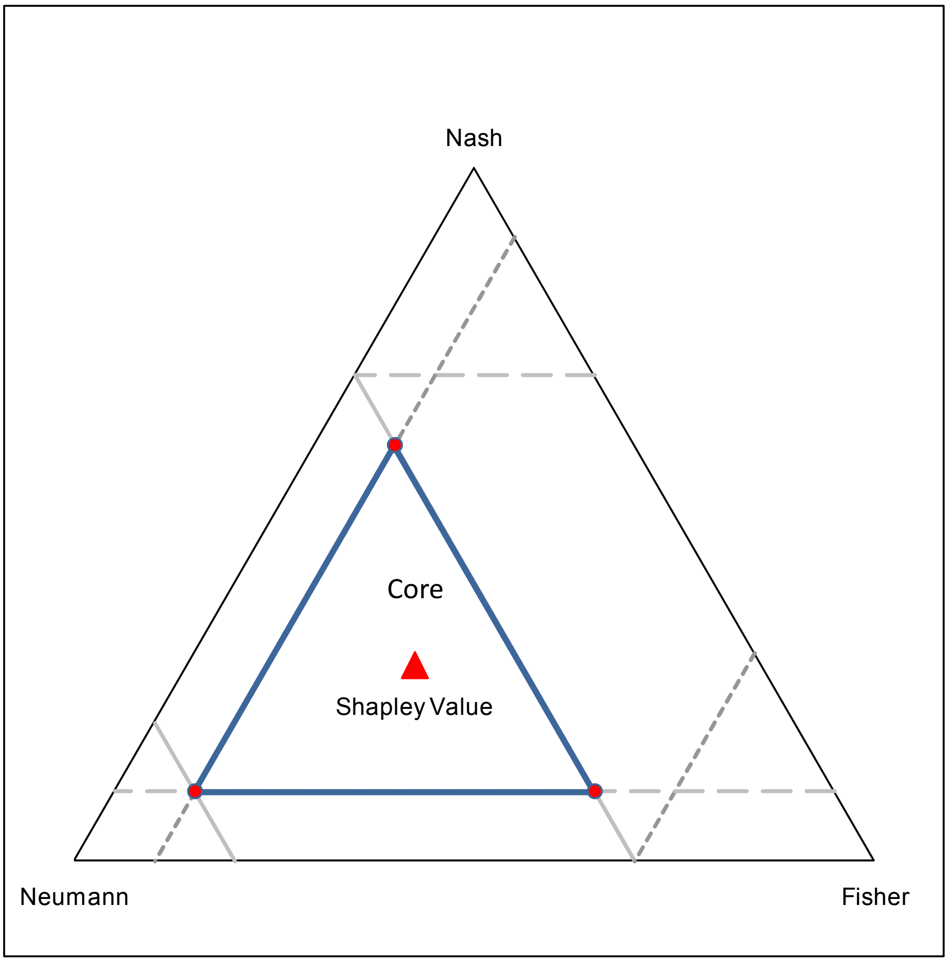

Figure 8 – Simplified 3 Field Example – Shapley value

The allocation according to the Shapley value is much more centrally located in the Core compared with that according to proportional allocation and weights the allocation more evenly between all three fields. The Shapley value reflects the fact that Fisher and Nash's individual and collective fuel consumption requires the compressor to be in recycle.

The Shapley value correctly reflects the average impact that each field has on fuel consumption over all possible orderings in which the fields are brought on stream.

A real life application of the Shapley value is the allocation of landing fees at Birmingham airport [9]. The landing fees are established to cover the costs of building and maintaining the runways. Equity demands that the landing fees reflect the burden that the different types of aircraft, using the airport, put on the system. Jumbo jets are assessed more than twin-engine Cessna's for example, because the larger planes require longer runways.

Though often in the Core, the Shapley value is not necessarily located within it. The next approach describes a method that uses the Core boundaries to provide an equitable allocation.

3.5 Equitable Core Solutions: The Nucleolus

It is not necessarily the case that there will always be a Core solution. When it does exist however, the next method is always located within it and shares the savings bounded by the Core equally among all fields.

The Core for the simplified 3 field example is reproduced below in Figure 9. Consider the case where the allocation to Nash is held constant at some fixed value represented by the horizontal dashed line indicated. The split of the remaining fuel gas between Neumann and Fisher is represented by any point along that line. A natural solution is to choose the midpoint of the line between the limits of the Core, and this represents an equal share of the savings.

Similarly Neumann's allocation could be held constant (indicated by the solid line) and Fisher and Nash split the remaining gas at the midpoint of the line bounded by the Core. Finally Fisher's held constant and Neumann and Nash split the savings.

If the quantities allocated to each field are adjusted so that the three lines intersect each other then the allocation is such that all three fields equally share the savings enjoyed as a result of co-processing. This point is represented by the green square in Figure 9 and is termed the nucleolus [5].

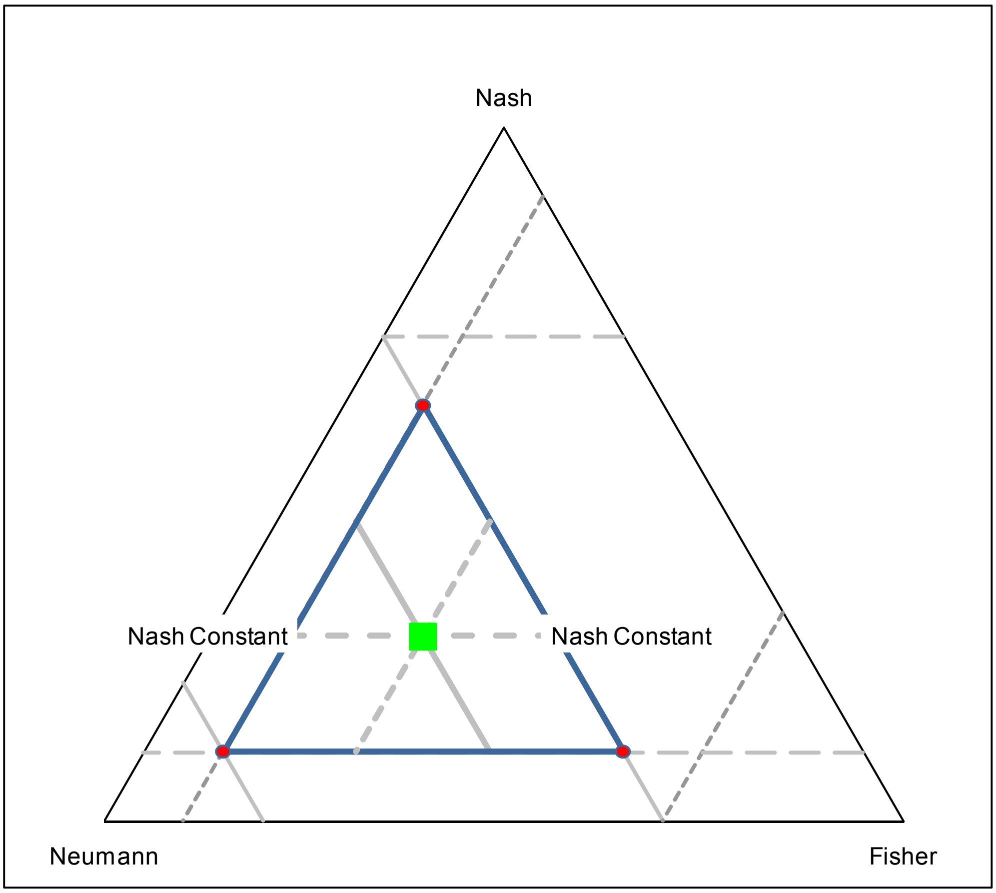

Figure 9 – Nucleolus – Simplified 3 Field Example

To calculate the nucleolus, the fuel consumption for each field and all combinations of fields being co-processed is required (this has already been presented in Table 2).

Now, consider any arbitrary allocation of fuel between the three fields. Each field should enjoy a saving in the allocation compared with the allocation it would have got if processed stand-alone. Similarly, any group of two fields' allocation added together should be less than the fuel consumed if both were processed without the third present.

Thus for all individual fields and groups of two, a comparison can be made between the sum of the allocated quantities and the fuel they would have incurred were only those fields being processed. Each such individual and group should enjoy some cost saving as a result of being in the allocation, otherwise it would be better off being processed alone or in combination with one other field. The nucleolus is the allocation that maximises the saving for the least well-off group. This is illustrated using the above example.

Imagine an allocation to the three fields is guessed at, say using the proportional values. The saving each individual field and each group incurs as a result of the allocation is calculated as the difference between these allocated values and the fuel loading for each combination of fields producing (i.e. each group). The results are presented in Table 4:

Table 4 Proportional Allocation: Field and Group Savings

Fields Flowing	Fuel Gas Consumprion	Nucleolus Allocation				
		Neumann	Fisher	Nash	Group	Saving
	mcm/d	mcm/d	mcm/d	mcm/d	mcm/d	mcm/d
		0.0160	**0.0020**	**0.0020**		0.0000
Neumann, Fisher, Nash	0.0200					
Neumann, Fisher	0.0180	0.0160	0.0020		0.0180	0.0000
Neumann, Nash	0.0180	0.0160		0.0020	0.0180	0.0000
Fisher, Nash	0.0140		0.0020	0.0020	0.0040	0.0100
Neumann	0.0160	0.0160			0.0160	0.0000
Fisher	0.0140		0.0020		0.0020	0.0120
Nash	0.0140			0.0020	0.0020	0.0120

For example, the sum of the Fisher Nash group's allocation is 0.004 mcm/d, but if they were processed on their own the fuel costs would be 0.014mcm/d. Hence, they enjoy a 0.01 mcm/d saving as a result of being in the allocation.

The minimum saving is zero and occurs in all groups containing Neumann. Can the minimum saving be improved by adjusting the allocation?

Since Nash and Fisher have the same throughputs their fuel allocation must be identical. Neumann's allocation must be the remainder of the total fuel consumed. Hence the allocation to Neumann can be varied and the minimum cost saving of all the groups calculated and plotted as a function of the Neumann throughput. This is presented in Figure 10.

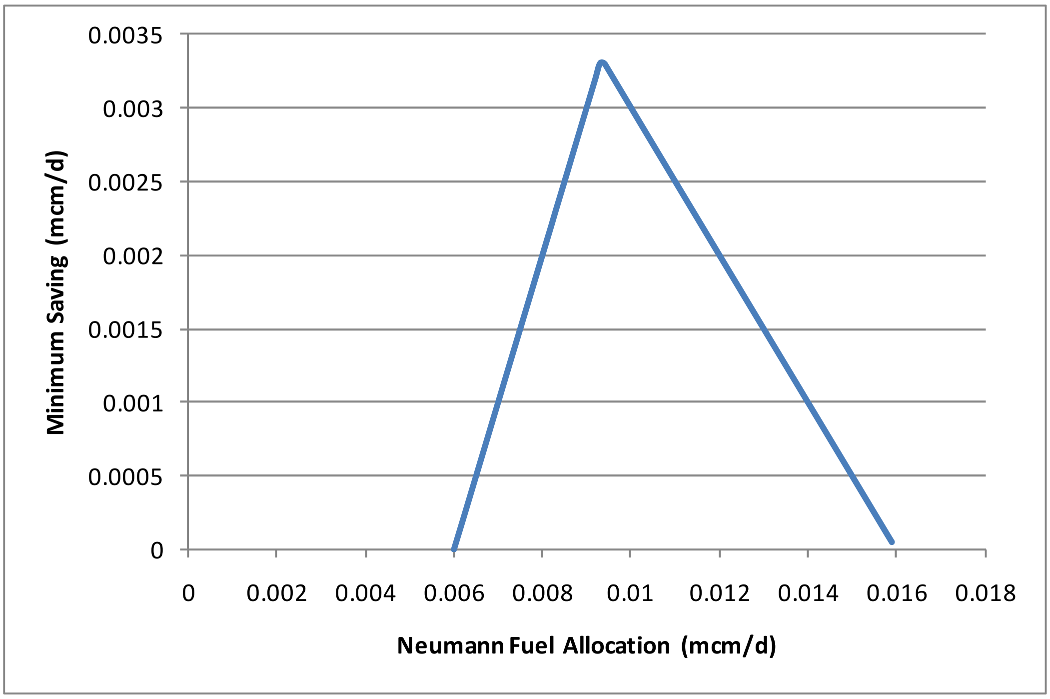

Figure 10 – Minimum Group Cost Saving – Simplified 3 Field Example

The optimal minimum saving occurs at 0.0093 mcm/d fuel allocated to Neumann and the allocation solution is presented in Table 5.

Table 5 Nucleolus Allocation: Field and Group Savings

Fields Flowing	Fuel Gas Consumprion	Nucleolus Allocation			Group	Saving
		Neumann	Fisher	Nash		
	mcm/d	mcm/d	mcm/d	mcm/d	mcm/d	mcm/d
		0.0093	**0.0053**	**0.0053**		0.0033
Neumann, Fisher, Nash	0.0200					
Neumann, Fisher	0.0180	0.0093	0.0053		0.0147	0.0033
Neumann, Nash	0.0180	0.0093		0.0053	0.0147	0.0033
Fisher, Nash	0.0140		0.0053	0.0053	0.0107	0.0033
Neumann	0.0160	0.0093			0.0093	0.0067
Fisher	0.0140		0.0053		0.0053	0.0087
Nash	0.0140			0.0053	0.0053	0.0087

All fields save fuel compared with their stand-alone fuel costs and all combinations of groups of two fields being co-processed experience a saving of 0.0033 mcm/d. Hence the savings are shared equally between all fields and possible groups they could form.

The solution to the nucleolus is a linear programming optimisation problem, where the minimum saving is maximised subject to the constraint that all the fuel is allocated. This is easily solved on a spreadsheet.

A case where the logic of the Core was applied to cost sharing was the Tennessee Valley Authority [10] in the 1930s. This was a US Government project to control flooding, provide hydroelectric power and improve navigation through a series of reservoirs in the Tennessee River basin. Economists charged with analysing the costs and benefits of the project were concerned with how to allocate common costs among the three objectives. It was stated that:

"The method should have a reasonable logical basis... It should not result in charging any objective with a greater investment than should suffice for its development at an alternate single purpose site. Finally it should not charge any two or more objectives with a greater investment than would suffice for alternate dual or multiple purpose development".

In effect the second part of the statement describes the Core and in fact foreshadowed its formal game theoretic development.

The TVA asserted that the cost allocation was not based on any one mathematical formula, but on judgement. However, application of this “judgement” it was later realised had in fact allocated the costs using a variant of the nucleolus [11].

3.6 Comparison of Methods

The allocation results for the proportional, Shapley value and nucleolus are compared in Figure 11.

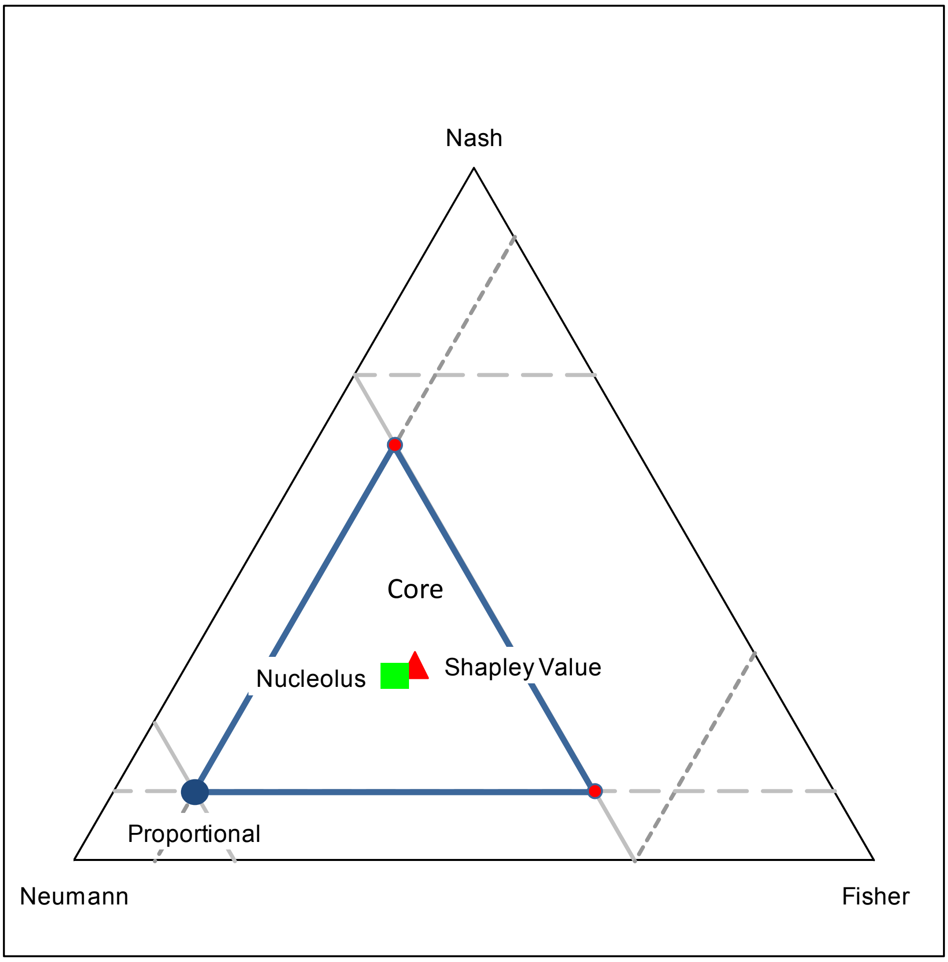

Figure 11 – Comparison of Compression Fuel Allocation – Simplified 3 Field Example

As can be seen the proportional approach heavily weights the allocation towards Neumann because of its relatively high throughput, despite the fact that much of the compressor fuel consumption is not flow dependent. As previously stated Neumann’s fuel costs are as much as it would have incurred if processed alone and receives zero benefit as a result of sharing the compressor.

