UPM 16010

# Using Measurement Uncertainty in Production Allocation

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## Abstract

The effect of production measurements uncertainties is evaluated on different oil and gas production allocation methods, proportional, by difference, and uncertainty based. The scope is further expanded by examining and proposing an allocation method where measured and allocated quantities uncertainties are considered to achieve fair and equitable production allocation results.

The proposed approach uses data validation and reconciliation (DVR) methodology (governed by establish industry standards) to account for the measurement and fluids properties uncertainties rarely considered in traditional production allocation schemes. The DVR approach has the advantage to balance a complete production system, from subsea to custody transfer point, by estimating the most likely flow quantities available to sales within the known accuracies of the measurement devices and by obeying the physical constraints/laws of the producing network.

The DVR methodology is used for the first time in a multi-tier allocation system. It considers and quantifies measured and unmeasured parameters including their uncertainties in an all-encompassing production allocation scheme. The methodology also allows for measurement error diagnostics that can be integrated in a condition-based measurement maintenance program.

## Introduction

Generally, upstream oil and gas export measurements are made on separated and depressurized bulk oil and gas flow streams collected from a group of wells. In depressurized conditions, where phase separation can be ensured, single phase measurements can be made with the best possible accuracy. These measurements follow measurement standards and recommended practices, such as from the API MPMS, Chapter 20, Section 1.

Wherever export production contains fluids from more than one producer (or unique ownership group, whether it be for one well or several), there must be an equitable distribution of the production export to each and every contributing producer. The allocation process serves to determine in the most fair manner the quantities of oil and gas produced, flared, consumed for fuel, or otherwise spent out of the total export over a given time period for each contributing producer. The allocation process starts at the end of upstream production, from the point of custody transfer to the midstream transporter, and works back upstream to the source of production, the well. In determining each producer’s fair share of the export production, the resulting revenues and costs, such as production handling service fees, royalties and other costs, can be completely resolved.

The allocation process of quantifying the volume or mass of fluids produced from each well applies similarly to non-fiscal activities, such as the management of well performance, process facility operations, and reservoir recovery. While these applications are also important, they generally do not involve the resolution of inter-company financial transactions in accordance with an agreement. The elements of upstream metering and allocation carried out for fiscal allocation often encompass most of the needs for well or fluid allocation; however, the unique measurement requirements of reservoir and production management should be considered separately in order to get a complete set of metering and allocation requirements for all end uses of the flow measurement data.

Finally, if the allocation fully serves its purpose, it should be auditable and defensible.  A good allocation minimizes disputes between partners in a production agreement.

In practice, how is this achieved? Unmixing the mixed streams of hydrocarbons from different wells, zones and fields is not straightforward. It can be downright challenging, and it certainly can be done in different ways leading to different outcomes, which leads back to the possibility of dispute. A good allocation, therefore, is one that is agreeable to all parties involved.

For each producer to get a consistently good, equitable allocation, it requires:

1. a written agreement that defines the objectives and methods of the allocation
2. a metering system that can deliver the required flow and other measurements
3. an auditable, independent execution of the allocation process

As with many physical phenomena, a deterministic approach to defining the outcome of certain pre-established procedures and agreements is not always realistic. Errors and uncertainties in measurements, processes, and models, visible and hidden are also critical to the allocation process requiring attention and understanding by all parties involved, the producers and regulator alike.

The risk of revenue loss by any of the parties, big or small due to ill-defined statistical factors will strongly reflect on the sense of fairness felt by everyone. Such situation can trigger with individuals a sense of unfairness as they learn that the production allocated to their lease is deemed less certain than the one from next door despite the fact that they both use the same equipment to measure production! Can this knowledge be used to mitigate “unfairness” and reduce the exposure faced by producers and regulators in the execution of their duties?

## A word on Uncertainty in Allocation

There are three basic methods employed today for allocation. These are proportional or pro-rata (most popular), by difference (least recommended), and uncertainty based (UBA). Except for the UBA method, allocation schemes rarely incorporate measurements (flow, fluids properties) uncertainties, random or systematic, in the allocation computation algorithms. Uncertainties are either assumed to be similar, therefore producing similar effect on the allocated quantities or are monitored by assessing the magnitude of imbalance factor. Generally corrective actions to minimize imbalances are taken by following stringent proving, and maintenance and calibration procedures to achieve best measurement accuracy, then monitored month to month to ensure that allocation factors remain within agreed margins. The net result is that the true uncertainty of the allocated quantities are rarely evaluated or known which may result in inequitable production allocation.

Measurements and physical parameters always contain some type of error. Two types of errors can be identified in a production and allocation network: random and systematic errors. Random errors (measurement noise), expressed in relative or absolute terms, are usually small errors due to the normal fluctuation of the process or to the random variations inherent in instrument operations. Systematic errors are larger errors due to incorrect calibration or malfunction of the instruments or flowmeters, wrong fluids properties, etc. The systematic errors occur occasionally, that is, their number is small when compared to total number of devices in a production network. Random errors tend to even-out over time while systematic errors persist until corrected. Since they often occur most on one or more streams than the rest of the network, systematic errors are usually hidden, and if not identified, they are feared by traditional allocation methodologies due to the non-equitability they may cause in an allocation scheme. The ability to ‘unhide’ such errors, preferably with minimal intervention, is therefore advantageous in any monitoring and control system covering the entire production path from the subsea well to the sales meter on the exporting facility.

**Figure 1** is a graphical representation of precision (random) and accuracy (systematic) of a measurement. Commonly, precision is defined by the standard deviation of a Normal distribution around the mean of a measurement. In the presence of bias, the standard deviation and the mean are different from the true value and its standard deviation as shown in **Figure 2**.