The Shapley value and nucleolus lie centrally in the core and provide similar though not exactly equal allocation solutions.

However, the question remains which one is the most equitable allocation? In essence there is no right or wrong answer and the correct one is whatever has been agreed. What can be said though is that one or other of these methods is the fairest if the allocation is deemed to have certain properties. These might include:

- The benefits of co-processing should be shared – this could be re-stated as the allocation should be in the Core
- The benefits of the co-processing should be shared equally
- The incremental impact of each field coming on stream should be accounted for

Each of the methods can satisfy some of these properties but none can be guaranteed to satisfy them all.

4 HYPOTHETICAL FUEL ALLOCATION EXAMPLES

Fuel gas allocation has been modelled for a variety of simple hypothetical production scenarios for Neumann, Fisher and Nash. In each scenario, fuel gas has been allocated proportionally to throughput and by calculating the Shapley value. The results of the model are intended to demonstrate the differences in allocation methods, and provide a simple means for understanding the features of allocation using the Shapley value, in particular fuel allocation dependency on throughput.

The allocation results using the nucleolus are omitted. Allocation according to the Shapley value and nucleolus give the same result in the two-field scenario. For three-field scenarios, allocation according to the Shapley value and nucleolus give similar, though not identical, results. The throughput dependent features of Shapley value allocation discussed here also apply to the nucleolus allocation method.

In the models gas compression is by a bank of identical compressors, each compressor is assumed to have operating parameters described in 2.2 and shown in Table 6.

Table 6 – Compressor Operating Parameters

Operating Parameter	Value
Compressor Capacity	2 mcm/d
Recycle Threshold	70%
Fuel usage	0.01 mcm/mcm of gas throughput

4.1 Fuel allocation to two producing fields

Fuel gas allocation has been modelled assuming production volumes of:

- Neumann: varying from 0 to 1.6 mcm/d;
- Fisher: constant at 0.4mcm/d.
- Nash: no production

Figure 12 shows compares Neumann's proportional and Shapley value allocation results as a function of Neumann throughput and Figure 13 shows the analogous results for Fisher.

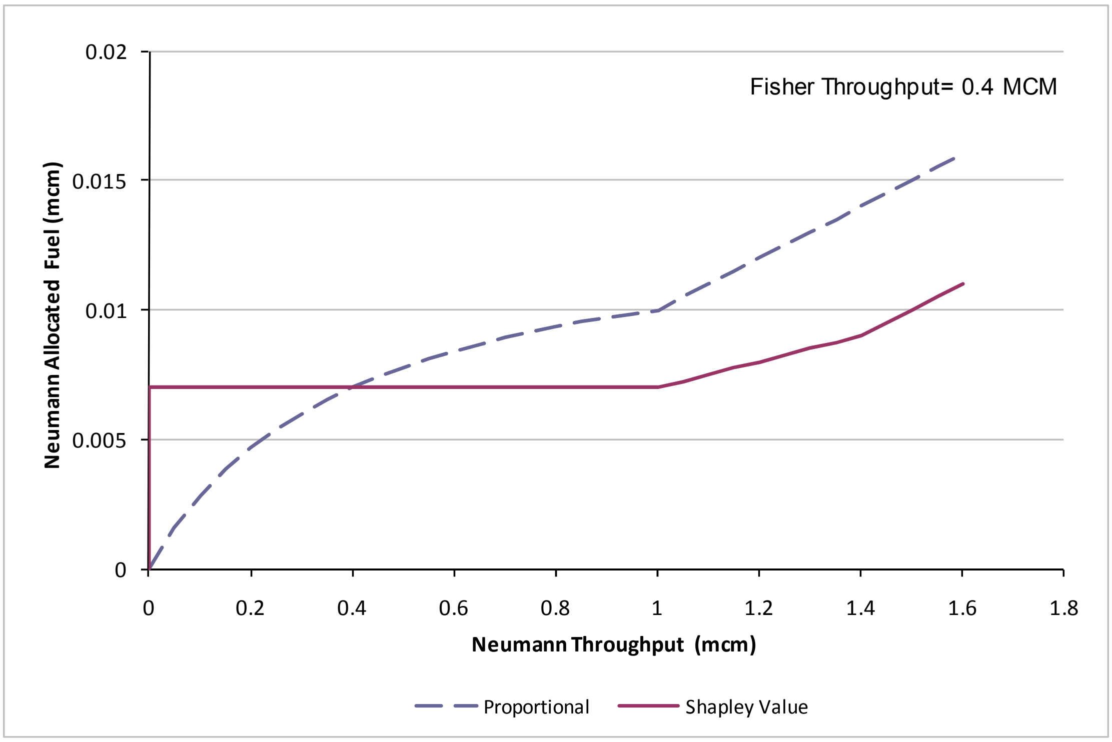

Figure 12 - Neumann fuel allocated in proportion to throughput and according to the Shapley value, plotted against Neumann throughput, when Fisher throughput is 0.4 mcm/d

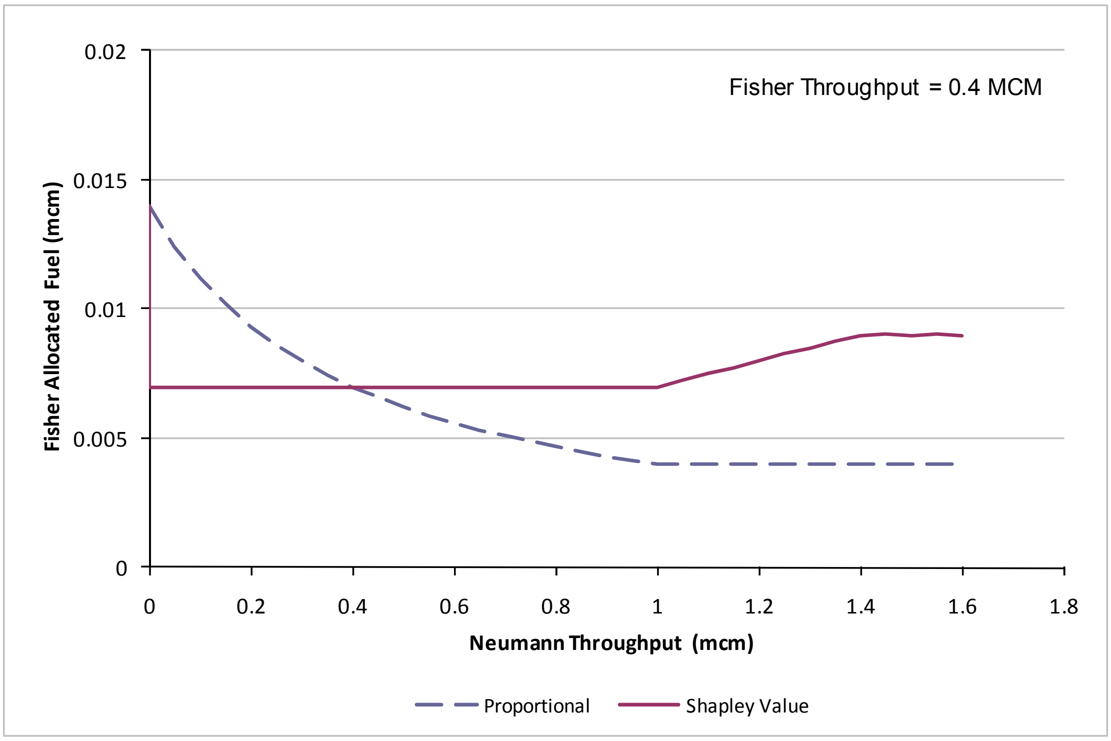

Figure 13 - Fisher fuel allocated in proportion to throughput and according to the Shapley value, plotted against Neumann throughput, when Fisher throughput is 0.4 mcm/d

In the proportional allocation case, Fisher fuel allocation decreases and Neumann fuel allocation increases as Neumann throughput increases until Neumann throughput reaches 1 mcm/d. Below that throughput the compressor is always on recycle so the total fuel usage to be allocated is constant. When the total Fisher and Neumann throughput crosses the compressor recycle threshold, fuel usage increases linearly with Neumann throughput while Fisher fuel allocation remains constant.

The dependency of Shapley value fuel allocation results on Neumann throughput are explained as follows:

$V_{Neumann}$ = 0 mcm/d. Fisher is allocated all fuel usage when Neumann is not producing.

0 < $V_{Neumann}$ < 1 mcm/d. As soon as Neumann starts producing, Fisher and Neumann are allocated half of the total fuel usage. Their fuel allocation remains at that level until $V_{Neumann}$ = 1 mcm/d at which point total throughput crosses the compressor recycle threshold. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d as the compressor must be on recycle. The marginal cost of Neumann then starting to produce is zero. Fisher fuel allocation is 0.014 mcm/d and Neumann fuel allocation is 0 mcm/d; and
- Neumann is producing in the range 0 to 1 mcm/d so its fuel usage is 0.014 mcm/d as the compressor must be on recycle. The marginal cost of Fisher then starting to produce is zero. Fisher fuel allocation is 0 mcm/d and Neumann fuel allocation is 0.014 mcm/d.

1 <= $V_{Neumann}$ < 1.4 mcm/d. The combined Fisher and Neumann throughput is now above the compressor recycle threshold. Both Fisher and Neumann fuel allocation are identical and increase with Neumann throughput. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Neumann producing is ($V_{Neumann}$ + $V_{Fisherl}$)*0.01 – 0.014. Fisher fuel allocation is 0.014 mcm/d and Neumann fuel allocation is the marginal cost of Neumann production; and
- Neumann is producing in the range 0 to 1 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Fisher producing is ($V_{Neumann}$ + V_{Fisher})/ 100 – 0.014. Neumann fuel allocation is 0.014 mcm/d and Fisher fuel allocation is the marginal cost of Fisher production.

The Shapley value approach to allocation here is that although fuel usage is now higher, the increased fuel usage cannot be said to be due to Fisher or Neumann alone. It would seem unfair to pin the blame on one field for the increased fuel usage and in that sense it is fair, according to Shapley, to allocate fuel cost equally.

1.4 <= $V_{Neumann}$ < 1.6 mcm/d. Neumann throughput is now above the compressor recycle threshold. Increasing Neumann throughput does not however affect Fisher fuel allocation, which is constant for 1.4 < $V_{Neumann}$ < 1.6 mcm/d. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Neumann producing is ($V_{Neumann}$ + $V_{Fisherl}$)*0.01 – 0.014. Fisher fuel allocation is 0.014 mcm/d and Neumann fuel allocation is the marginal cost of Neumann production; and
- Neumann is producing in the range 1.4 to 1.6 mcm/d so Neumann fuel allocation is 1% of Neumann throughput. The marginal cost of Fisher producing is 1% of Fisher throughput. Neumann fuel allocation is 1% of Neumann throughput and Fisher fuel allocation is the marginal cost of Fisher production.

According to the Shapley allocation method, as Neumann throughput is above the compressor recycle threshold, Neumann is allocated the fuel usage above the threshold.

Figure 12 and Figure 13 clearly demonstrate why it is worthwhile asking what constitutes a fair allocation methodology. Where fuel usage is throughput independent ($V_{Neumann}$ + V_{Fisher} <1.4 mcm/d) both Neumann and Fisher need the compressor to be on recycle consuming 0.014 mcm/d fuel, irrespective of the other field's production. In this instance it is arguably fairer to allocate fuel equally between Fisher and Neumann as Shapley does. If this is accepted then in comparison, it would seem that the use of proportional allocation results in

Fisher subsidising Neumann fuel allocation for $V_{Neumann}$ < 0.4 mcm/d while Neumann subsidises Fisher's fuel allocation for $V_{Neumann}$ > 0.4 mcm/d.

As total throughput increases yet further and more stages of compression are required, the concepts of fairness and equity can be examined further. Figure 14 and Figure 15 show Neumann and Fisher fuel allocation as Neumann throughput is increased to 2.5 mcm/d while Fisher throughput remains at 0.4 mcm/d.

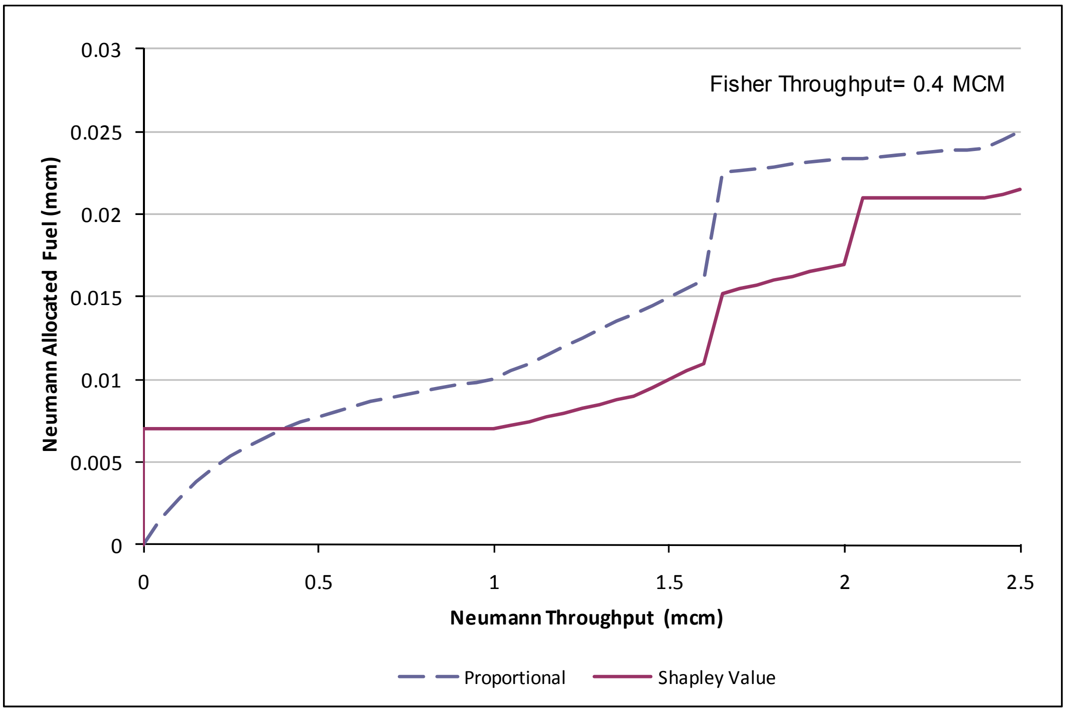

Figure 14 - Neumann fuel allocated in proportion to throughput and according to the Shapley value, plotted against Neumann throughput, when Fisher throughput is 0.4 mcm/d

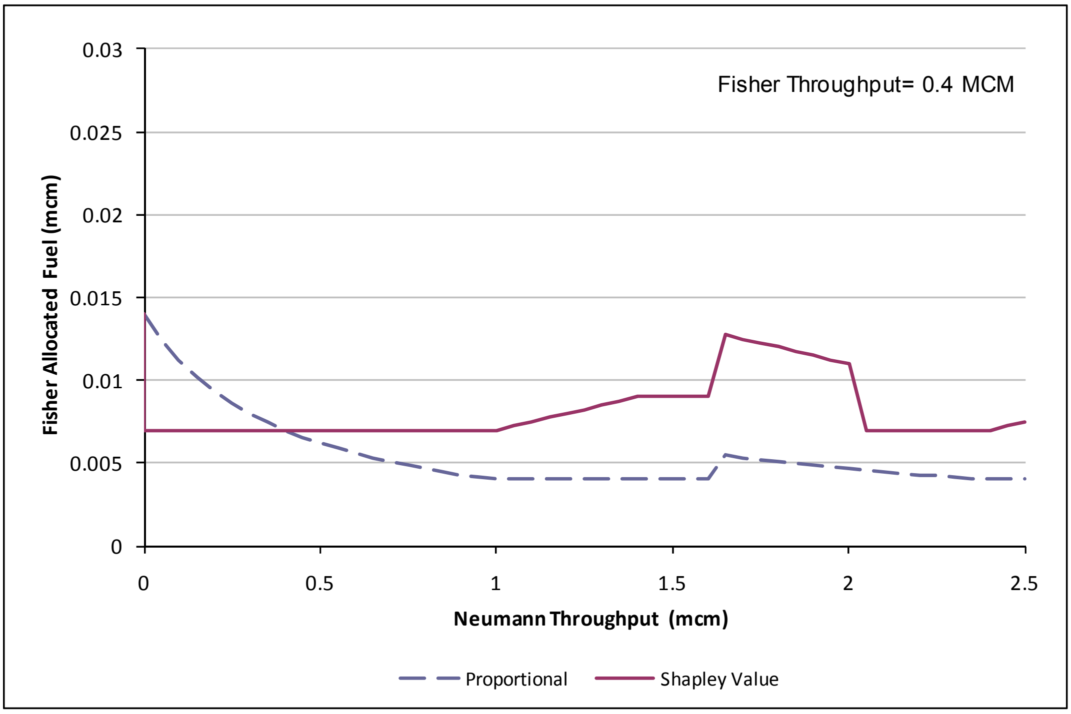

Figure 15 - Fisher fuel allocated in proportion to throughput and according to the Shapley value, plotted against Neumann throughput, when Fisher throughput is 0.4 mcm/d

For Neumann throughput above 1.6 mcm/d two compressors are now required both operating below their recycle threshold and the total fuel amount to be allocated is 0.028 mcm/d.

If fuel is allocated proportionally to throughput both Neumann's and Fisher's fuel allocation suddenly increase. As Neumann throughput increases further the proportion of fuel allocated to Neumann and Fisher increases and decreases respectively, until $V_{Neumann}$ = 2.4 mcm/d. At this point both compressors cross the recycle threshold and Fisher fuel allocation remains constant while Neumann fuel allocation increases with throughput.

The dependency of Shapley value fuel allocation results on Neumann throughput are explained as follows:

1.6 <= $V_{Neumann}$ < 2.0 mcm/d. Total throughput is now above a single compressor's capacity and both compressors are operating in recycle mode. Increasing Neumann throughput leads to higher Neuman and lower Fisher fuel allocation. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Neumann producing is 0.014 mcm/d as the second compressor is required. Fisher and Neumann fuel allocation are each 0.014 mcm/d; and
- Neumann is producing in the range 1.6 to 2.0 mcm/d so its fuel usage is 1% of Neumann throughput. The marginal cost of Fisher producing is (0.028 – $V_{Neumann}$*0.01). Neumann fuel allocation is 1% of Neumann throughput and Fisher fuel allocation is the marginal cost of Fisher production.

2.0 <= $V_{Neumann}$ < 2.4 mcm/d. Neumann throughput is now above a single compressor's capacity though both compressors are still operating in recycle mode. Increasing Neumann throughput does not however affect Neumann or Fisher fuel allocation. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Neumann producing is 0.014 mcm/d as the second compressor is required. Fisher and Neumann fuel allocation are each 0.014 mcm/d; and
- Neumann total fuel usage is 0.028 mcm/d. The marginal cost of Fisher throughput is zero as its inclusion does not require a further compressor online and both compressors remain operating in recycle mode even with Fisher online.

$V_{Neumann}$ >= 2.4 mcm/d. Total throughput is now above the compressor recycle threshold for both compressors. Increasing throughput leads to increased Neumann and Fisher fuel allocation. This situation is similar to 1 <= $V_{Neumann}$ < 1.4 mcm/d. No one field can be said to be entirely responsible for the increasing fuel costs so the increase in fuel allocation is shared equally between each field. Shapley value allocation equates to the average of two fuel allocation results:-

- Fisher is producing at 0.4 mcm/d so its fuel usage is 0.014 mcm/d. The marginal cost of Neumann producing is V_{Cap}*0.01 - 0.014 + ($V_{Neumann}$ + V_{Fisher} – V_{Cap})*0.01 = ($V_{Neumann}$+ V_{Fisher})*0.01 – 0.014. Fisher fuel allocation is 0.014 mcm/d and Neumann fuel allocation is the marginal cost of Neumann production; and
- Neumann requires two compressors on so its fuel usage is 0.028 mcm/d. The marginal cost of Fisher producing is ($V_{Neumann}$ + V_{Fisher})*0.01 – 0.028. Neumann fuel allocation is 0.028 mcm/d and Fisher fuel allocation is the marginal cost of Fisher production.

4.2 Fuel allocation to three producing fields

A similar analysis has been performed assuming Nash is also producing. In this scenario fuel gas allocation has been modelled assuming production volumes for Neumann, Fisher and Nash fields across the Neumann platform were:

- Neumann: varying from 0 to 1.6 mcm/d;

- Fisher: constant at 0.2 mcm/d;
- Nash: constant at 0.2 mcm/d.

Figure 16 shows the results of fuel gas allocation for Neumann plotted against Neumann throughput. Figure 17 shows the results of fuel gas allocation for Fisher plotted against Neumann throughput. In this scenario, Nash fuel allocation is identical to Fisher's and the Nash graphs have been omitted for brevity.

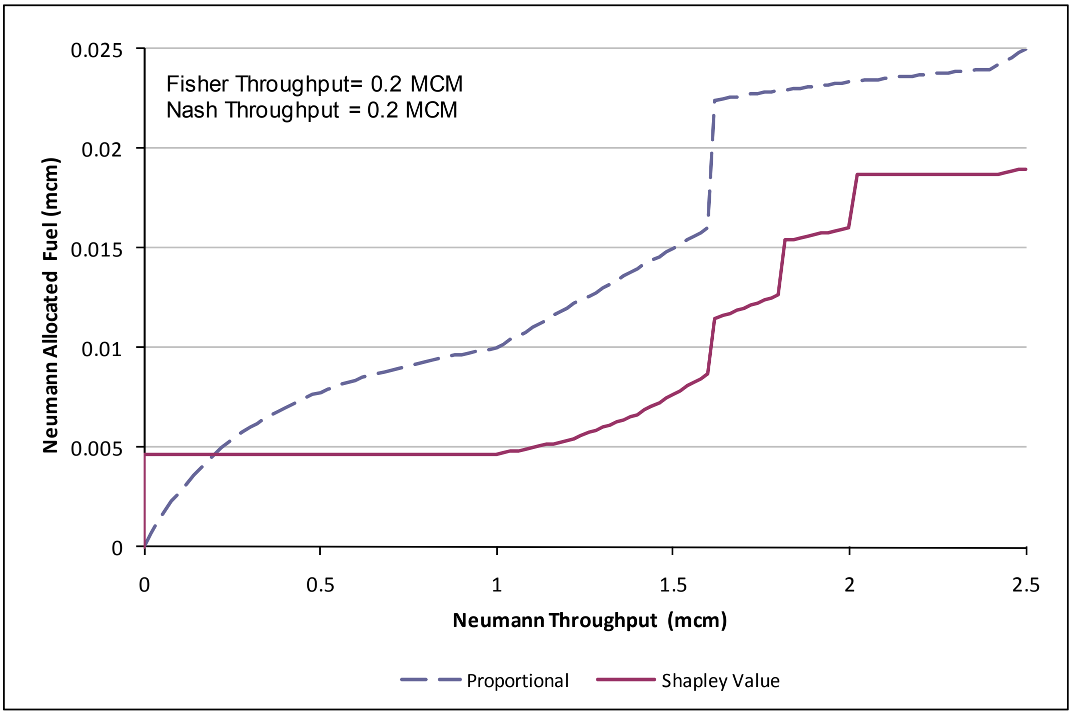

Figure 16 - Neumann fuel allocation plotted against Neumann throughput, when Fisher and Nash throughput are both 0.2 mcm/d

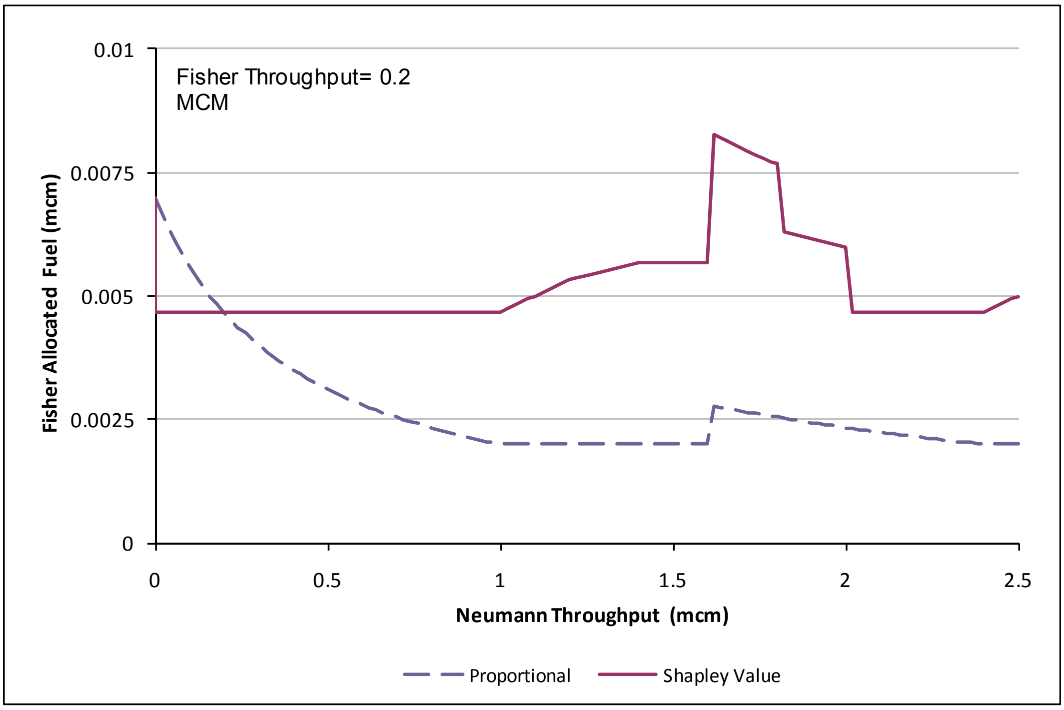

Figure 17 - Fisher fuel allocation plotted against Neumann throughput, when Fisher and Nash throughput are both 0.2 mcm/d

If fuel usage is allocated proportionately to throughput, similar features to the Neumann-Fisher two field scenario examined in Section 4.1 are observed. As would be expected summing the Fisher and Nash fuel allocation in this scenario gives the same results as presented in Section 4.1.

However, if fuel allocation is performed according to the Shapley method then the results of fuel allocation appear more complex than in the two field scenario. As Neumann throughput increases fuel allocation is subject to more step changes and throughput dependency. While Fisher and Nash are allocated fuel equally, it is not the case that summing the Fisher and Nash fuel allocation in this scenario gives the Fisher fuel allocation derived in Section 4.1.

For Neumann throughput up to 2.5 mcm/d, the fuel allocation results derived according to Shapley's method can be explained as follows:-

$V_{Neumann}$ = 0 mcm/d. Fuel usage is allocated equally to Fisher and Nash when Neumann is not producing.

0 < $V_{Neumann}$ < 1 mcm/d. As in the two field scenario the cost of Neumann's admission into the system is an equal share of total fuel usage with Fisher and Nash. Each field is allocated a third of total fuel usage. This remains true for Neumann throughputs up to the level where the total throughput crosses the compressor recycle threshold, in this case $V_{Neumann}$ = 1 mcm/d.

1 <= $V_{Neumann}$ < 1.2 mcm/d. The combined Neumann, Fisher and Nash throughput is now above the compressor recycle threshold. Increasing throughput leads to increased Neumann, Fisher and Nash fuel allocation. No one field can be said to be entirely responsible for the increasing fuel costs as throughput increases above the recycle threshold. Thus the increase in fuel allocation is shared equally between all three fields. Each field is still allocated a third of total fuel usage.

1.2 <= $V_{Neumann}$ < 1.4 mcm/d. The combined throughput of Neumann and any one of Fisher or Nash is now above the compressor recycle threshold. Increasing throughput leads to increased Neumann, Fisher and Nash fuel allocation. Notably, Neumann fuel allocation increases twice as fast as for 1 <= $V_{Neumman}$ < 1.2 mcm/d, and Fisher or Nash fuel allocation increases at half the rate. This is because Neumann now only needs production from one of Fisher and Nash for throughput to go above the recycle threshold. In contrast, the compressor is still below recycle threshold if the combination of Fisher and Nash production is considered together. It is only when Neumann production is added to throughput that the compressor recycle threshold is crossed.

1.4 <= $V_{Neumann}$ < 1.6 mcm/d. Neumann throughput is now above the compressor recycle threshold. Increasing Neumann throughput does not however affect Fisher or Nash fuel allocation, which is constant for 1.4 < $V_{Neumann}$ < 1.6 mcm/d. As in section 4.1, Neumann is allocated the fuel usage above the threshold.

1.6 <= $V_{Neumann}$ < 1.8 mcm/d. Total throughput is now above a single compressor's capacity so there is a corresponding step change in fuel allocation to each of Neumann, Fisher and Nash. However, since Fisher and Nash can produce together without exceeding the compressor capacity their fuel allocation is lower. The rate of change of Neumann fuel allocation with throughput is the same as for 1.2 < $V_{Neumann}$ < 1.4 mcm/d. As Neumann throughput increases Fisher and Nash are allocated less because Neumann's marginal cost increases.

1.8 <= $V_{Neumann}$ < 2.0 mcm/d. Throughput is now above a single compressor's capacity for either combination of Neumann and Fisher or Neumann and Nash and there is again a step change in the fuel allocation. Neumann is now allocated more fuel as it requires only one more field's production to cross the compressor capacity threshold. Fisher and Nash are allocated a correspondingly smaller amount. In addition the rate of change of fuel allocation for each of Neumann, Fisher and Nash is half of that in 1.6 < $V_{Neumann}$ < 1.8 mcm/d. As

Neumann throughput increases Fisher and Nash are allocated less because Neumann' marginal cost increases.

2.0 <= $V_{Neumann}$ < 2.4 mcm/d. Neumann throughput is now above the single compressor capacity. There is again a step change in Neumann fuel allocation as it requires the second compressor to be online. Fisher and Nash are allocated correspondingly less. Fuel allocation remains constant as both stages of compression are in recycle mode.

$V_{Neumann}$ >= 2.4 mcm/d. The combined Neumann, Fisher and Nash throughput is now above the compressor recycle threshold on both compressors. Increasing throughput leads to increased Neumann, Fisher and Nash fuel allocation. This situation is similar to 1 <= $V_{Neumann}$ < 1.2 mcm/d. No one field can be said to be entirely responsible for the increasing fuel costs so the increase in fuel allocation is shared equally between all three fields

4.3 Comments on Fuel Allocation Scenarios

As stated before, it seems that proportional allocation is instinctively fair. But what do the modelled scenarios show us about fairness in fuel allocation?

If the assumptions upon which the Shapley allocation is based are seen as reasonable, then proportional allocation leads to fields subsidising each others fuel costs. As the models have shown, the subsidising field(s) and beneficiaries and the amount of subsidy varies with total throughput.

This can be seen, for example, at low throughput where fuel usage is independent of throughput and Shapley allocation results in all fields being allocated fuel equally. In the examples considered here, the subsidising field and beneficiary change as the total throughput crosses the compressor recycle threshold.

In scenarios where Fisher and Nash were modelled with higher throughputs (e.g. V_{Fisher} = V_{Nash} = 0.8 mcm and 1 mcm) then the amount of subsidy tends to become smaller than the examples in sections 4.1 and 4.2. The beneficiaries also alternated between fields as total throughput crossed compressor recycle thresholds and capacities.

The models have also illustrated the dependence of fuel allocation results with throughput when using Shapley allocation. The Shapley allocation results presented here exhibit step changes and linear dependence with throughput which are explained as being due to total throughput or a combination of field throughputs crossing compressor recycle thresholds and capacities.

5 OIL AND GAS ALLOCATION APPLICATIONS

The following examples use real data from actual allocation systems and compare the actual proportional based allocation results with those that would be obtained using the Shapley value and nucleolus.

The data has been anonymised using the field names Neumann, Fisher and Nash from the preceding simplified examples.

5.1 Fuel Gas Allocation for a Compression System

This example concerns an offshore platform that processes three fields. On the platform there are three stages of compression with three parallel compressors installed at each stage. Neumann's and Fisher's gas is compressed in all three stages but Nash enters only at the third stage. Between stages there is some knockout of liquids. The compression system is illustrated schematically in Figure 18

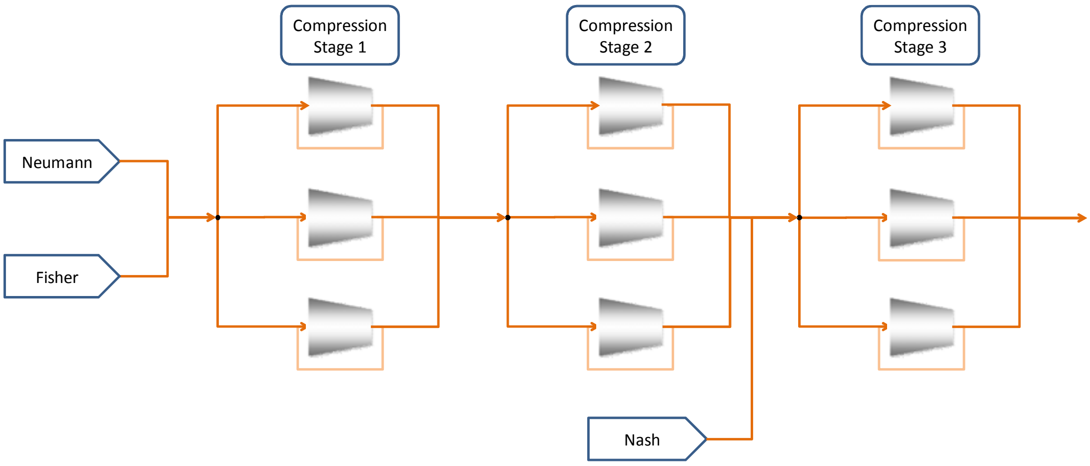

Figure 18 – Schematic of Compression

The compressor performance characteristics are presented in Table 7:

Table 7 Compressor Performance Characteristics

Individual Compressor Attributes	Compression Stage 1	2	3
Nominal Mass Capacity (tonnes/day)	2,055	1,970	2,060
Surge Point (% of Capcacity)	70%	70%	70%
Electrical Energy Consumption (MJ/te)	297	165	246

The capacities and power consumptions of all three sets of compressors do differ. The three fields' throughputs at each compression stage are presented in Table 8.