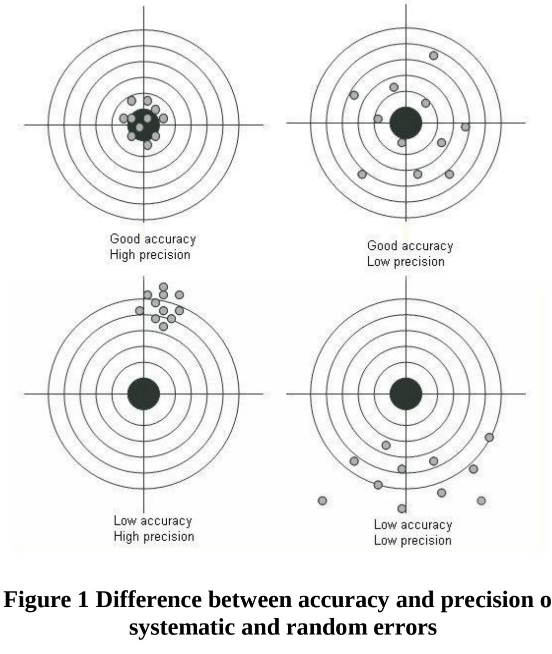


**Figure 1 Difference between accuracy and precision or systematic and random errors**

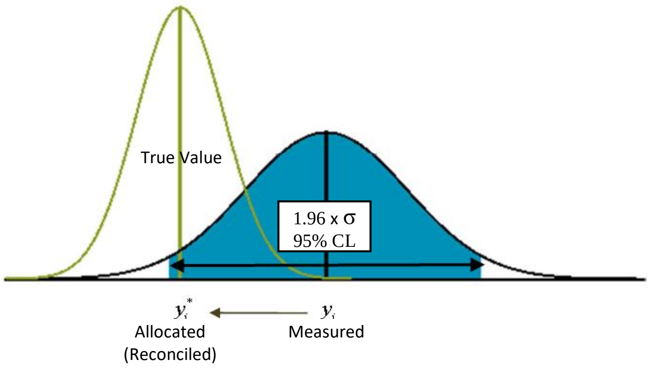


**Figure 2 Illustration of measurement and reconciled values with their uncertainties assuming Gaussian distributions**

Ideally an optimal/equitable allocation is obtained when the allocated quantities are within the 95% confidence level (CL) of the source measurement, i.e. minimal or no bias, close to their true values, i.e. improved accuracy, and have lower uncertainty, i.e. improved precision. To achieve this objective, the allocation method should be capable of using all available information (redundancies) in the production system, simultaneously.

### *Uncertainty Determination*

While incorporating the knowledge about measurement uncertainty seems attractive and beneficial to optimizing allocation equitability, the task of determining uncertainty can be overwhelming requiring in depth understanding of the type of errors and how to identify them and quantify them in a production system. A comprehensive review of this subject is found in [**1**] with proposed techniques to quantify the random errors by use of:

1. Conventional Uncertainty Determination: Measurement of Fluid Flow - Evaluation of Uncertainty (ISO 5168) [**2**]; ISO Guide to Uncertainty in Measurement (GUM) [**3**].
2. Uncertainty determination by flow lab testing.
3. Uncertainty determination by Monte Carlo Simulations [**4**].

In addition to these techniques, it should be possible to determine random uncertainty (standard of deviation) in real-time using on-line histogram analysis over relatively stable periods. **Figure 3** from [**5**] is an example of a case where the standard deviation of separator measurement is shown to be larger than the multiphase flowmeter measurement. This type of information may be used directly in allocation methodologies based on uncertainty or to evaluate the uncertainty of allocated quantities when using proportional allocation.

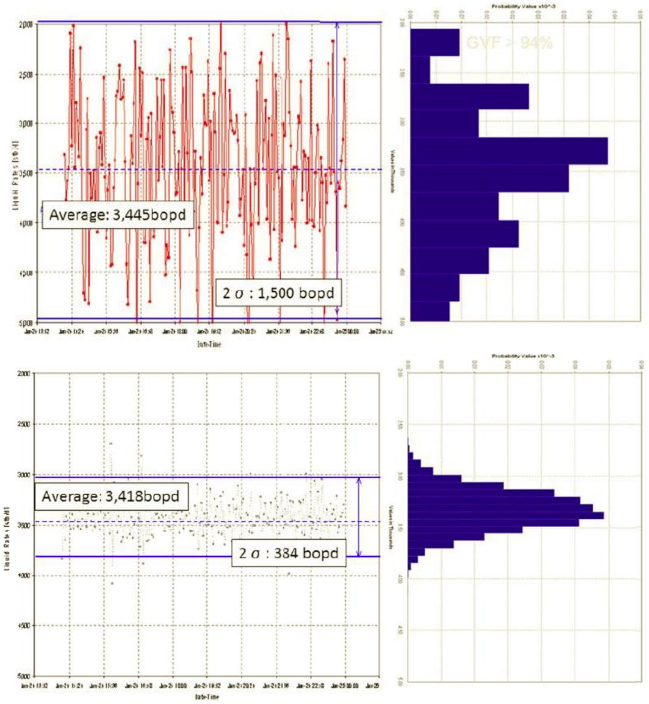


**Figure 3 Histogram plots of separator measurement (top) and MPFM measurement (bottom) [5]**

When systematic errors are present, almost all allocation methodologies require that these errors are first identified and eliminated from the system before commencing the allocation process. This demands constant efforts by operations and others to diligently monitor and calibrate all related instruments and flowmeters and be on the look for process changes responsible for these errors. Such task is not always easy due to the "hidden" nature of these errors. It should also be noted that one key source to systematic errors is due to unexpected changes in fluids properties such as the effect of erroneous fluid density on the flow measurement of a differential pressure device. A simple situation like this would be harder to detect in a subsea commingled production stream where the sampling of individual streams may not be possible.

### **Allocation Methodologies**

There are three basic methods employed today for allocation. These are proportional or pro-rata, by difference, and uncertainty based. The by difference method is recognized for its shortcomings by failing to balance the system because of the missing measurement(s); When allocated by difference, one stream's quantity is subtracted from the sales quantity to arrive at the other streams' available quantities. By difference is used in some instances, but is not generally recommended. This method erroneously forces a perfect balance, imposing all imbalances, errors, and uncertainties to one stream.

The proportional and uncertainty-based allocation methods are discussed here in more details along with the Data Validation and Reconciliation (DVR) method. DVR brings the mathematical rigor to allocation and serves as a way to extend the use of uncertainty to multi-tier allocation schemes.

### *Proportional Allocation (PA)*

The proportional basis will allocate any overage or underage to each stream in accordance with the stream's production share. It is considered the 'simplest' and most intuitive allocation method and suitable for straight forward application to single or multi-tier allocation schemes.

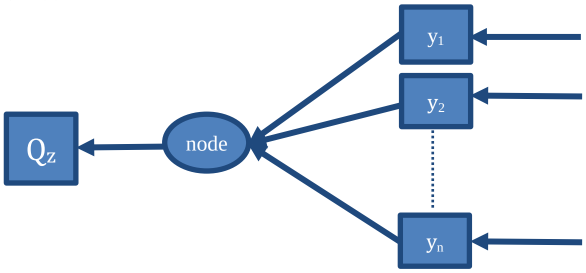


**Figure 4 Single tier allocation system with n inputs**

The proportional allocation formula can be expressed as follows

$$Q_i = \frac{y_i}{\sum_{j=1}^{n} y_j} \cdot Q_z \qquad (1)$$

Where $Q_z$ is the measured sales, $y_i$ is the measured quantity of individual input streams, and $Q_i$ is the corresponding allocated quantity.