Table 8 Field Gas Throughputs at Each Compression Stage

Field		Compression Stage 1	2	3
Neumann	tonnes/day	2,029	1,939	1,722
Fisher	tonnes/day	788	747	534
Nash	tonnes/day	0	0	59

The flow of Fisher and Neumann reduces slightly as they progress through the stages reflecting the drop out of condensed liquids. Nash enters the process at the inlet to the third stage and hence has zero flow through the first two stages.

The total electrical power demand associated with compression was calculated in the allocation system using the above parameters and total gas throughputs at each stage. Compression was one component of the total fuel consumed on the platform along with export oil pumping, water injection etc. for which similar power calculations were performed. The actual fuel consumed was then divided between these various components in proportion to the estimated power demands.

The fuel associated with each stage of compression was then allocated in proportion to each field's mass throughput at that stage. Using the methodologies described in Sections 3.4 and 3.5 the Shapley value and nucleolus can be calculated for the compression fuel consumption. The actual allocated quantities are compared with those according to the Shapley value and nucleolus in Table 9 and Figure 19.

Table 9 Comparison of Compression Fuel Allocation Methods

		Neumann	Fisher	Nash
Proportional	(MJ/d)	1,470,911	529,224	18,762
Shapley Value	(MJ/d)	1,121,241	777,017	120,640
Nucleolus	(MJ/d)	1,126,720	774,906	117,271
Differential from Proportional				
Shapley Value	%	-24%	47%	543%
Nucleolus	%	-23%	46%	525%
Differential from Proportional				
Shapley Value	(MJ/d)	-349,671	247,792	101,878
Nucleolus	(MJ/d)	-344,191	245,682	98,509
Approx cost differential				
Shapley Value	$/d	-2,498	1,770	728
Nucleolus	$/d	-2,459	1,755	704
Per year				
Shapley Value	$/y	-911,641	646,030	265,611
Nucleolus	$/y	-897,355	640,527	256,828

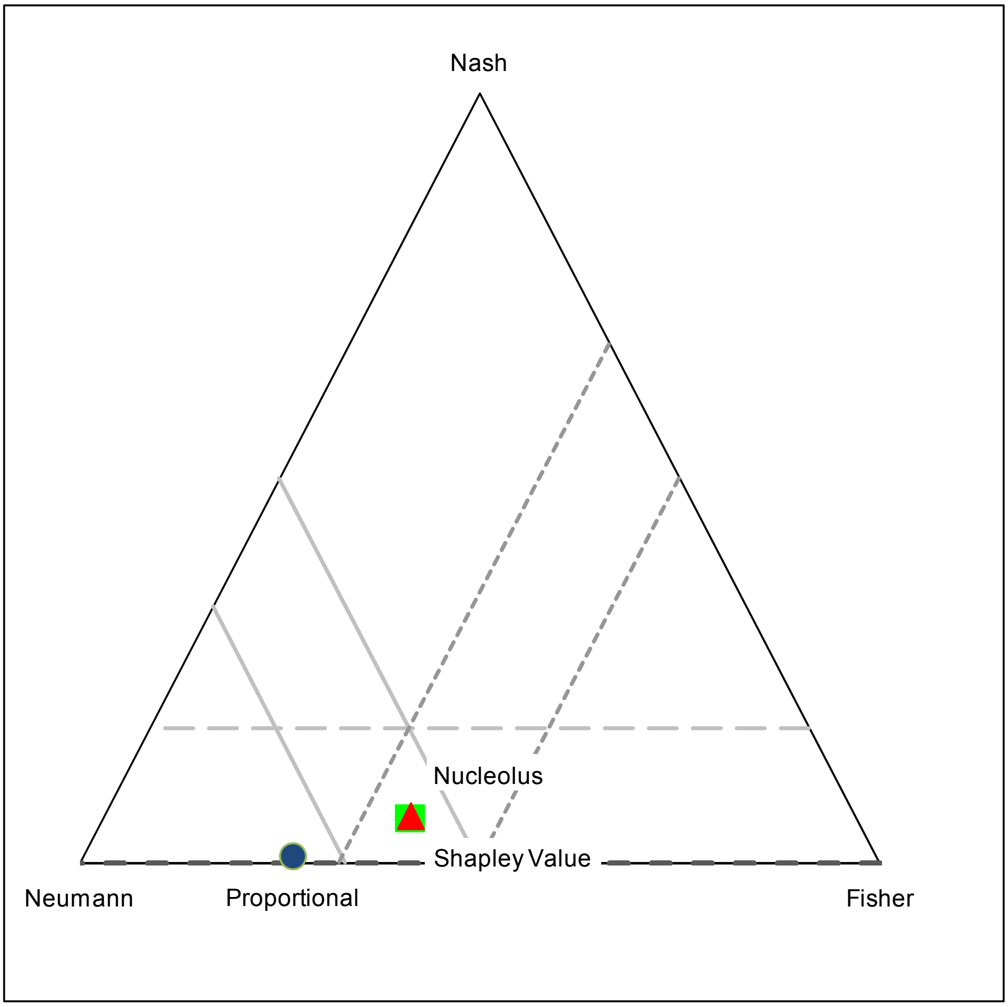

Figure 19 – Comparison of Compression Fuel Allocation

As can be seen the proportional allocation lies outside the core and illustrates that Neumann is disadvantaged. Inspection of the data reveals that it would incur less fuel gas if it was compressed on its own: in effect it is subsidizing both Fisher and Nash's compression costs. Both the Shapley value and nucleolus appear to provide more equitable (almost identical) solutions.

The cost impacts[6] of the three methods are also compared in Table 9. Though small on a daily basis, the impact accumulates to hundreds of thousands of dollars over a year. Another impact to consider is the CO_2 emissions attributed to each field from fuel.

5.2 Allocation of the Effect of Commingling

A concern that is expressed sometimes when a new field is tied back to an existing process is the impact it may have on the existing fields' allocated quantities. In particular if the new entrant has a significantly different composition to the existing fields, it can change the gas oil product split.

If a relatively lean field with a high GOR is tied back to a facility in which relatively low GOR fields are being processed, the lean field will tend to strip components from the oil to the gas phase. This may result in a small but significant reduction in allocated oil production to the incumbent fields.

The following real world example, involves just such a scenario, a relatively high GOR lean field Neumann, is being tied back to an existing offshore platform already processing two low GOR fields, Fisher and Nash.

The allocation is mass based and a simulation model is used to estimate the exported oil production from each field, in the commingled mixture of all the fields, at a component level. The measured oil export is allocated to the Fields in proportion to these estimated quantities.

Using the same model the oil production for all the various combinations of Fields producing can be calculated and incremental impacts calculated at a component level. The allocation according to the Shapley value and nucleolus can be calculated and these are compared with the actual allocation results in Table 10, Figure 20 and Figure 21.

6 Based on a fuel gas GCV of 50 MJ/kg, generator efficiency of 25% and a fuel price of $0.75/therm.

Table 10 Effect of Commingling Oil Allocation

		Neumann	Fisher	Nash
Proportional	(te/d)	2,375	2,964	533
Shapley Value	(te/d)	2,117	3,172	584
Nucleolus	(te/d)	2,116	3,172	586
Differential from Proportional				
Shapley Value	%	-11%	7%	10%
Nucleolus	%	-11%	7%	10%
Differential from Proportional				
Shapley Value	(te/d)	-258	207	51
Nucleolus	(te/d)	-259	207	52
Approx Cost Differential (at $75/bbl)				
Shapley Value	$/d	-143,459	115,101	28,358
Nucleolus	$/d	-144,018	115,035	28,984
Per Year				
Shapley Value	10^6 $/y	-52.4	42.0	10.4
Nucleolus	10^6 $/y	-52.6	42.0	10.6

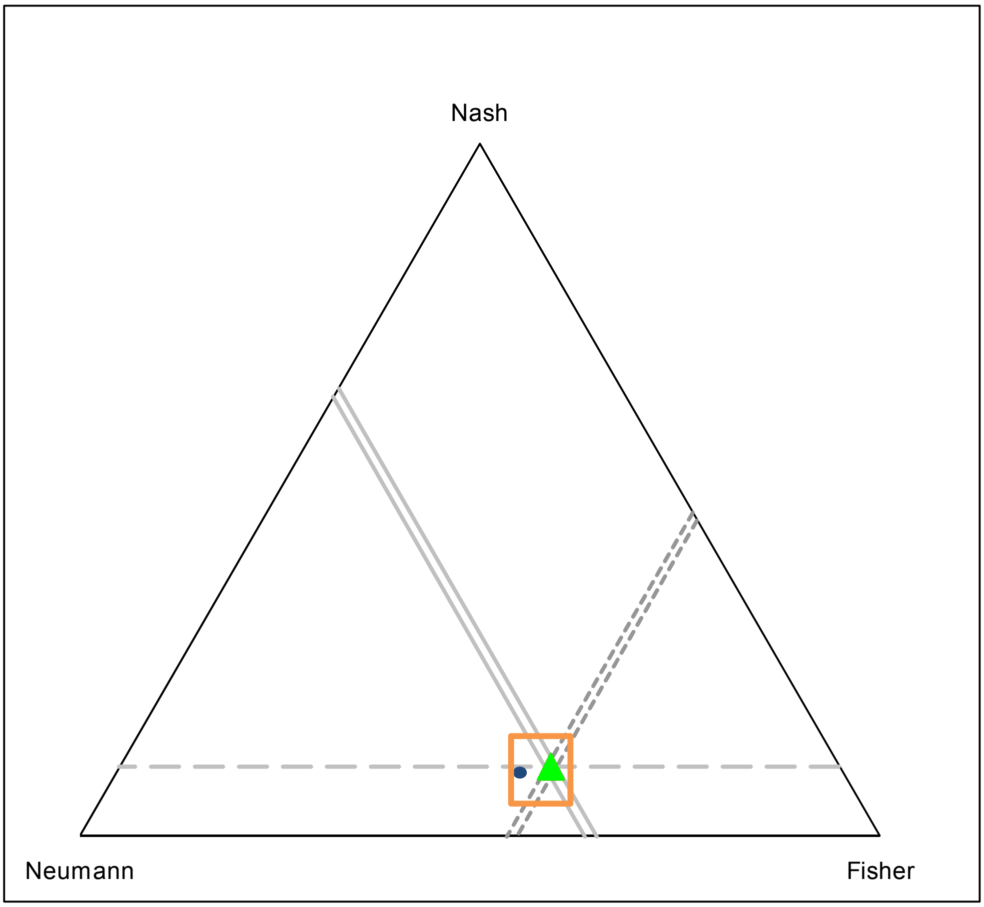

Figure 20 – Effect of Commingling Oil Allocation

The changes in the allocation incurred by the three methods are small compared to the total oil production. Hence the square region is exploded in Figure 21.

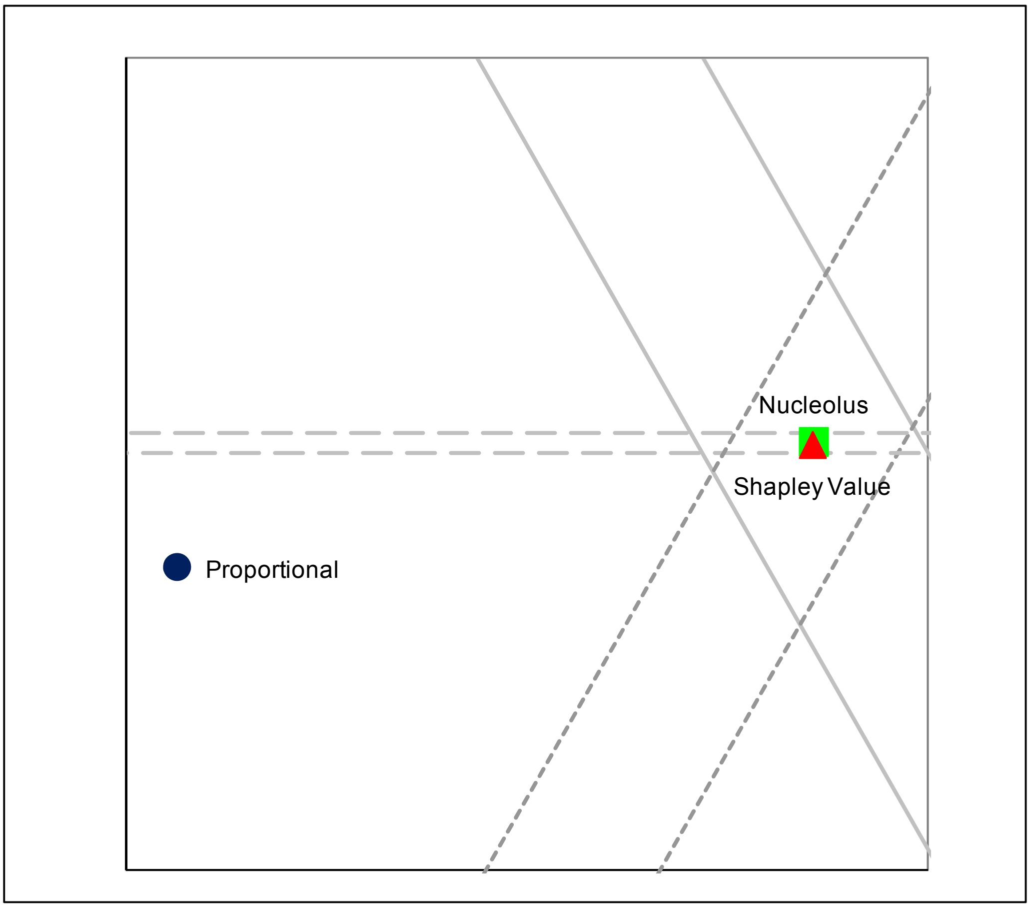

Figure 21 – Effect of Commingling Oil Allocation

Both the Shapley value and nucleolus provide more equitable solutions, which lie in the Core, than the proportional approach. Indeed with the proportional approach, not only has Neumann stripped components out of the oil phase into the gas phase it has increased its oil allocation compared with its stand-alone case and both Fisher and Nash are allocated less oil than either their stand-alone or joint commingled case. Assuming both Fisher and Nash's components are more valuable to them in the oil phase rather than the gas, the introduction of Neumann has a doubly negative impact.

However, adoption of the Shapley value or nucleolus in preference to proportional allocation provides a much more equitable share of the loss of components from the oil to the gas phase. They still afford the use of the mass component based allocation with the use of shrinkage factors derived from a model.

An alternative sometimes adopted by the incumbent fields when introducing a new entrant is to calculate what they would have been allocated prior to the introduction of the new field and then allocate the new field the remaining oil. This has a number of drawbacks since it does not treat all fields in a consistent manner and is not readily extensible for the introduction of further new fields. In contrast the Shapley value and nucleolus achieve the desired outcome but use a consistent, extensible approach, based on sound mathematical principles.

In terms of approximate oil revenue (based on $75/bbl oil price) the three approaches are compared in Table 10. The changes in oil allocation translate into tens of millions of dollars per year of oil revenue to the fields. These figures are offset by gains and losses in the value of the gas allocation. However, it can be concluded that these considerations of equitability in the allocation method does have significant financial implications.

5.3 Capacity Restrictions

As a final example of how game theory can be applied, access to processing capacity when restricted is now examined. Consider a gas terminal with a daily processing capacity of 30mcm/d. The terminal processes gas from two users, Neumann and Fisher, which have booked a daily capacity of 21 and 9 mcm/d respectively. How should the processing capacity be split between Neumann and Fisher if there is a capacity restriction at the terminal?

This could be in proportion to their booked capacities and this is the normal approach adopted in practice. The ‘Contested Garment Rule’ highlighted in Section 2.1 provides an alternative solution to such a claims problem from proportional allocation. The general rule is:

Calculate each claimants uncontested portion, that is the amount left over after the other claimant has been paid in full or has been paid all that is available. Give each claimant their uncontested portion of the claim plus half of the excess above the sum of the uncontested portions.

Figure 22 shows the result of applying the contested garment rule as the terminal capacity restriction varies, 0 <= V_T <= 30 mcm/d.

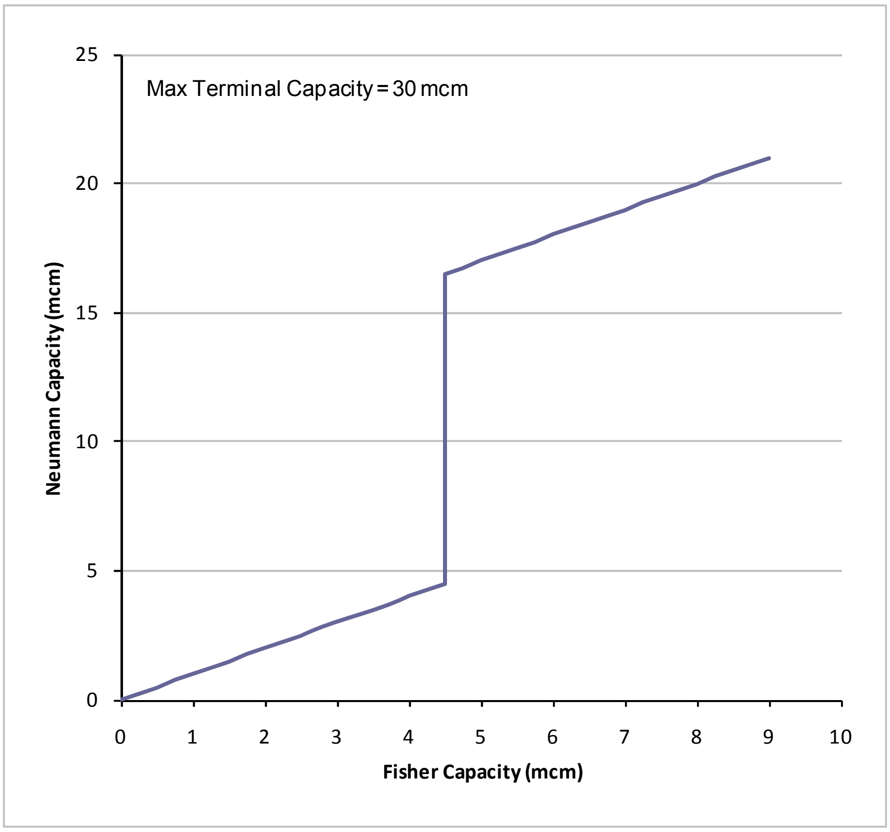

Figure 22 – Division of restricted terminal processing capacity between two users as processing capacity goes from 0 to 30 mcm/d

When the terminal capacity is small, say V_T = 6 mcm/d then Neumann and Fisher’s uncontested portions are both zero, so they each receive half of the terminal capacity. This applies for 0 < V_T <= 9 mcm/d.

For 9 < V_T <= 21 mcm/d, Neumann’s uncontested portion is non-zero so Neumann receives additional processing capacity.

For V_T > 21 mcm/d, both Neumann and Fisher's uncontested portions are non-zero. For a terminal capacity V_T = 24 mcm/d, Neumann and Fisher would receive 18 and 6 mcm/d capacity respectively. In this terminal capacity range the loss in terminal capacity is shared equally between the users.

The general features of this method are that:

- users gain an equal share of terminal capacity, when that is less than the smallest booked capacity;
- users lose an equal share of terminal capacity, when that is more than the highest booked capacity; and,
- for terminal capacities between the user's capacities, the user with lowest capacity receives 50% of their booked capacity until the other user receives 50% of their booked capacity.

The perceived benefit of the Contested Garment approach is that it shares the gains equally among users when the capacity is low and shares the losses equally when the capacity is high. If these are deemed desirable properties then this approach provides an alternative to the proportional allocation.

Although the example described here relates to two users, the method can be extended to any number of users. In that situation a solution could be obtained from a variety of techniques, including Shapley's method. Interestingly the above method is equivalent to calculating the nucleolus and is expanded on in the next section.

6 CONCLUSIONS

It has been demonstrated that when a quantity to be allocated does not vary continuously and directly with a metric such as throughput, proportional allocation does not always produce equitable results.

In many systems allocation in proportion to "something" is adopted just because that "something" is a convenient metric without considering the equitability of the resulting allocation.

Rather than assuming a method is equitable, it is more valuable to consider what desirable properties a method should have that would render it to be deemed equitable. Such features include all users receiving the benefits of sharing costs.

Two alternative methods have been presented: the Shapley value and the nucleolus. These have been developed from the science of co-operative game theory. Such methods have been adopted in many industries to allocate costs. In this paper these methods have been applied to real oil and gas allocation systems and have been shown to provide more equitable allocation results than the incumbent proportional approach.

A 'perfect' solution to an allocation is unattainable. A solution concept must be chosen on the basis of what properties are considered desirable and what counter-intuitive examples are to be avoided.

Finally, though game theory has been formally developed only recently, considerations of equitability are very ancient indeed as has been illustrated in the writings of Aristotle and the Jewish Rabbis. To conclude, a final example provides a fascinating convergence of the ancient ideas of equitability and modern game theory. This was another problem from the Talmud describing how claims on an estate should be divided between three claimants who have claims of 100, 200 and 300 respectively. This is illustrated in Table 11:

Table 11 Division of Estate from the Talmud

		Claim		
		100	200	300
	100	33⅓	33⅓	33⅓
Estate	200	50	75	75
	300	50	100	150

The logic of these divisions puzzled scholars for centuries. What was apparent was that if the estate is "small" it is divided equally and if "large" sized it is divided proportionately. However, the 200 estate division is harder to fathom and in fact was thought to be due to a transcription error until two game theorists provided a beautiful answer in 1985 [8]: it is in fact the nucleolus.

Though the sages of the Talmud would have not known anything about co-operative game theory, let alone the nucleolus, the example illustrates that the principles underlying the nucleolus are very ancient indeed.

7 NOTATION AND ABBREVIATIONS

BOE	Barrel of Oil Equivalent
GCV	Gross Calorific Value
GOR	Gas Oil Ratio
TVA	Tennessee Valley Authority
V_{Cap}	Compressor capacity
V_{Fisher}	Fisher field gas production
V_{Nash}	Nash field gas production
$V_{Neumann}$	Neumann field gas production
V_T	Total gas throughput, terminal processing capacity

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North Sea FLOW Measurement Workshop

Paper 2.2

Developing Measurement Infrastructure in BP Azerbaijan

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1 INTRODUCTION

This paper covers the development of a sustainable Measurement Operation in BP Azerbaijan Strategic Performance Unit (AzSPU).

The Early Oil Project (EOP) metering consisted of 7 BP operated Fiscal, or Class 1 [1], metering stations in 2004, burgeoning to 16 operated and 3 non-operated Fiscal metering stations in 2009 through the Azeri-Chirag-Guneshli (ACG) Field Development Project Phases. In addition to the Fiscal meters, there are around 120 Allocation, or Class 2, [1] meters either as standalone instruments or as 'virtual' meters.

The challenge has been to address the scope growth through the introduction of an SPU Measurement Strategy.

The strategy describes an SPU Management of Measurement structure based on an ISO10012 [2] model. The model identifies interfaces between 10 direct measurement personnel and subcontract meter operators, measurement service providers, Hydrocarbon Accountants, Customs Inspectors and itinerant auditors.

Other key objectives of the strategy are:

- Meeting the 'localisation' agenda - National Engineer and Technician competency development;
- Development of Regional calibration services;
- Sustainable resourcing policy
- BP Operating Management System (OMS) compliance for Measurement
- Develop meaningful, cross-Asset key performance indicators (kpis) for all Fiscal and Allocation class measurements

To supplement the Strategy, a lower level SPU Measurement Operations Management Procedure has been adopted to 'standardise' on practices across three Export pipelines and two marine terminals spread across three countries.

The next objective of the Strategy is to 'land' the calibration and management of Allocation level meters under the existing framework leading to kpis and demonstrable OMS compliance.

2 MEASUREMENT INFRASTRUCTURE IN BP AZERBAIJAN TODAY

BP Azerbaijan is involved with Exploration and Production Operations under Production Sharing Agreements (PSA):

- The ACG PSA, signed in September 1994, covers the 30 year development of the Azeri-Chirag-Guneshli contract area. During 2009 around 310 million barrels of crude oil and 32 billion cubic feet of gas were exported from the contract area.

- The SD Production Sharing Agreement (PSA), signed in June 1996, covers 30 year development of the Shah Deniz contract area. During 2009 around 15 million barrels of condensate and 185 billion cubic feet of gas were exported from the contract area.

2.1 Azeri-Chirag-Guneshli (ACG) Field Development

The field has been developed in several Project phases, initially as the EOP, and then as ACG Field Development Project Phases running in tandem with Sangachal Terminal Expansion Project, STEP.

The ACG Field Development encompasses:

- Chirag offshore facility, which has been producing since 1997 as part of Early Oil Project EOP.
- Central Azeri offshore complex - CA PDQ and CA CWP facilities which came on stream in 2005 was known as ACG Project Phase 1
- West Azeri (WA) and East Azeri (EA) facilities which came on stream 2006 and 2007 respectively as ACG Project Phase 2 delivery.
- ACG Project Phase 3 delivery - Deepwater Guneshli (DWG) offshore facility complex, DWG DUQ and DWG PCWU, which began production in 2008.
- ACG Project Phase 4 or the Chirag Oil Project, (COP), will deliver a further offshore facility, West Chirag.

2.2 Sangachal Terminal Expansion Project - STEP

Sangachal Terminal was built as part of the EOP to receive and process Chirag, or ACG Partner, crude exporting crude oil to Novorossiysk or Supsa Terminal in Georgia.

Expansion of the terminal came through STEP phases to accommodate increased production from the Azeri and DWG fields, adding additional stabilisation trains, a gas processing plant and three new stabilised crude oil export routes.

- EOP facilities were designed to process around 100,000 bbld from the Chirag platform and comprised crude stabilisation facilities (flash gas separators and fired heater trains), stabilised crude storage tanks and export pumps supporting two Export routes - Western Route Export Pipeline (WREP) and Northern Route Export Pipeline (NREP).
- STEP Phase 1 – added Azeri Field pipeline reception facilities, additional heater trains, additional storage tanks and EOP interface, completed 2005. Notional processing capacity 600,000 bbld.
- STEP Phase 2 – added additional processing trains and heaters, completed 2006, Notional processing capacity 1,000,000 bbld.
- STEP Phase 3 – Shah Deniz gas plant, completed 2006.
- Combined STEP has: two Import Class 1, or ‘Fiscal’, crude oil meters; three Export Class 1 crude oil meters; three Sales Gas Meters and one Export Class 1 Condensate meter

2.3 Shah Deniz (SD) Field Development

Initial development of Shah Deniz field saw the installation of an offshore facility, subsea pipeline and gas processing plant.

- Shah Deniz Stage 1 – Shah Deniz Alpha (SDA) TPG Platform, subsea pipeline, gas processing plant, two Sales Gas Export routes and one condensate Export route
- Shah Deniz Stage 2 – subject to final investment decision, is likely to entail around 30 subsea wells, 2 further platforms, gas plant expansion and additional Class 1 meters currently under development as Shah Deniz 2 Project by the Shah Deniz Full Field Development Project organisation.

2.4 Baku-Tblisi-Ceyhan (BTC) Pipeline

The pipeline is owned by BTC Company and operated, on behalf of the BTC shareholders, by BP. The Turkish section of the pipeline and tanker loading terminal are operated, on behalf of BTC, by BOTAS International Ltd. (BIL).

- 1,768 km pipeline, with 4 pump stations
- 1 operated Class 1 crude oil meter and 2 non-operated Class 1 crude oil meters.
- 80 block valve stations,
- Ceyhan Marine Terminal with two Class 1 crude oil meters

2.5 Southern Caucus Pipeline (SCP)

The pipeline is owned by SCP Company and the Technical Operators whilst Statoil are the Commercial Operators.

- 690 km pipeline with 2 compressor stations
- 2 pipeline Class 1 gas meters
- One Sales Gas Class1 meter take off in Georgia
- One 'check' Custody Transfer meter in Georgia
- Subject to final investment decision the SCP Expansion Project will significantly increase gas processing capacity and bring additional gas metering.

As described, the field development and Regional infrastructure indicates multiple PSA and Operations organisations. These represented, diagrammatically, in Figure 1 below.

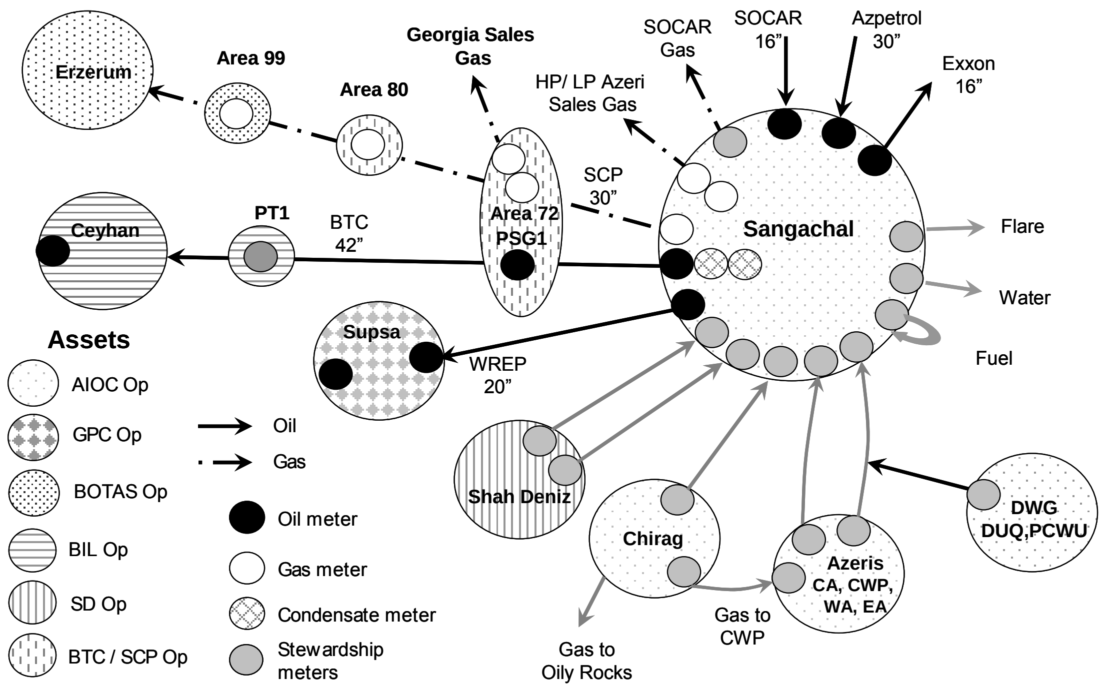

Figure 1 - AzSPU 2010 Measurement Infrastructure

3 SPU MANAGEMENT OF MEASUREMENT STRATEGY

Several interfaces can be identified in the AzSPU Measurement infrastructure that, in the main, can be grouped as follows:

- Geographic - pipelines crossing three countries
- Organisational - operated and non-operated meters
- Regulatory - Azerbaijan, Georgian and Turkish Government Revenue Agencies
- Commercial - different shareholder groups

3.1 Measurement Strategy Objectives

Through cross SPU consultation and in line with ETP 64 requirements, an SPU Metering strategy [3] was drafted. This document indentified a number of objectives as being key to measurement discipline ‘health’. The high level objectives are identified below:

- Metering ‘functional’ management achieved through workgroup representation.
- Establish key performance indicators for Metering Function
- Sustainable develop of Local Resource and Service Provision.
- Competency Development
- Equipment Rationalisation

The ensuing sections of this paper take a closer look at each of these objectives, describes how they were achieved using a mix of existing, Regional capability with out of Region development support and offers critical comment on the level of success realised.

3.2 SPU Management of Measurement Model

BP Engineering Technical Practice (ETP) approach to a Management of Measurement Model is defined, in [1], as:

- compliance with ISO 10012:2003 [2] for BP operated meters
- for non-operated meters, the BP SPU with exposure to liability for measurement shall influence and monitor the Operator for compliance with ISO 10012:2003, as far as is reasonably possible.

Reference [2] covers the lifecycle of a Measurement Operation from Commercial negotiations, through Contractual agreements and Regulatory interfaces to Internal Accounting and Operations. BP Commercial requirements for Measurement are also described in Hydrocarbon Value Realisation draft practice, [4].

The Management of Measurement process and continuous improvement cycle is shown in Figure 2.

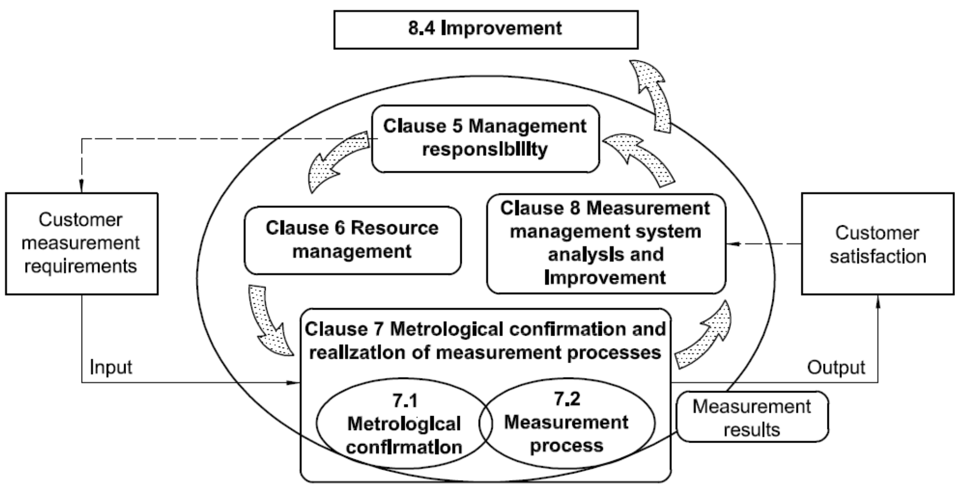

Figure 2 - Measurement Management System Model [1]

Given the model, it was possible to identify and fit existing SPU roles to each of the clauses shown in the Figure 2.