Measurement or process uncertainties are rarely considered in PA. More particularly, even when the uncertainty of the input streams are quantified (random), the allocated quantities uncertainties are not evaluated or used in estimating their impact on back allocation, namely when there is important differences among the input streams' quantities. Having the same relative uncertainty for all input streams does not necessarily result in same relative uncertainty being assigned to the allocated quantities. The smaller stream tends to absorb most of the uncertainty in the system (in relative terms). The only case when the uncertainties are evenly allocated in absolute terms is when the input 'absolute' uncertainties are the same. However, it is customary to use relative (percentage of quantity) instead of absolute uncertainties which often results in widely varying uncertainties of the allocated quantities even if the input streams uncertainties are similar.

It is therefore inaccurate to state that the uncertainty is distributed more evenly among the streams when PA is used. However, It can be shown that, if the measurement errors are stochastically independent from one another and have zero mean (i.e., the measurement errors are unbiased), then the result will even-out overtime.

In the case of bias or systematic errors, a permanent imbalance will be created in the system which can only be eliminated with the removal of the source causing the error. In the presence of such error, assuming that one of the streams has a biased reading, the error will be distributed "rather unfairly" to all the streams in proportion to their individual throughputs. Other scenarios involving multiple biases that either add-up or offset each other will add more complexity and unfairness to the allocation process.

The PA method is particularly adaptable to multiple tier allocation schemes where allocated quantities can further be allocated upstream to wells. A typical two-tier allocation is where sales is allocated to each of the production trains on a host facility, and then further allocated to the producing wells (direct access or subsea). The method can be further extended to more tiers if required because of differences in royalty or working interest ownerships. Needless to mention that performing multiple-tier allocation requires that all streams at different states (P,T) be normalized to a common state usually chosen to be the sales meter conditions.

Like with UBA, the evaluation of the uncertainties of allocated quantities requires the knowledge of the uncertainty at each node in order to perform the uncertainty evaluation from sales to the individual wells. This evaluation is discussed in the section on "Uncertainty Formulation".

### *Uncertainty-Based Allocation (UBA)*

Uncertainty based allocations are used in situations where the uncertainties of the individual stream measurement systems are not similar or their measurement uncertainty changes regularly. UBA uses the random uncertainty of each measurement as a weight factor in allocating imbalance. The correction is applied in proportion to the measurement variances (square of the absolute uncertainty) – the more accurate is the measurement, the less is the applied correction.

The uncertainty based allocation formula derived in API Recommended Practice 85 [**6**] for the single tier system of **Figure 4** is expressed as follows:

$$I = Q_z - \sum_{j=1}^{n} y_j \tag{2}$$

$$\alpha_i = \frac{\sigma_i^2}{\sigma_z^2 + \sum_{j=1}^{n} \sigma_j^2} + \frac{y_i}{\sum_{j=1}^{n} y_j} \cdot \frac{\sigma_z^2}{\sigma_z^2 + \sum_{j=1}^{n} \sigma_j^2} \tag{3}$$

$$Q_i = y_i + \alpha_i \, . I \tag{4}$$

Where $\alpha_i$ is the fraction applied to the imbalance $I$ for stream $y_i$ in order to calculate the allocated quantity $Q_i$, and $\sigma_i^2$ and $\sigma_z^2$ are the variances of the streams measurements and the sales measurement respectively.

In contrast with PA allocation methodology, the above formulation requires more work to apply to multi-tiered allocation schemes. Intuitively, the uncertainty of each of the $Q_i$ terms should be evaluated first in order to be used at next level in a sequential allocation. The evaluation of the uncertainty of allocated quantities $Q_i$ is discussed in the section on PA and UBA “Uncertainty Formulation”. However it should be noted that the sequential application of the Least Mean Square optimization (LMS) approach originally used to derive the UBA formulation may not be valid for multi-tiered systems. Rather, LMS will have to be applied to the entire system at once to be mathematically correct.

To address this concern, the two approaches will be examined in the section where a comparative example is discussed in details.

### Uncertainty Formulation

This section is common to PA and UBA with the aim to evaluate the uncertainty (random) of the ALLOCATED quantities. As shown before, it is not enough to know the uncertainty of the inlet streams for an allocation scheme to be considered equitable. Equitability is also gauged by the uncertainties of the allocated quantities.

Except for the case of By Difference Allocation method where one or more flowrate measurements are missing, all other allocation methods use the added redundancy from the system balance to improve the precision of allocated quantities. The improvement also depends on the constraint formulation that characterizes each of the allocation methods.

It was shown that in the particular case of UBA, it is necessary to know the uncertainty of the allocated quantities at one level in order to proceed with the allocation of the nodes upstream assuming that the sequential process is valid.

Performing this calculation provides additional information about the magnitude of the uncertainty associated with each of the allocated quantities as these are closely impacted by the relative size of each of the incoming streams. The impact of the size of streams on the uncertainty is discussed in [**7**] and [**8**]. An important conclusion from this evaluation is that the smaller size stream tends to absorb most of the system uncertainty in relative terms even if its measurement is more precise than the larger stream measurement.

For a given node it can be shown [**2**] that for independent measurements, the uncertainty of an allocated quantity is function of the combined uncertainty of the measurements of other streams as well as the uncertainty of the reference meter.

$$U_{Q_i}^2 = (\frac{\partial Q_i}{\partial y_1})^2 U_{y_1}^2 + \cdots + (\frac{\partial Q_i}{\partial y_n})^2 U_{y_n}^2 + (\frac{\partial Q_i}{\partial Q_z})^2 U_{Q_z}^2 \tag{5}$$

Where $U^2$ denotes the measurement variance.

By applying **Eq.5** to the simple PA of two branch node where the allocated quantities are defined as:

$$Q_1 = \frac{y_1}{y_1+y_2} Q_z \quad \text{and} \quad Q_2 = \frac{y_2}{y_1+y_2} Q_z \tag{6}$$

the allocated quantities variances can be shown as:

$$U_{Q_1}^2 = \frac{y_1^2}{(y_1+y_2)^2} \cdot U_{Q_z}^2 + \frac{Q_z^2}{(y_1+y_2)^4} \left[ y_2^2 \cdot U_{y_1}^2 + y_1^2 \cdot U_{y_2}^2 \right] \tag{7}$$

$$U_{Q_2}^2 = \frac{y_2^2}{(y_1+y_2)^2} \cdot U_{Q_z}^2 + \frac{Q_z^2}{(y_1+y_2)^4} \left[ y_1^2 \cdot U_{y_2}^2 + y_2^2 \cdot U_{y_1}^2 \right] \tag{8}$$

It is clear that the above analytical approach will not be practical to evaluate for more complex systems. Luckily a numerical alternative can be used instead by applying small perturbations to **Eq.5** Ref.[**2**] to calculate the partial derivative (sensitivity) terms. Such approach is relatively easy to implement numerically and can be expanded to any number of tiers and branches.

The same approach can also be applied to UBA’s **Eq.4** where a similar rate proportionality term is present in the fraction term $\alpha_i$.

The numerical method was implemented in a multi-tiered allocation tool to evaluate the uncertainties of the allocated quantities from the PA and UBA methods. The results were validated against the analytical solutions with very good agreement. The calculated uncertainties where used subsequently to study the results obtained from the three allocation methods in a two-tiered comparative example.

## Proportional versus Uncertainty Based Allocation. What is next?

Before introducing DVR-based allocation methodology, it is worth mentioning at this point that comparative studies [**1**][**7**] (including field example from North Sea [**8**]) were made between PA and UBA methodologies. The studies examined the differences between the methods by varying the relative input quantities to show the dependency of allocated quantities and their uncertainties on this parameter. The differences in relative uncertainties were also examined in the field example of [**8**]. However both evaluations were limited to a single tier allocation scheme.

In all cases, the analysis demonstrated the robustness and superior accuracy of the UBA method. By accounting for flow measurement uncertainty, UBA assigns the imbalance observed at the sales meter to the stream with higher uncertainty, therefore honoring the measurement reported by the stream with more accurate measurement.

The improved equitability of UBA is evident provided no biased measurements are present in the system. This requirement applies to all allocation methods. To overcome this challenge, a truly equitable allocation methodology will have to:

1. Detect and unveil important biases in the system as part of the measurement validation and allocation procedure.
2. Tolerate the presence of some bias in the system and account for it until corrective actions are taken.
3. Adapt to the system's tiering requirements without compromising rigor.
4. Account for all available information in order to ensure consistency across the entire system.

## Data Validation and Reconciliation

### *Background [9]*

Industrial process data validation and reconciliation, (DVR), is a technology that uses process information and mathematical methods in order to automatically correct measurements in industrial processes. The use of DVR allows for extracting accurate and reliable information about the state of industry processes from raw measurement data and produces a single consistent set of data representing the most likely process operation.

DVR has become more and more important due to industrial processes that are becoming more and more complex with applications aiming at closing material balances in production processes where raw measurements were available for all variables. At the same time the problem of gross error identification and elimination has been addressed. Later, unmeasured variables were taken into account and the process matured by considering general nonlinear equation systems coming from thermodynamic models. Quasi steady state dynamics for filtering and simultaneous parameter estimation over time were introduced by Stanley and Mah.[**10**] Dynamic DVR was formulated as a nonlinear optimization problem by Liebman et al. in 1992.[**11**]

Data reconciliation is a technique that aims at correcting measurement errors that are due to measurement noise, i.e. random errors. From a statistical point of view the main assumption is that no systematic errors exist in the set of measurements, since they may bias the reconciliation results and reduce the robustness of the reconciliation. However, systematic errors will be flagged if they are the cause for measurements excessive deviation from the "expected" values that best balance the system

DVR finds application mainly in industry sectors where either measurements are not accurate or even non-existing, like for example in the upstream sector where flow meters are difficult or expensive to position; or where accurate data is of high importance, for example for security reasons in nuclear power plants. Another field of application is performance and process monitoring in oil refining or in the chemical industry.

As DVR enables to calculate estimates even for unmeasured variables in a reliable way, the German Engineering Society (VDI Gesellschaft Energie und Umwelt) has accepted the technology of DVR as a means to replace expensive sensors in the nuclear power industry (VDI norm 2048) [**12**].

### *DVR Basic Theory*

Given n measurements $y_i$, data reconciliation can mathematically be expressed as an optimization problem of the following form:

$$\min \sum_{i=1}^{n} \left(\frac{y_i^* - y_i}{\sigma_i}\right)^2 \tag{9}$$

Subject to $F(x, y) = 0$

where $y_i^*$ is the reconciled (allocated) value of measurement $y_i$, and $x_j$ is the unmeasured variable $((j = 1\ to\ m)$.

$\sigma_i$ is the absolute uncertainty (standard deviation) of measurement $y_i$ and $F(x, y) = 0$ are the $r$ process equality constraints.

The term $\left(\frac{y_i^* - y_i}{\sigma_i}\right)^2$ is called the penalty of measurement $i$. The objective function is the sum of the penalties.

In other words, one wants to minimize the overall correction (measured in the least squares term) that is needed in order to satisfy the system constraints (ex. mass, energy balances at each node). Additionally, each least squares term is weighted by the standard deviation of the corresponding measurement.

Data reconciliation relies strongly on the concept of redundancy to correct the measurements as little as possible in order to satisfy the process constraints. Redundancy arises from combining sensor data with the model (algebraic constraints such as mass balance).

Redundancy can be used as a source of information to cross-check and correct the measurements $y_i$and increase their accuracy and precision. Further, the data reconciliation problem also includes unmeasured variables $x_j$. Based on information redundancy, estimates for these unmeasured variables (ex. missing flow measurement) can be calculated along with their accuracies. In industrial processes these unmeasured variables that data reconciliation provides are referred to as soft sensors or virtual sensors, where hardware sensors are not installed.

An important feature of DVR is results validation and gross error detection. Result validation may include statistical tests to validate the reliability of the reconciled values, by checking whether gross errors exist in the set of measured values. These tests can be for example:

1. The Global test of the entire system requiring that the summed penalties for a given number of constraints $r$ should be less than the criteria defined in VDI norm 2048 [**12**].
2. The Individual test compares each penalty term in the objective function with the critical values of the normal distribution. If the $i$-th penalty term is outside the 95% confidence interval of the normal distribution, then there is reason to believe that this measurement has a gross error as illustrated in **Figure 1**.

Advanced data validation and reconciliation is an integrated approach of combining data reconciliation and data validation techniques, which is characterized by:

1. Complex models incorporating besides mass balances also thermodynamics, momentum balances, equilibria constraints etc. This is particularly applicable to complex allocation schemes where a Process Simulation Model (PSM) is used to account for mass transfer between phases in a commingled stream.
2. Gross error remediation techniques to ensure meaningfulness of the reconciled values in the presence of moderate biases.
3. Robust algorithms for solving the reconciliation problem.