[1] Figure 2 adapted from reference [2]

In terms of the SPU structure, the SPU Engineering Authority (EA) [5] is accountable for implementing BP procedures and practices so has management responsibility for the Management of Measurement Process, relating to Clause 5 of the model.

Clause 6, the resources and equipment associated with execution the measurement processes are attached to individual SPU Assets i.e. Measurement Discipline Responsible Engineers (DRE), Metering Technicians and Metering Test Equipment are under the management of the Asset Maintenance and Asset Engineering Organisations

Approved procedures, designed to preserve meter design uncertainties, are used for the Metrological Confirmation, Clause 7. The 'Custodian' of the procedures is the Asset DRE, whilst the Measurement Process is implemented through 'Maximo' [6] maintenance scheduling package, supplemented by 'Metrology' [7], a proprietary specialist Metering Maintenance software tool.

To address the requirements of Clause 8, monitoring and improvement of the Measurement cycle is delegated to the SPU Measurement Technical Authority (MTA) by the SPU EA. Monitoring is achieved through a combination of mechanisms:

- Measurement 'health' reviews e.g. metering personnel competencies assessments & training recommendations, equipment reliability and obsolescence assessments
- site inspections
- MTA participation in Partner audits
- MTA review of Class 1 and Class 2 meter Management of Change (MOC) activities
- MTA approval of Measurement related procedures
- Regular SPU and E&P Segment Measurement Community of Practice meetings

Performance is reported in Annual Measurement Reviews and recommendation raised to address any issues identified.

The SPU Measurement function can be represented as in Figure 3 below.

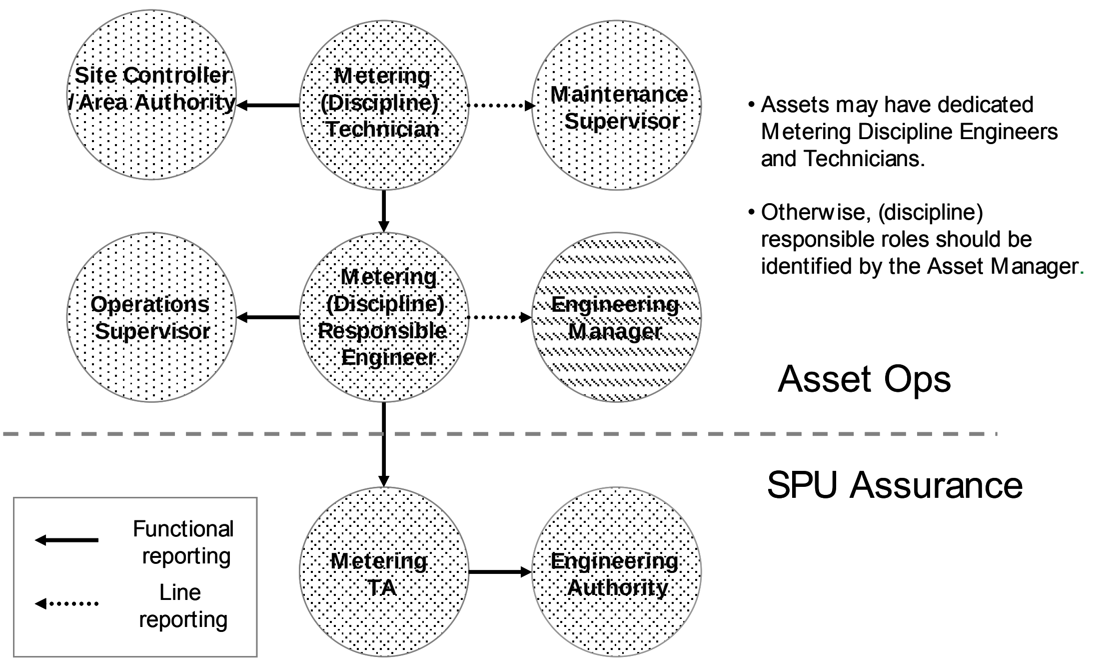

Figure 3 - SPU Measurement Function Structure

3.3 Measurement Function Customer Requirements and Expectations

Also identified in the model are Customer Measurement Requirements and Customer Satisfaction elements which bring a wider lens to the SPU Measurement Function.

The Customer Measurement requirements are identified early in the field development cycle to meet Contractual and Regulatory development obligations. These obligations are translated into Operational systems through the collaboration of the Commercial HVR organisation, SPU Operations organisation, Project Organisations and System Manufacturers. In BP the link between the Projects organisation and the Operations organisation is through the Discipline TAs, in the case of Measurement, through the MTAs. The Project Organisation may not have an explicit, full time MTA in which case the function is embedded in a suitable role e.g. Control Systems or Instrument TA.

Customers of the Measurement cycle are manifold but are managed through the Commercial HVR organisation in accordance with local Regulatory requirements and Commercial Agreement. The Development and Operations phase of a meter can be represented diagrammatically, as in Figure 4 below, below with SPU Measurement model identified accordingly.

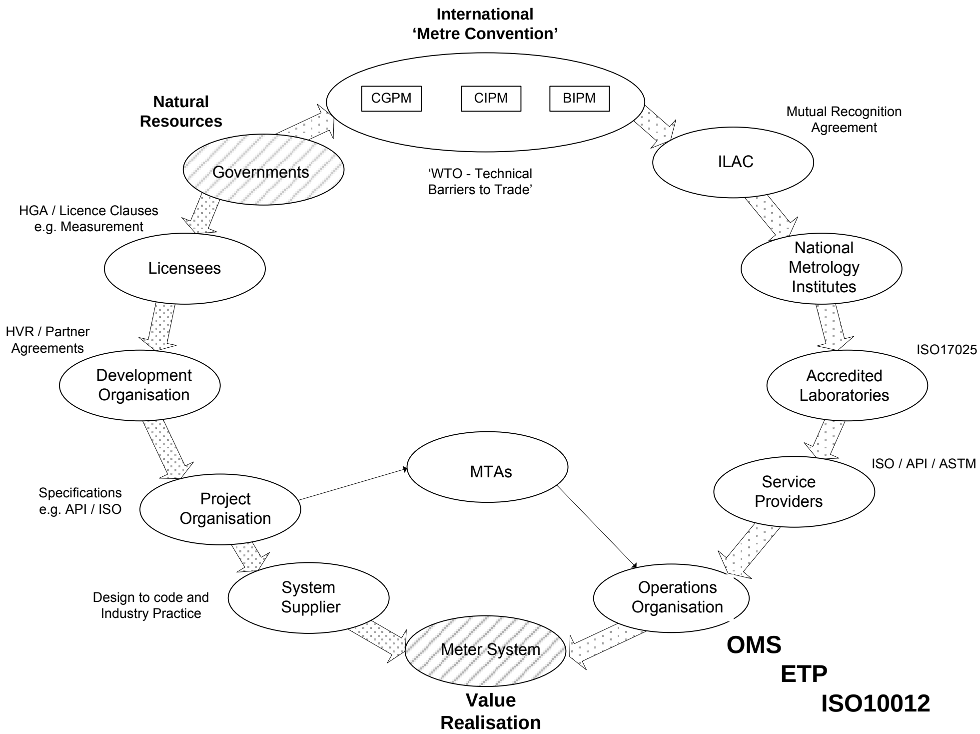

Figure 4 - Meter Development - Operations Phases

4.0 MEASUREMENT FUNCTIONAL MANAGEMENT

Metering Strategy measurement 'functional' management is described in terms of workgroup representation.

The workgroups are not formally defined in terms of 'committees' but are composed of personnel who, through their day to day activities influence, or can be influenced by measurement activities.

Depending on the area of the 'function' requiring attention, different representation from the SPU may be required. This can include Asset Operations and Maintenance (O&M) personnel, Procurement & Supply Chain Management (PSCM) representatives, Service Providers, Commercial Analysts and Partner Representatives. To assure consistency and continuity of measurement practice it is also usual to involve the MTA.

Examples of objectives achieved, some of which are described in greater detail in the following sections, include:

1. Development of Regional vendor prover calibration service delivery to Internationally accepted performance delivery: various people, at various times over a two year period, input to this process including SPU Senior Management and representatives from BP PSCM, BP Engineering, AzSPU O&M, Fabricators, Regional Service Provider, Accreditation Agencies and MTA.

2. Development of metering 'manning' strategy: assessing the requirement of existing and increasing workload and the logistics of manning remote meter stations. This was discussed between Project, O&M personnel and MTA, resulting in a resourcing model.

3. Development of competency standards for Metering Technicians using BP common business processes: in terms of the Measurement function, an existing model was enhanced to monitor training progress and a proposal made for funding which resulted in successful contract placement. The work group involved with this process included Asset Maintenance Management, Discipline Coaches, PSCM and MTA.

4. Development of an 'in Region' generic calibration capability with robust traceability: calibration costs for general plant test equipment from across all of the SPU Assets were high and subject to long turnaround. A strategy and plan to develop an 'in Region' calibration facility through partnership of a UK calibration service provider and local partner was worked by SPU Discipline Engineers, Asset O&M personnel, PSCM, Service Providers and TAs.

5. Development of a Measurement Operations Management Procedure [8]: the document reflects a cross SPU common approach to the high level guidance or the minutiae not captured in [6] and it will form the basis of a Site Technical Practice. The document was developed by a work group of Measurement DREs, Measurement Technicians and MTA.

6. Coordination of close out of third party Measurement Audits by cooperation between HVR, Asset O&M, Measurement DREs and MTA.

Whilst this approach may seem entirely reasonable it should be noted that there have been as many as a dozen or so discipline engineers involved in item 2. and 3. above, as well as O&M and Project Operations staff. Management of the number of personnel involved, diversity of representation and on occasion Commercial sensitivity, has been greatly simplified through the adapted ISO10012 model.

5.0 KEY PERFORMANCE INDICATORS

The Metering Strategy [3] identifies high level performance expectation statements for Class 1 meters.

These are that Class 1 oil Export meters are Operated such that the measurement uncertainty will be managed within ± 0.25% dry mass and that Class 1 gas Export meters will be operated within ± 1% uncertainty tolerance. This is generally accepted industry practice today.

These tolerances are derived from uncertainty calculations which assess component and then system uncertainty based on assumptions around instrument repeatability and stability.

To manage the system uncertainty, sets of calibration and maintenance processes have been created for all Class 1 oil and gas meters - there are around 12 sets in place. The activities associated with these procedures are scheduled in Maximo [6] but output from the procedures is stored in Metrology [7].

Maximo is the BP Common business tool but is used primarily as a scheduler for Class 1 meter calibration. The reason for this is that Maximo does not have the capability to calculate complex 'expected' values required for the calibration procedures e.g. Maximo does not have the capability to calculate local gravity and deadweight tester temperature compensations nor can it calculate API VCF for densitometer referral. Metrology does have this capability and provides an electronic record of Operations and Calibration activities along with 'uploaded' calibration certificates for some Field Equipment and Test Equipment.

Proposed key performance indicators for Measurement performance were therefore based around Maximo as follows:

- Maintenance related kpi:

'99.9% of Planned Maintenance will be complete to within 1 period of review date. At the review date 100% of Corrective Maintenance, will be complete or planned to completion'
i.e. at the time of the review, 99.9 % of the review period PMs will be completed. Where Corrective Maintenance has been required this will be completed or commitment given to a completion date with supporting plan.

% PM completion	Performance rating %
>99.9	100
>99	50
<99	30

Table 1 - Maintenance related kpi

- Operations related kpi

'No Corrective Maintenance is required as an outcome of Audit / Inspection findings'
i.e. during the review period all corrective maintenance has been identified and completed or planned to completion. This is designed to ensure that where equipment or procedure failure is identified, this is communicated onward for resolution

No. CM [2] actions raised through audit	Performance rating %
0	100
1	50
>1	30

Table 2 - Operations related kpi

- Commercial Compliance related kpi

'No non-compliances with PSA, Commercial Agreements or Industry Good Practice, identified as an outcome of Audit / Inspection findings'
i.e. during the review period, no non-compliances with 3rd Party obligations are identified as an outcome of Audit / Inspection findings

[2] Corrective maintenance

No. of non-compliances raised through audit	Performance rating %
0	100
1	50
>3	30

Table 3 - Commercial Compliance kpi

The proposed kpis have not been formally agreed but current metrics, based on audit performance, currently run at around the 50 % performance rating level for Exports measurement.

6.0 DEVELOPING LOCAL RESOURCE COMPETENCY

Industrial oil production in Azerbaijan started the 19th Century with hand dug wells. Development of the Oil industry continued through the period 1885 -1920. By the beginning of the 20th century, Azerbaijan was producing more than half of the world's supply of oil. In 1941 Azerbaijan extracted 23.5 million tonnes of oil - around 70% of the former Soviet Union oil production. In November 1949, the first Azerbaijan offshore oil well was drilled in "Oily Rocks".

After the signing of the "Contact of the Century" in 1994, foreign investment in the oil industry rapidly increased with the construction of modern Offshore platforms, oil and gas pipelines through the EOP, ACG, STEP and Shah Deniz Projects.

The rapid expansion from a few to several oil meter systems clearly required additional skills and placed increased demand for O&M Engineering and Technician resources.

6.1 Initial Local Technician Resourcing / Competency Development Strategy

In recognising the requirements of localisation, under the 'Contract of The Century', the strategy [3] identified the need for managed localisation of measurement personnel. A Regional service provider had provided metering technicians for some calibration work on EOP meter systems but they were not fully competent in some areas required by the calibration & maintenance procedures in support of the STEP / ACG Project Class1 meter kpis.

The BP personnel who had been involved with EOP meter systems were split, along with one set of test equipment, between the emerging Exports and Sangachal Performance Units exacerbating the issue of metering cover.

A Workgroup, section 4, item 2, discussed and identified two key resourcing issues:

- BP 'in Region' capability was not fully competent and was extremely limited by available numbers
- 'in Region' vendor capability was not fully competent and would require training to bridge between GOST and API / ISO practices to support STEP / ACG Project Class 1 meter systems

The resourcing model used for the early stage of Phase 1 Project development was to use Expatriate discipline coaches, supplemented by local technicians and trainee technicians recruited into BP. After 3 months basis discipline training, at the Caspian Technology Training Centre (CTTC) based near Sangachal Terminal, and successful 'passing out' the technicians would assist the coaches on live plant in O&M activities. Following a period of training on plant the trainees could then be competency assessed against discipline criteria in [9] and become fully competent discipline technicians.

It was clear to the Workgroup, that metering discipline coaches would be required. Since the number of systems would ramp up over 18 months, or so, it was concluded that coaches could do meter system O&M related work part time and coach metering technician trainees part time. A business case was developed and successful application made to the various Partner Group Contract Committees for funding based on a manning strategy of 'back to back' Expatriate Metering coaches - 4 based in Sangachal Terminal, 2 at Pump Station 1, on the BTC Pipeline in Georgia (PSG1), and 2 based at Area 80, on the Southern Caucuses Pipeline (SCP) in Georgia. In 2005 a 2 year contract was awarded to a European Service provider for the supply of Metering Coaches who would train and assess technicians to NVQ level competency. Trainee Instrument Technicians, from the CTTC training pool, who demonstrated an aptitude for metering or a bias towards the technological end of the instrument discipline spectrum would be assigned to the coaches for metering competency development.

After some time it became clear that localisation progress would be at the lower end of expectations. This was attributed to a number of factors, most significantly:

- The workload on the coaches - as well as routine O&M work, some considerable time was spent supporting Commissioning activities as new systems came into Sangachal i.e. the Sangachal coaches workload was underestimated
- Trainee technician availability - priority was given to filling Instrument Technician vacancies to support plant Operations, although one Trainee Technician per shift had been assigned some way into the program

In considering how to move forward from this position it should be noted that concern was expressed that competency standards should be biased toward European type competency standards as opposed to the local GOST competency standards. On investigation it was found that the GOST competency requirement was more around licensing and registration of Engineers and Technicians than supporting competency development. No hard and fast 'curriculum' could be found.

Further concerns were expressed that local vendor technicians were no longer called upon for calibration work they had previously carried out so the initial strategy, in fact, appeared to reduce local content of work.

A one year contract extension, through 2008, was approved as a buffer to consider ways to localisation and still provide metering O&M cover in the interim period.

6.2 Rationalising Technician Resource Loading

In light of Regional operating experience, a more 'formulaic' approach could be taken to establishing work loads in the context of local competency development.

At each of the three locations, where metering technicians were based, a load index was calculated based on the number of meter streams each technician would maintain. (For the purposes of the index each sampler loop, analyser loop and prover was also taken to be a single meter stream). At each location we also asked the question - "How does your workload feel" and the answer could be anyone of three from 1. "too high"; 2. "about right" or 3. "have time to get involved in other plant systems". The results of the survey are shown in Table 4:

	O&M Resource (expat + local + trainee)		Class 1 meter stream per fcr[3]	"feels like" / "should feel like"
a) Asset based resource, continuous operation	Sangachal PSG1 Area 80 Supsa	4 + 0 + 4 2 + 1 + 0 2	49 / 4 ≈ 12 18 / 2 ≈ 9 4 / 2 ≈ 2 9 / 0	Over loaded Slightly under loaded Under loaded ?
b) Country based resource, campaign operation	Azerbaijan Georgia	4 + 0 + 4 4 + 0 + 1	49 / 4 ≈ 12 31 / 4 ≈ 8	Over loaded Slightly under loaded
c) SPU central resource, campaign operation	SPU	8 + 0 + 5	80 / 8 ≈ 10	About right

Table 4 - Meter Technician loading

From Table 4, optimal resource loading would appear to be more likely with a central resource, based in Sangachal, servicing the whole SPU, option c, than the existing option a. The drawbacks to that however, were that it would not readily support development of Georgian local technicians, nor would it support first line intervention in the case of equipment failure. (It could take two days to mobilise a technician to PSG1 from Sangachal, subject to commercial flight availability).