### DVR-based Allocation

In production allocation, the DVR approach differs from traditional methods by fully accounting for the system uncertainties associated with measurement devices, process parameters or fluids properties, and by allowing system redundancy to improve the accuracy and precision of the allocated quantities. This ensures that the allocated quantities are estimated in accordance with the physical principles/laws and constraints of the producing system. The approach is therefore more equitable where the allocated quantities are qualified by their degree of agreement with the original measurements (or lack thereof) in the form of global and individual penalties that can be monitored and quantified.

In production allocation schemes, where the balancing of multiple nodes may be required along the production path from subsea to sales, the minimization of **Eq.9** results in a series of equations that are solved simultaneously for the entire system (including redundancies) to determine the adjustments vector . The adjustment is then added to the measurements vector $\boldsymbol{y}$ in order to calculate the reconciled/allocated values $\boldsymbol{y}^*$:

$$\boldsymbol{y}^{*} = \boldsymbol{y} + \boldsymbol{v} \tag{10}$$

In the majority of allocation cases involving straightforward mass or energy balances, the calculation is reduced to linear algebraic matrix operations solvable using spread sheets embedded functionalities. Such algorithm was incorporated in an allocation tool to perform this type of calculations.

On the other hand, more elaborate allocation schemes involving phase equilibrium calculations (PSM) will require the use of DVR software with built-in thermodynamics package to allow for the simultaneous solving of system's equations. Such software will have to be auditable and compliant with normative standards such as VDI norm 2048 [**12**].

In solving the algebraic equations leading to **Eq.10**, it is generally assumed that the measurements used in the calculations are statically independent, i.e. represented by a diagonal covariance matrix. While this may be true for the measurements it does not mean that the nodes' expressions for a multi-tiered allocation system are independent. In fact nodes in this configuration are inherently linked by one or more measurements that are common to more than one node. The only way to account for this dependency across successive allocation nodes is to simultaneously solve all equations at once.

The above condition is illustrated in **Figure 5**

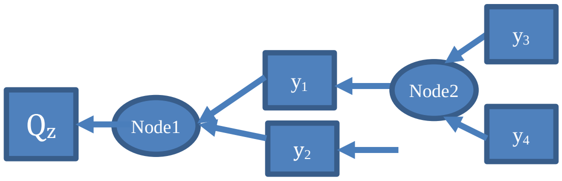


**Figure 5 Example of two-tier allocation system**

The balance of nodes 1 and 2 is defined by the expressions in **Eqs.11** and **12** where measurement $y_1$ is common to both expressions. Such dependency will result in a non-diagonal covariance matrix for the nodes expressions.

$$Q_z - y_1 - y_2 = 0 \tag{11}$$

$$y_1 - y_3 - y_4 = 0 \tag{12}$$

Due to the above dependency it would be intuitive to conclude that sequential allocation calculation procedures (if used with UBA) will yield different results than those obtained from DVR. A sequential treatment lacks the mathematical rigor by ignoring such dependency and should not be used with UBA as will be discussed in the following section.

### *UBA and DVR Based Allocation*

The adaptation of the DVR methodology to the production allocation problem is not new. In fact UBA was derived using the same optimization approach [**12**], albeit with the constraint that the allocation system consisted of <u>one node only (i.e. one constraint)</u>. The other minor difference between the two approaches is related to UBA's treatment of the reference measurement. That is $Q_z$ (the sales meter with very small uncertainty) is considered constant, i.e. cannot be adjusted within the bounds of the uncertainty assigned to it. While this has minimal effect on the allocation quantities of a single tier allocation, the effect on other upstream nodes in multi-tiered allocation systems can be significant. This limits UBA's flexibility and ability to deal with more complex allocation schemes.

The following example (**Figure 6** and **Figure 7**) of a <u>single node allocation</u> shows the match between the two allocation methods; the allocated quantities and their uncertainties are almost identical, however a slight adjustment is made to the reference measurement in the case of DVR but not allowed by UBA.

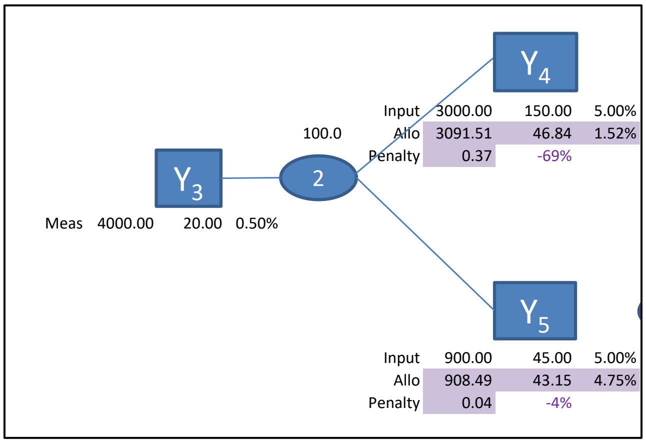


**Figure 6 Single tier allocation system - UBA results**

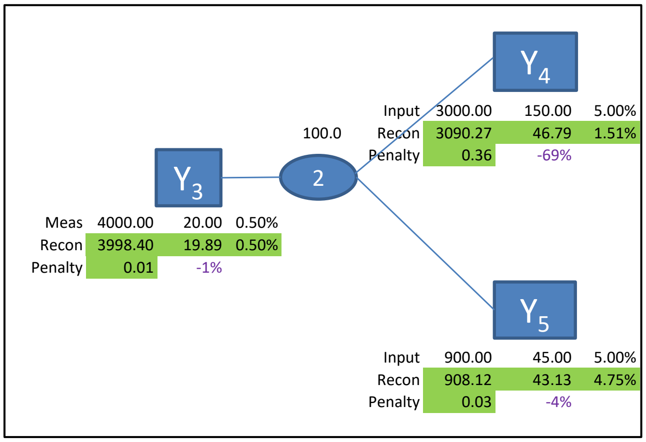


**Figure 7 Single tier allocation system - DVR results**

The example consists of two inlet streams (y4 3000 and y5 900) feeding in node 2 with similar relative uncertainties of 5% each. The outlet of node 2 is measured by y3, a reference meter having a relative uncertainty of 0.5%. The colored cells show the resulting allocated/reconciled quantities and their absolute and relative uncertainties. The penalty term described above is also shown.

In examining **Figure 6** and **Figure 7** one cannot but notice that the relative uncertainties of the allocated quantities are not equal anymore. Their dependency on the flow rates is obvious. Moreover, it is worth noting that the reference quantity that would be used upstream y5 in a two tier allocation scenario will have to carry 4.75% relative uncertainty, much higher than the 0.5% uncertainty of y3. Can we expect the two methods to continue to perform the same way in a multi-tiered allocation scheme?

## Comparative Evaluation

In order to clarify the questions and observations made in the previous sections, the three methods (PA, UBA, and DVR) were used in a comparative example consisting of two-tier allocation system as shown in **Figure 8**.

The example consists of:

1. First level allocation from the sales point (Y3) to two separation trains (Y4 and Y5) with 5% separator measurement uncertainty.
2. The second level allocates the allocated quantities of each train to two MPFMs with 7% flowrate measurement uncertainty.

The measured flowrates are chosen in the ratio of 3:1 for node 2, 2:1 for node 3, 1:1 for node 4. All theoretical flowrates are assumed at the conditions of the reference meter (Y3).

The evaluation consists of performing allocation scenarios to:

1. Examine the results obtained from each methodology; how they compare to each other in a relatively well balanced system with allocation factors of 97.5%, 96.7%, 104.4% for nodes 2, 3, and 4 respectively.
2. Compare their ability to detect and identify the source of systematic errors in a multi-tiered allocation system.
3. Assess and compare the impact of bias on allocation results (i.e. results sensitivity to bias).
4. Compare the allocated quantities uncertainties.

### *Allocation Base Case*

The allocation results of the base case from the three methods are shown in **Figure 8**. The bar chart shows the relative difference between the allocated quantities and their corresponding measurements. As expected, the relative deviation resulting from PA allocation method is the same for all inlet streams at each node.

UBA's relative changes are mostly driven by the square of the inlet stream ratios because their relative uncertainties are the same.

DVR and UBA results have similar trends except for the allocated quantities at the 2nd separation train (Y5). Differences between the two methods were to be expected in this multi-tier allocation scheme; like with PA sequential allocation, UBA allocation was successively applied to node 2 then to nodes 3 and 4. This contrasts with the simultaneous estimation of all streams adjustments performed by the DVR method.

The above comparison is in fact meaningless considering that UBA in its current configuration cannot be applied to multiple-tier allocation schemes. The alternative is to use the more rigorous DVR treatment to account for measurements uncertainties in allocation.

### *Bias Detection*

The individual penalty term of **Eq.9** is used with DVR to detect gross errors. The same parameter was also calculated for PA and UBA allocated quantities as a quasi-penalty term.

Generally, the penalty term is deemed significant when it approaches or exceeds 3.84 ($1.96^2$). This is when the allocated/reconciled quantity defers from the measurement's mean value by 2 or more standards of deviation (95% CL) (see **Figure 1**).

To highlight the penalty term in Figures 8 to 11, the values were bracketed and displayed in an outlined box when above 1 (i.e. difference is bigger than one standard deviation) and on a colored background when the value is above 2 (red for the penalty and orange for the quasi-penalty terms). While the instant penalty values are of interest, the trending of this parameter is more meaningful for measurement error detection.

Systematic errors were introduced to the base case at Y4 (**Figure 9**), Y5 (**Figure 10**), and Y5&Y6 (**Figure 11**). The errors locations are shown in red circles.

By examining the above figures it becomes clear that the use of a quasi-penalty term for PA and UBA methods yields erratic and inconsistent indications of the presence and location of bias. Conversely, the DVR method detects and locates errors of significance as shown by the increase of penalty value where bias was introduced to the measurement system.

For example, it can be shown from **Figure 10** that only DVR was able to confirm the error at separation train 2 (Y5) due to significant penalty increase (above 2) at this location. This contrasts with other methods inconsistent projections as they pointed to errors in MPFM meters at different locations where no errors were present. The same conclusions can also be derived from **Figure 11**.

### *Impact of Bias on Allocation Outcome*

The bar charts of the same figures (8 to 11) show the relative change of allocation quantities resulting from the bias added to the base case.

The superior error handling by DVR compared to PA and UBA is quite visible; all methods are affected by bias but DVR is the least sensitive with results maintained closer to the base case. This is seen from the smaller deviations (50% or less) compared to the performance of other methods.

### *Improvement of Allocation Uncertainties*

A common result obtained from all allocation methods is the uncertainty reduction (improved precision) of the allocated/reconciled quantities. The added redundancy imposed by the system balancing at various nodes is the reason for such improvement.

However, while this is shown to be true for DVR and UBA in all studied cases and for all measurements, the behavior of PA is exceptionally different for measurement Y6, Y5, and Y8. **Figure 12** shows bar charts representing the relative change of the allocated absolute uncertainties from the original measurements uncertainties. The introduction of bias as outlined before seems to have little effect on the magnitude of uncertainty improvement.

Once more, the DVR approach outperforms other methods in improving the precision of the allocated/reconciled quantities.

## Conclusions and Recommendations

1. Using measurement uncertainty in allocation is appropriate even if it calls for more effort to identify and quantify the sources of uncertainty. It should be recognized that there is almost always variations in meters uncertainties within an allocation system. Ignoring it by continuing to use proportional allocation does not make the problem go away. The problem is further amplified in multi-tiered allocation situations where the uncertainties of allocated quantities, often ignored, are propagated upstream the system even when proportional allocation is used. Ignoring uncertainty is not any different than knowingly performing allocation using a dysfunctional measurement system. In both cases there will be errors that will result in inaccurate or inequitable allocation.

2. Measurement uncertainty is either random or systematic. Although random uncertainty impact on allocation may be more forgiving, both uncertainties should be considered together for allocation to be truly equitable. Systematic errors are best dealt with by diligently calibrating and maintaining meters, however this may not eliminate them because the errors could be hidden or building gradually from other sources than just the flowmeters, namely fluids properties and flow regime changes.

3. The determination of single, combined or propagated uncertainties should be required and agreed on in ALL allocation schemes. It should not be limited to UBA where uncertainty is required to perform the calculations, but also to proportional allocation where the uncertainty of the allocated quantities can be significantly different from the measurements uncertainties.

4. PA can be applied to multi-tiered systems but UBA in its current configuration is limited to single level allocation schemes. The study confirmed that mis-allocation may occur if UBA methodology is extended to upstream nodes in a multi-level allocation scheme such as from sales to separators then to wells. In its uncertainty treatment, UBA ignores the dependency between the successive nodes due to shared streams.