Of the remaining options, country based resourcing was closest to optimal however; according to previous experience the technicians at Sangachal would still be 'overloaded'. In considering resourcing options it was acknowledged that there were 'near competent resources' (ncr), or technicians, available from a Regional service provider. It was believed that certain activities could be carried out by the ncr with minimal supervision which would reduce the loading on the Sangachal fcr. In fact, to engage two ncr would reduce the loading index to somewhere around 8 for Sangachal. In principle, this reduction should also free up more time for coaching. For the manning situation in Georgia it was also noted that the trainee there was in fact near competent so the final strategy identified loadings as 49 / 6 ≈ 8 for Sangachal (Azerbaijan) and 31 / 3 ≈ 10 for Georgia, noting that this now included the Supsa meters.

The forward resourcing strategy, from 2008, would be to have 4 fcr and 2 ncr based in Sangachal Terminal and to have 2 fcr and 1 ncr based at PSG1 in Georgia. The decision to engage, full time, ncr from the Regional Service Provider satisfied the concern that local resources work load had dropped. An outline shift pattern could be developed, show for Azerbaijan, in Figure 5:

[3] Fully competent resource

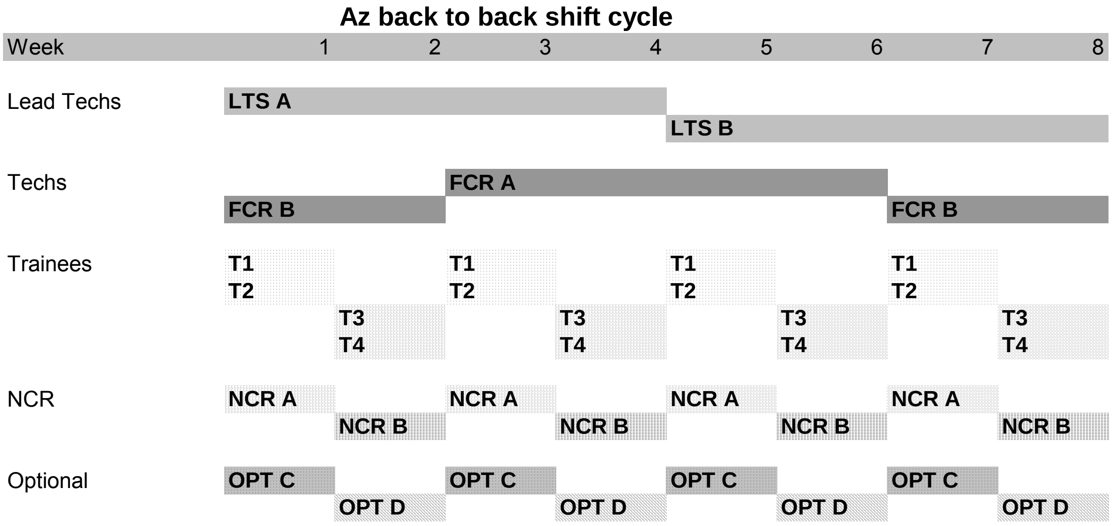

Figure 5 - Outline Shift Pattern

The Azerbaijan shift pattern indicates resourcing for any one shift:

- one Lead Technician (also and fcr)
- one fcr
- one ncr
- two trainee
- one optional training slot (this was never taken up due to fcr work load but was used for intermittent training for Engineer training)

similarly, the Georgian shift pattern resourcing:

- one fcr
- one ncr
- one trainee

With manning levels now established, the next consideration was how to implement local technician competency development in an effective manner, and to set and commit to localisation targets. It was felt that competency development, within a BP framework i.e. CMAS [9], would be most likely to be effective with direct control over competency standards, assessments and give better insight into competency development progress. The choice of BP CMAS obfuscated the discussion around competency standards and the use of CMAS, in relation to metering competency, is described in the next section.

6.3 Local Technician Resource Competency Development and CMAS

CMAS is BP's Competency Management Assurance System. It defines technician competency, and records assessed competency level, i.e. competent or not competent, in terms of 5 generic standards:

1. Implementation of Maintenance Procedures and Adjustment:
   management of a maintenance task involving e.g. requirements for permit to work, isolation certification, P&IDs, loop drawings, recording adjustments, Maximo sign off.
2. Interrogation and Fault Finding Skills:
   clarifying and diagnosing the cause and extent of faults in equipment and systems
3. Inspect and Repair Systems for Restoration to Required Performance:
   repairing system components and equipment, evaluate the feasibility of the repair.
4. Return Equipment to Service by Component removal and replacement:
   remove and replace system components and equipment
5. Monitor and Assess Performance and Condition of Equipment:
   monitor and assess performance and condition of equipment using different methods, e.g. control charts, visual inspection, documented information, measurement spot checks.

These 5 standards are applied to Units. Units are, effectively, subsets of Disciplines. The Metering Technician Discipline has the following Units:

- Supervisory, Control and Data Acquisition System interface
- Temperature Measurement
- Pressure Measurement
- Flow Measurement
- Proving Operations and Maintenance
- Analytical
- Density Measurement
- Valves

Each Unit has Elements - for the 8 Metering Units there are 26 Elements and each Element has a Training Plan which will contain a number of critical tasks. The Elements are dependent on the installed equipment and therefore are, to some extent, site specific. For example, the AzSPU Density Measurement Training Plan has only one element (Density Measurement) consisting of 4 critical tasks, with applicable CMAS standards noted:

- Routine replacement of densitometers and update of densitometer constants in flow computers (Standards 1 and 4)
- Good practice in Log Book records of densitometer rotation / replacement and constants update. (Standard 5)
- Clean a contaminated densitometer and perform air check (Standard 1, 2 and 5)
- Procedure for returning a densitometer to manufacturer for repair / calibration (Standard 4)

In practice Standard 3 is rarely used as faulty or failed equipment is replaced (where spare are available), not repaired.

Occasionally, through Standard 5, it may be necessary to initiate Corrective maintenance e.g. excessive discrepancy between on line densitometers or between on line density measurement and Laboratory Measured Density.

The competency cycle of each critical task is 'SEE - DO - ASSESS', whereby a trainee will: watch a critical task being done, asking questions and will then participate in doing that critical task. When both trainee and coach are satisfied with experience and learning for all of the critical tasks in an element, the trainee is ready to undergo Competence assessment by the coach. In part, the decision to ASSESS is guided by the self assessment questions contained in each of the training plans. It may take several SEE-DO repeats before ASSESS is undertaken. The standard of assessment is reviewed by a Discipline Assessor to ensure consistency in competency assessments between trainees and the Assessor may recommend further training or Approve competence achievement in an element. The record of competence is kept in the iCANN database.

SEE-DO is a key metric for the coaches - it is effectively the training process - too many SEE-DOs for one task is indicative that the training has omissions or that, perhaps, the trainee does not have the aptitude for the task. To prevent possible turnover of trainees it was decided that only technicians who had completed the core elements from the Instrument Technician competency profile, would be assigned as Metering Trainee Technicians. If the aptitude or vocation for metering competency was not evident the Metering Trainee could return to the general Instrument Technician pool. In this way attrition of a scarce resource i.e. the local technician resource, would be avoided. The SEE - DO - ASSESS cycle is shown in Figure 6.

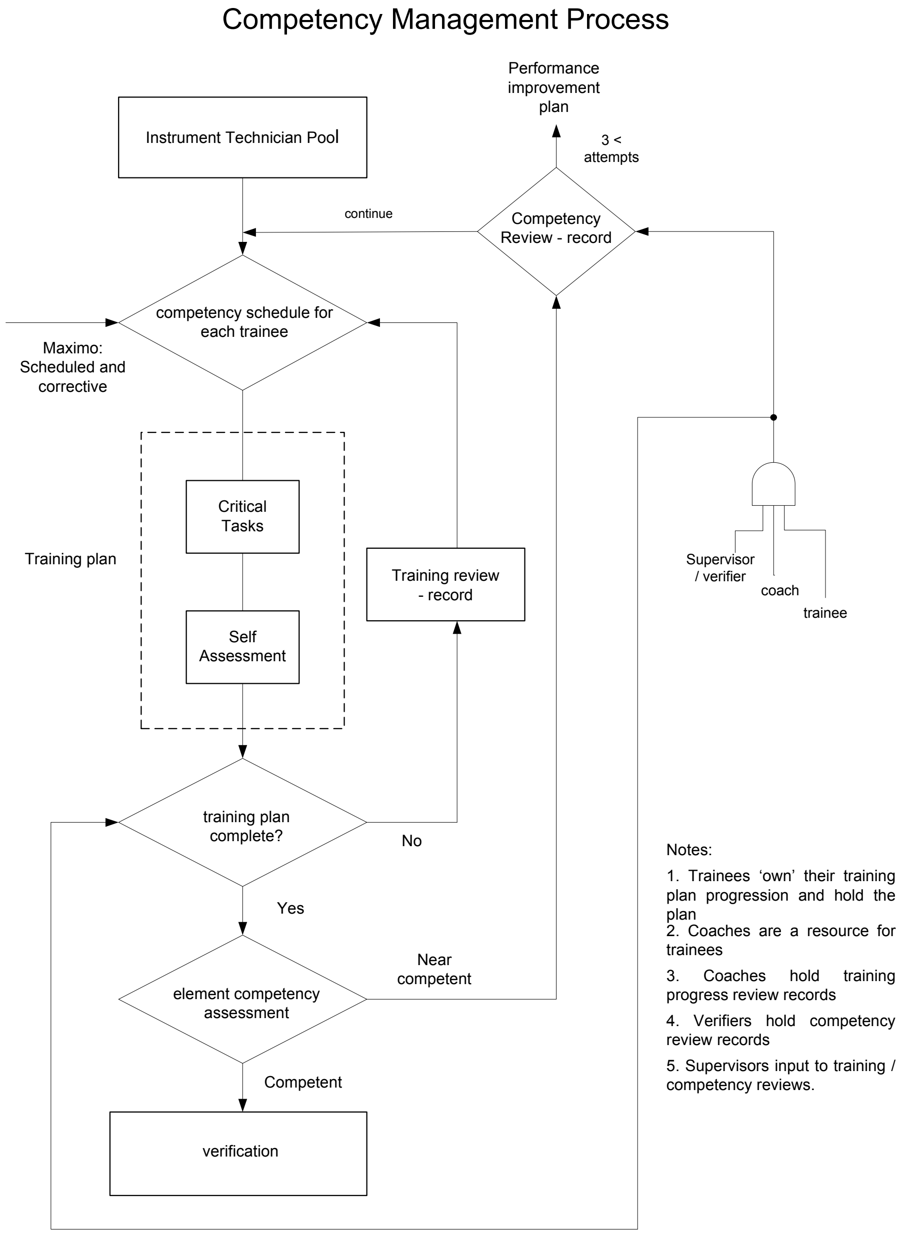

Figure 6 - SEE-DO-ASSESS Competency Development Cycle

Using Density Measurement Element as an example, the competency development of the local Metering Technician was structured in the following way. SEE - DO - ASSESS could only be undertaken when the relevant job plans were called up through Maximo, according to the Calibration & Maintenance schedule for Meter Systems. So for densitometer rotation / air checks the possible opportunities were mapped out in Figure 7.

According to his schedule there would be 12 possibilities to SEE - DO - ASSESS the four critical tasks in the Densitometer Training plan.

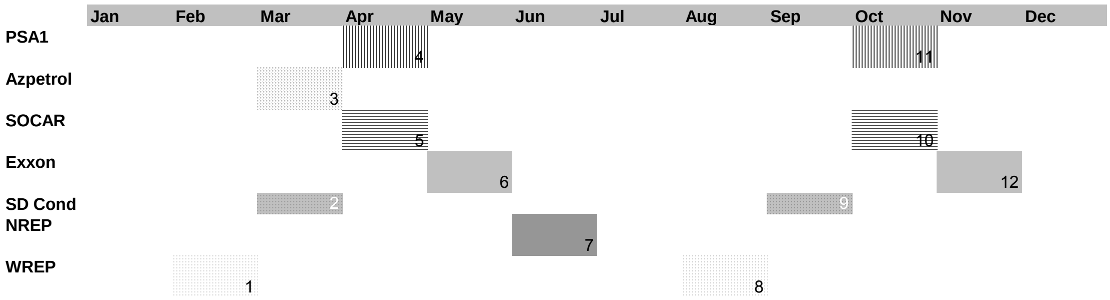

Figure 7 - Densitometer Job Plan Occurrence

So a Trainee may SEE on 2, DO on 7 and ASSESS on 12 and may supplement experience of the Training Plan through the intermediate occurrences.

To optimise SEE - DO - ASSESS opportunities it was decided to 'rationalise' Maximo and create a training schedule to include all Metering elements for up to eight trainees i.e.: Technicians 1, 2, 3 and 4; near competent resources A and B and Optional Training slots C and D. The rather complex task of fitting Maximo job plans to CMAS training plans to individual Trainees, to optimise training opportunities constrained by meter calibration & maintenance schedule requirements, was done by the Maximo planners.

On the basis of this resourcing strategy, a budget estimate was prepared and a business case presented to Partner groups for Approval. Budget was approved and 2 contracts were placed - 1 contract with a European Service Provider for the supply of 6 Metering Technician / Coaches and 1 contract with a Regional Service Provider for the supply of 2 'near competent' technicians.

At the time of writing the contract duration was around 80% complete and metering competencies in Azerbaijan are around 65% complete. The remaining competence elements are largely around metering ancillary equipment such as valve positioners. It is anticipated that localisation targets of having four competent BP local metering technicians, at contract end, will be met. The Regional Service Provider resource has been subject to some turnover and it is expected that 1 of the 2 ncr will be fully competent by contract end. Having the additional resource available in the market place, trained and competent to CMAS standards, will provide some flexibility in managing resourcing strategies going forward. The systematic approach described here can be readily repeated by local technicians and from that perspective; the Metering resource can be sustained using local resources.

In other areas of the SPU the progress is not quite so encouraging and it is reflects the underlying difficulties encountered in 'working' the interfaces within the SPU and so indicates where the Workgroup approach and communication of the Metering Strategy hasn't been quite so successful. Whilst training of local technicians has been ongoing there have been some delays to change out of coaches and availability of trainee technicians. The training which has been done has not been converted into completed Assessments and so there is little demonstrable record of competency attainment. At the time of writing this backlog was being worked as a priority and it is expected that a similar level of competency attainment, to that achieved in Azerbaijan, will be evident on completion of the Assessment backlog.

6.4 Developing Engineering Competencies

Along with increased demand for Metering Technicians and Engineers, the addition of gas orifice plate meters and analyser systems necessitated a more systematic, formal structuring of training and competency tracking. As already described, for technicians this was achieved using BP Competency Management Assurance System (CMAS) [9].

For Engineers this involves, on the job training, course attendance and assessment using BP Competency on Line (CoL). The competency set for Measurement Engineering in BP Exploration & Production Segment is still evolving; however, in 2008 a draft set of

Hydrocarbon Measurement Engineering Competencies was released via the BP Competency on Line System [10].

This was the first explicit set of Measurement Engineering competencies supplementing the Measurement skill set identified in the Commercial Network HVR Competency set and the Flow Measurement related element of the Discipline Instrument Engineer Competency set.

The significant difference with the Hydrocarbon Measurement Engineering us that it covered Phase behaviour, Laboratory and analytical Techniques and Measurement Uncertainty. On the release of these competencies the AzSPU Metering Technical Authority undertook Measurement Competency Assessment with the participation of Metering personnel. The outcome of the Assessment session was a recommendation for training, in specific competency areas, and development in other areas e.g. HVR skills.

The assessment session took the form of a technical discussion, with pencil & paper & sketches, which started at a basic level around meter type selection for an application. The discussion then moved onto influence factors which affect meter type e.g. pressure, temperature, phase, Re number. Having identified influence factors the discussion moved around how the influence factors could be characterised and implemented.

The types of response expected were e.g.:

- use a p.d. meter for crude oil Export installed in accordance with API 5.2.
- a meter of this type should only be used on a crude oil well above its bubble point. Bubble point can be inferred from a phase diagram for the crude
- minimise influence factors by using a prover described in API 4.1, for flow rate sensitivity, and utilise pressure and temperature measurements, for fluid corrections
- pressure and temperature effects on crude oil factors can be characterised by a VCF calculated in accordance with API codes (Chapter 11) and programmed in a flow computer
- VCF is dependent on dry oil gravity which can be inferred through using a variety of ASTM methods to determine water cut or from online densitometer measurement.
- Representative samples for determining crude oil density can be obtained using a sampler design in accordance with API 8.