5. Data Validation and Reconciliation (DVR) allocation methodology is introduced as a potential alternative to UBA for multi-tiered

allocation schemes. The study concluded that both techniques provide identical results for single tier cases but can be quite different when applied to more complex allocation schemes. DVR methodology is well recognized and governed by normative industry standards.

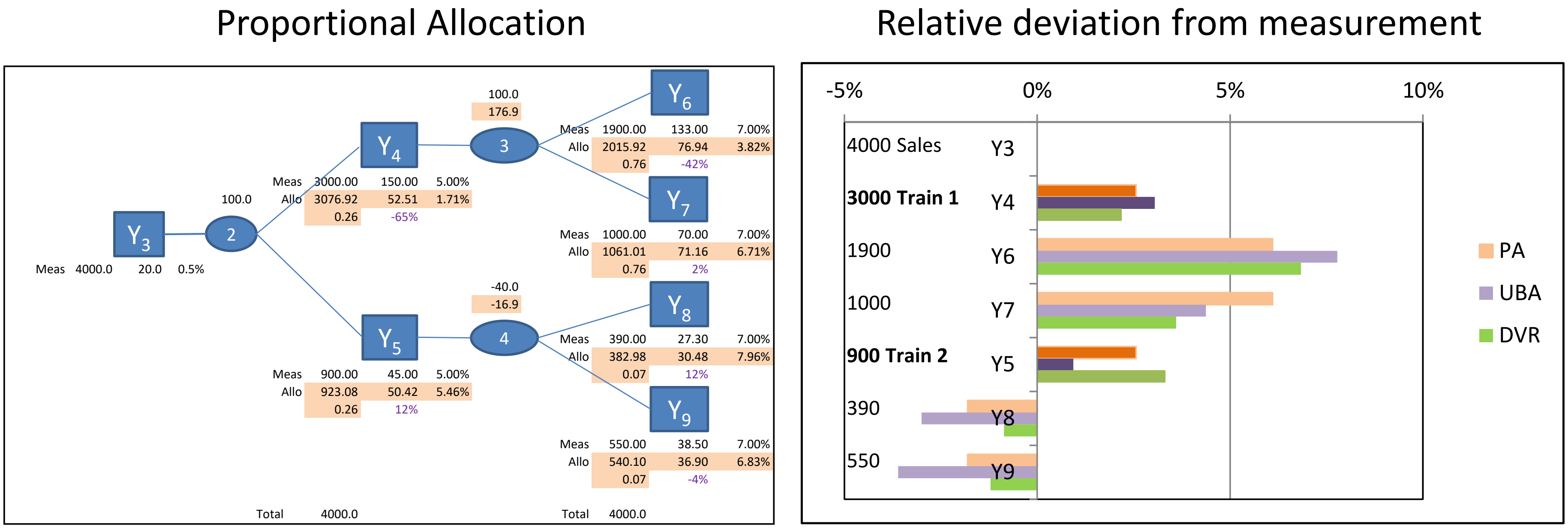
6. The comparative study using PA, UBA, and DVR approaches in a multi-tiered allocation scheme led to the following conclusions:
    a. Bias detection: Using a measurement penalty parameter as indicator, DVR had the clear advantage of being consistent in isolating gross measurement errors in a measurement network. Other methods showed more erratic behavior by exhibiting high measurement penalty at error-free locations and vice versa.
    b. Resilience to bias: The study indicated that UBA and DVR results trends were similar but DVR had the advantage of not being as affected by bias as UBA and PA. DVR's deviation from the base case after the introduction of bias was less than 50% of the deviation observed from PA and UBA allocation results.
    c. Reduced allocation uncertainty: The uncertainties of UBA and DVR allocated quantities are consistently lower than the initial measurement uncertainty with a slight advantage observed from the DVR results. On the other hand, PA exhibited increased allocation uncertainty in some cases.

7. Simplicity is a virtue, but not in production allocation if it leads to mis-allocations. The extra effort devoted to the identification and evaluation of system measurement uncertainties should be recognized and embraced by the industry and regulators as an essential step to equitable production allocation practices.

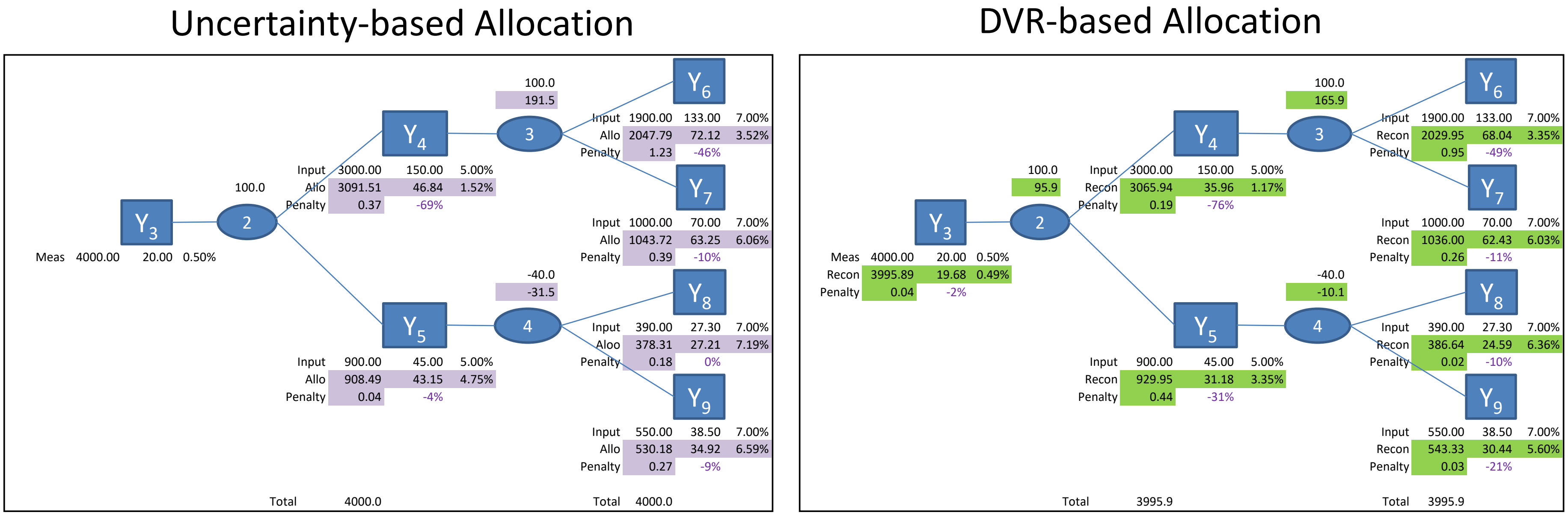
    While the PA approach has long been considered as the methodology of choice because of its plain arithmetic, it is time to adopt other approaches, as equally traceable and auditable as PA, despite their apparent complexity because of their superior performance and more equitable outcome. It is therefore recommended to move away from the PA approach by recognizing UBA as the truly equitable allocation method for single tiered systems. In extended schemes with multiple allocation levels, DVR is the only viable and all-encompassing technique worthy of consideration to ensure rigor and equitability.