This example is limited to crude oil metering but it’s an important view of crude Oil Export quantity and quality. Some of the part responses are shown in Figure 8 below and suggest where there is a satisfactory level of knowledge or where there may be opportunities for development and training.

Figure 8a depicts vortex shedding and indicates period between vortices as being relevant to flow measurement. Figure 8b indicates the response to a query regarding water cut techniques and limits of applicability. Figure 8c identifies the key elements in a gas analyser / sampler loop. Figure 8d represents a phase diagram with the key points and areas annotated.

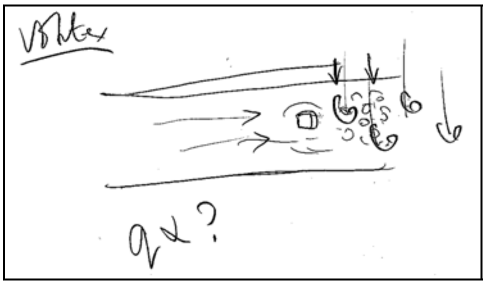

Figure 8a - Vortex Meter Principle of Operation

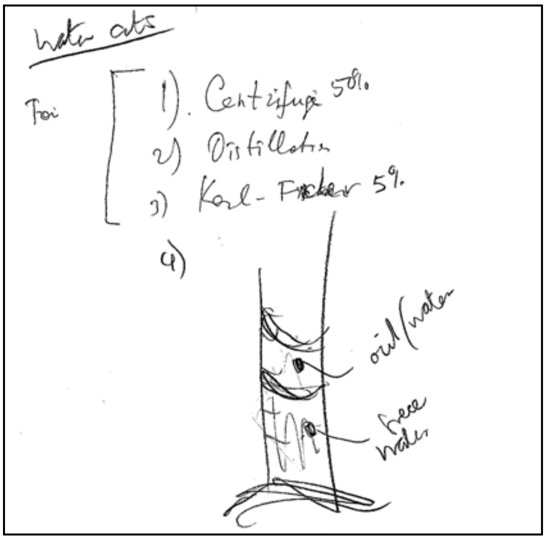

Figure 8b - Using a Measuring Cylinder for high water cuts

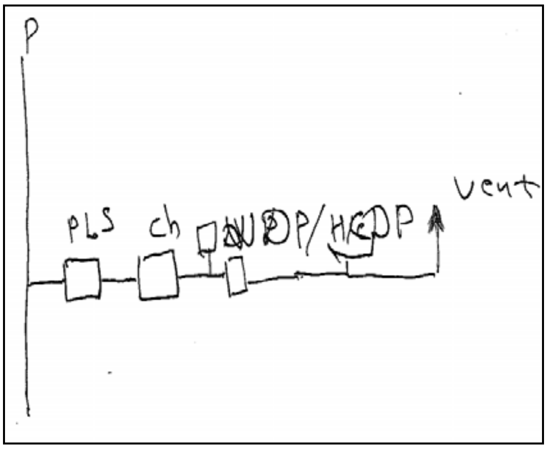

Figure 8c - Key Elements in a Gas Analyser / Sampler Loop

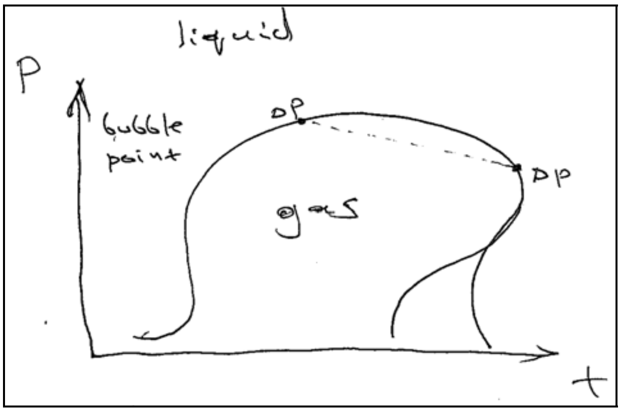

Figure 8d - Phase Diagram

7.0 DEVELOPMENT OF A REGIONAL PROVER CALIBRATION SERVICE

Azmetco is the Principal provider of metering services in Azerbaijan and has its roots in the Joint Stock Company of 'Complex Adjustment and Automation', established in 1981. 'Complex Adjustment and Automation' serviced the Regional oil industry in Azerbaijan, Georgia, Kazakhstan and Turkmenistan.

Following Azerbaijan's independence in 1993, 'Complex Adjustment and Automation' became an autonomous section of the State Oil Company of Azerbaijan Republic (SOCAR) and worked with many Regional Oil companies including Salyan Oil, Shirvan Oil, Binagadi Oil, AzGerneft, Karasu Operating Co. and in 1998, Azerbaijan International Oil Company. As it stands today, Azmetco was formed as an Open Joint Stock Company through the second Program of State Property Privatisation in 2002. [11].

7.1 Metrological Infrastructure in Azerbaijan Republic

In 2004, a BP review of Regional calibration capabilities identified that Regional calibration practices generally met industry accepted standards, however there were concerns regarding calibration equipment traceability and lack of detail in procedures. Then, as now, the

Azerbaijan Republic State Agency of Standardisation, Metrology and Patency (AzGOST) [12] maintained a register of metrological equipment and licensed the equipment for use in the State of Azerbaijan. Other than this activity there was no recognisable National Metrology Institute (NMI) or metrological infrastructure. The service offered by Regional providers centred on calibrating equipment using UKAS type accredited, calibrated 'standard' equipment and asserting that this provided traceability. None of the facilities visited carried accreditation from an independent Authority.

It should also be borne in mind that the former Soviet Union, whilst signatory to the Metre Convention, did not participate in what would become the International Laboratory Accreditation Co-operation (ILAC) [13] Mutual Recognition Agreement (MRA) and, as such, standards could be viewed as Regional, trading standards. The GOSTandard legacy has persisted in the former Soviet Union states, the Commonwealth of Independent States (CIS), although a European Union sponsored Project, Inogate [14], has promoted technical standards harmonisation across the Black Sea and Caspian Region. Participants in this programme are the 12 member states of the Eurasian Interstate Council for Standardisation, Metrology and Certification (EASC) [15] also known as MGS - межгосударственный совет по стандартизации метрологии и сертификации. The principle objective of the EASC is to develop common Standardisation, Metrology and Certification in support of trade in the CIS common economic area.

In the more specific area of Metrology, the Euro-Asian Cooperation of National Metrological Institutions (COOMET) [16] comprises 11 of the EASC member countries (excluding Turkmenistan) NMIs but also includes the NMIs of: Bulgaria; Cuba; Germany; DPR of Korea; Lithuania; Romania and Slovakia. The objectives of COOMET are stated as:

- assistance in effective addressing the problems relating to uniformity of measures, uniformity of measurements and the required accuracy of their results;
- assistance in promoting cooperation of national economies and eliminating technical barriers in international trade;
- harmonisation of activities of metrology services of Euro-Asian countries with similar activities in other regions.

One possible future metrological model for the Region is accreditation of calibration facilities by a Regional body, such as EASC, through an MRA between COOMET member states. The obvious link to standards harmonisation of metrological activities out with the Region would seem to be ISO17025 accreditation and participation in ILAC.

7.2 Developing AzMetco Metrological Capability

The metering requirements of BTC pipeline, crossing 3 countries to International markets, introduced a new level of International, as opposed to Regional, measurement compliance, the interpretation being that accepted industry practice required traceability to National standards level.

Several options were considered to develop a 'traceable' prover calibration service in Region. The options were:

1. A master meter / prover rig owned & operated by BP
2. A master meter / prover rig owned by BP, operated by a third party
3. A master meter / prover rig owned and operated by a Regional market place service provider

Economic modelling showed no particular cost advantage to BP by any option, but impartiality and Regional service development requirements was clearly led by Option 3. Having previous Regional experience, Azmetco were awarded a five year single source contract to calibrate BP AzSPU provers, subject to an agreed development plan

It was agreed with Azmetco that they would develop their prover calibration service in three stages:

- purchase measures, with National standards traceable certification
- purchase a new, smaller volume prover
- develop a gravimetric calibration capability

To facilitate the development program, Azmetco were the first local company to receive a loan from the Supplier Finance Facility (SFS). THE SFS is a multi million dollar fund set up BP, co-venturers and the International Finance Corporation, to provide loans to local companies awarded BP contracts.

In 2005 Azmetco purchased 2 Seraphim measures of nominal volumes 500 and 100 litres calibrated by NIST. The cans were used to calibrate their existing 5m^3 volume pipe prover and would be used to calibrate a new small volume pipe prover when it was delivered in Region, eventually in 2007. The gravimetric calibration facility is currently under development in AzMetco Ramana facility.

Water draw of the 5m^3 prover was carried out in July 2005 using the two new measures. The, lengthy, procedure required 5 fills of the 500 litre measure and 4 fills of the 100 litre measure per volume pass. The average deviation in volume between the prover volumes in use and the new water draw calibration volumes was 0.013%, with repeatability, in individual volumes, of 0.022%.

The new, nominal volume 1.1 m^3, pipe prover was built by Daniel-Emerson in Houston and was received by Azmetco in 2007. It was calibrated by water draw against the new measures in Region, prior to use. The results of the small volume prover water draw calibrations, for the last 3 years is shown in Figure 9.

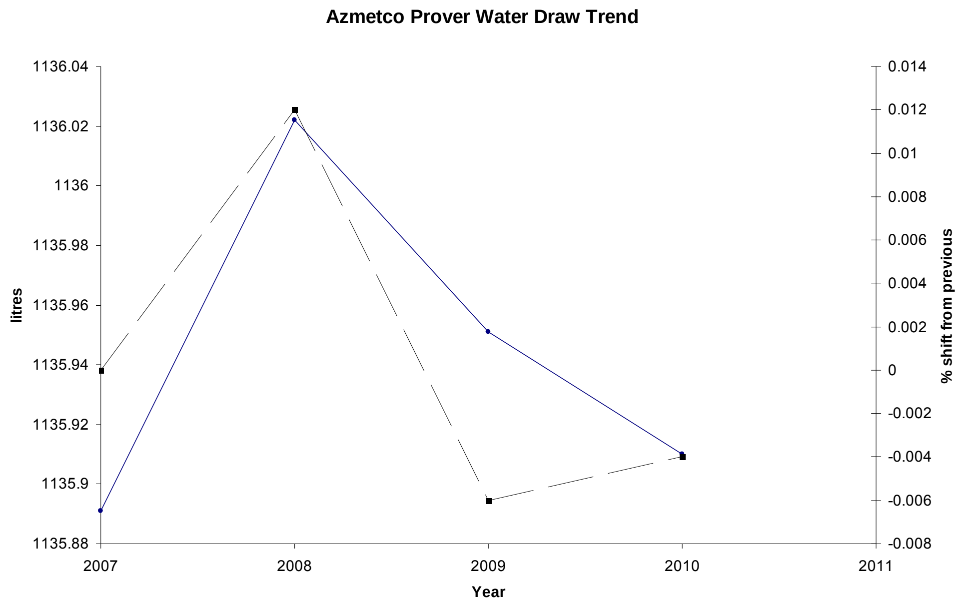

Figure 9 - Azmetco Prover Water Draw Trend

Unfortunately the seraphim measures were not received in Region in time to support calibration of the BTC pipeline PSA1 meter system prover in Sangachal Terminal. A European vendor was mobilised by Project to calibrate the prover in time for first oil operation, in 2005. The PSA1 meter prover was then calibrated by Azmetco in 2008. All four calibrated volumes agreed to within 0.005% of the European Vendor’s 2005 calibration.

The water draw trend and the calibration comparisons of the PSA1 prover, demonstrate exemplary calibration achievement by the Azerbaijani company, Azmetco, and are indicative of the level of skills and expertise they bring to the oil industry in the Black Sea and Caspian Region. Most recently Azmetco have travelled to Turkey to calibrate the prover at the Ceyhan Marine Terminal.

7.3 Recent Metrological Development in Region

At the time of writing there is a joint venture between a European service provider and CIMEX, an Azerbaijani company. The objective is to develop an 'in Region' calibration facility with ISO17025 accreditation for the calibration of General Plant Test Equipment and Fiscal Metering Test Equipment. The Plant Test Equipment is site calibrated to UKAS standards, however the Fiscal Metering Test Equipment is returned to the UK for calibration at an accredited laboratory.

Whilst the set-up of the laboratory may be straightforward, what is not so clear is how accreditation can be awarded given that there are no legal entities in Azerbaijan capable of conferring ISO17025 accreditation

8.0 EQUIPMENT RATIONALISATION

Across the BP operated systems in the SPU, there are:

- Of the 57 installed p.d. meters: 28 no. are 12" of interchangeable cartridge type and 17 no. are 16" of interchangeable cartridge type.
- Flow computers are standardised on OMNI model 600 or model 3000 with an installed base of 80 flow computers
- around 94 ultrasonic meters (usm) with two main types of variants - around 60 Khrone UFM 500 series and 15 Panametrics GF868 series. The remainder include around 10 Controlotron 1010 series clamp on meters.

There is apparent scope for rationalising spares e.g. rather than hold 9 off 16" spare p.d. meter cartridges distributed across 3 sites at a cost of around 100,000 USD per cartridge, could we hold, say, 6 centrally and call them off to site when required?

Similarly, there are 18 flow computer chassis, power supply units and cpu boards held across 7 Assets. To populate these chassis there are around 60 spare plug in boards. With an estimated mtbf of 192,300 hours this might be considered excessive, albeit at relatively low cost at an average of around 700 USD per board [17]. Would a local service provider be willing to hold a defined number of spare pre-configured flow computers and also manage turnaround of failed units?

The usms are installed mainly as fuel loading meters and in leak detection systems (lds). There is some redundancy in the lds the usm applications are largely non-critical. The spare that are held are fuses / cover gaskets / replacement transducers. Rationalisation of this equipment isn't considered to be of great Operational or cost benefit. Currently, the usm strategy is to call out vendor service reps as required. With the exception of the clamp on types, used for booster pump control, no spare meters are held. [18]

With potential equipment rationalisation in mind the following considerations arose:

- BP approached potential 'partners' who might be interested in managing spare holdings i.e. local agents acting as Regional Sales outlets for the Vendors concerned. None of the 'partners' approached indicated particular interest in investing in a spares management service. Without a commitment to hold Regional spares, hence reducing lead time, it is difficult to see what 'added value' this type of service could deliver
- Identical spare parts, in any one Asset, could have different ownerships and so different cost codes for replacement parts with automated re-order levels. Spare parts used for Group A owned systems which were taken from Group B spares holdings could, without

intervention, result in cost allocated against Group B, although ultimately the cost is re-imbursed by the State through SOCAR.
- Cross border movement of spares, between AzSPU Assets, incurs Customs considerations e.g. are the spares permanent or temporary Exports / Imports. These generally incur cost and potentially lengthy border hold ups if not straight refusal to Export the parts.

On balance, rationalisation of equipment is, probably, best achieved on an Asset basis within International borders.

9.0 CONCLUSIONS

9.1 The SPU Management of Measurement Functional Model

The Management of Measurement Infrastructure in BP Azerbaijan has been developed to a high level using a mixture of resources to meet specific, high level guidelines identified in a Metering Strategy.

Many of the steps along the way have been subject to strong challenge, particularly where these may have been at odds with existing local custom and practice. Consideration of these challenges, towards what is considered accepted practice in the European and North American Regions, has required reversion to a ‘first principle’ type rationale to satisfactorily implement development for all concerned. This has been particularly the case in the area of calibration standards and ‘traceability’ to International standards

The strategy functional model based on [2] has proved to be a very useful framework in identifying ‘Ownerships’ across several interfaces within the SPU, and external interfaces with Regional Service providers. Through this we have learned about measurement function expectations from diverse perspectives and have been able, in some cases, to set new expectations.

As a result of this, Regional Service providers have risen to reciprocal challenge and have demonstrated innovation and talent in developing and delivering their services to meet requirements on an International stage.

9.2 The Transferrable Management of Measurement Model

The achievements of the SPU Measurement function have, in many cases been ‘firsts’ at SPU level. This is, possibly, as the SPU structure has not been in use for very long, since around 2005. It is however probably the first time that an attempt has been undertaken to ‘gel’ the many facets of measurement as a ‘function’ from a relatively undeveloped state. This has been driven by the necessity to coordinate the activities of a relatively large measurement Infrastructure, still expanding, in a relatively short time, with little existing infrastructure.

The ISO10012 model has proved to be very flexible, and robust, in describing a measurement process, which can be embedded in a wider business context through appropriate, defined interfaces.

It is a model which could be usefully adopted for development of ‘Greenfield’ Measurement Operations and for ‘formalising’ measurement related processes within mature Organisations.

9.3 Future Work - Demonstrable OMS Compliance

The next phase of work is to consolidate the existing infrastructure and practice to demonstrate compliance with BPs Operating Management System (OMS) [19]. This will involve ‘evolution’ of the existing strategy [3] into a Site Technical Practice, (STP) - about ‘measurement the BP Azerbaijan way’, with particular emphasis on Class 2 meters.

This will be supported by incorporating reference [8]. the Operational Management procedure and by achieving a consensus and adoption of formal kpis

10 ACKNOWLEDGEMENTS

As the reader might imagine this work has been the considerable effort of many people, at various times, over several years. The authors thank BP Azerbaijan for allowing the publication of this story and also those who have participated in workgroup activities and, ergo, followed the strategy.

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