## References

1. WEBB, R.A., LETTON, W., AND M. BASIL, Determination of Measurement Uncertainty for the Purpose of Wet Gas Hydrocarbon Allocation, 20th North Sea Flow Measurement Workshop, St. Andrew's, Scotland, October 2002.
2. ISO 5168 Measurement of fluid flow — Procedures for the evaluation of uncertainties
3. ISO/IEC Guide 98-3:2008, Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)
4. ISO/IEC Guide 98-3:2008/Suppl.1:2008, Propagation of distributions using a Monte Carlo method
5. Pinguet, B., Vethe, E., Smith, M., Smith, G., Sbordone, A., Nighswander, J., Reducing Uncertainty from PVT by Representative Sampling System, OTC-23340, Offshore Technology Conference, 30 Apr-3 May 2012, Houston, Texas.
6. AMERICAN PETROLEUM INSTITUTE (API), Use of Subsea Wet-Gas Flowmeters in Allocation Measurement Systems, Recommended Practice RP 85.
7. WEBB, R.A. and LETTON, W., A Second Look at Uncertainty Based Allocation (UBA), Production and Upstream Flow Measurement Workshop, Houston, Texas, February, 2008.
8. P. STOCKTON, Experience of the Use of Uncertainty Based Allocation in a North Sea Offshore Oil Allocation System, Production and Upstream Flow Measurement Workshop, Houston, Texas, February, 2008.
9. Data validation and reconciliation - Wikipedia
10. R.S.H. Mah, G.M. Stanley, D.W. Downing, Reconciliation and Rectification of Process Flow and Inventory Data, Ind. & Eng. Chem. Proc. Des. Dev. 15: 175–183, 1976.
11. M.J. Liebman, T.F. Edgar, L.S. Lasdon, Efficient Data Reconciliation and Estimation for Dynamic Processes Using Nonlinear Programming Techniques, Computers Chem. Eng. 16: 963–986, 1992.
12. VDI 2048 Measurement Uncertainties of Acceptance Measurements on Energy-conversion and Power Plants Basic Principles, 2000.


Proportional Allocation

Relative deviation from measurement


Uncertainty-based Allocation

DVR-based Allocation

**Figure 8: Comparative analysis - Base case. Bar chart shows the relative percentage difference between the allocated and measured quantities**

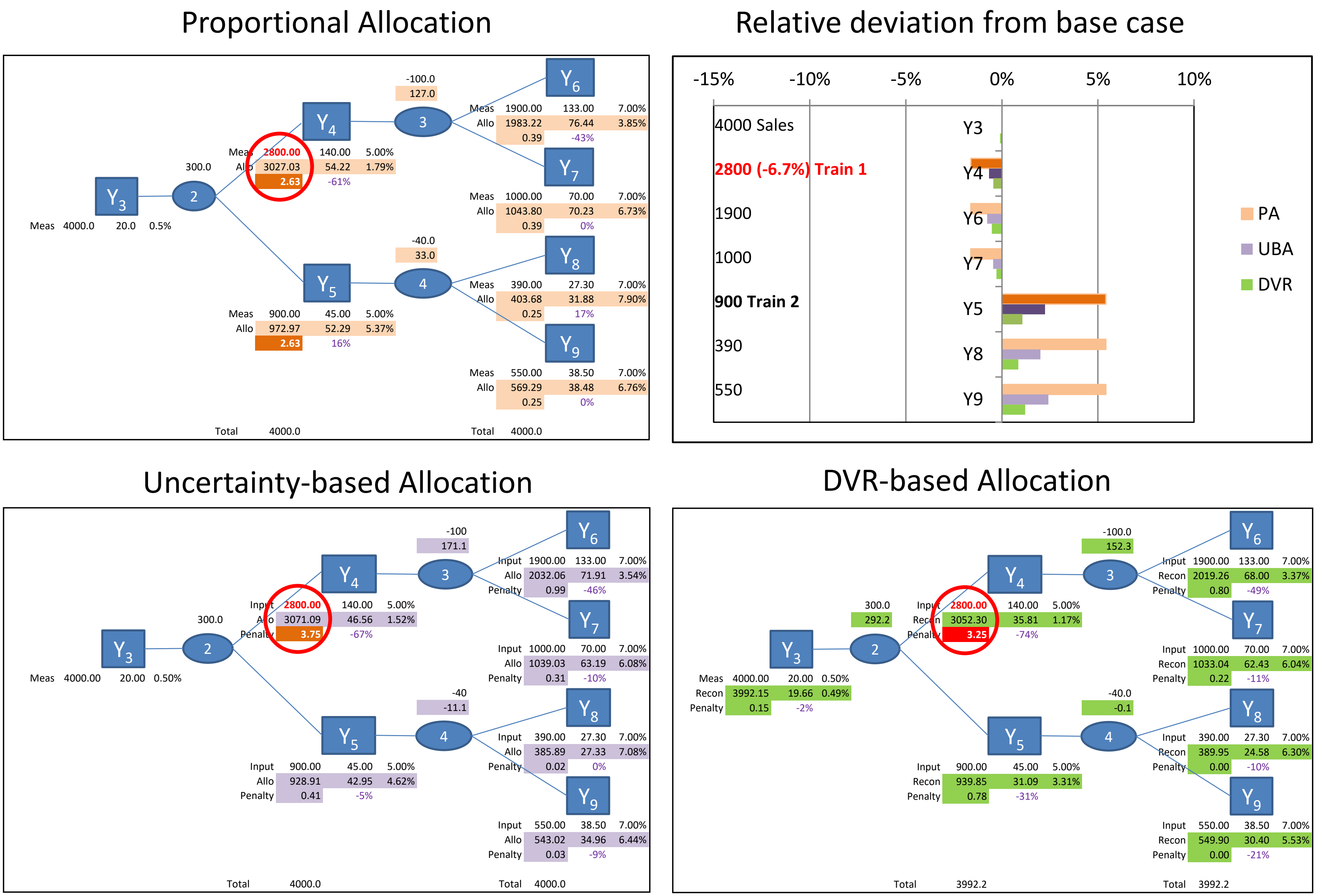
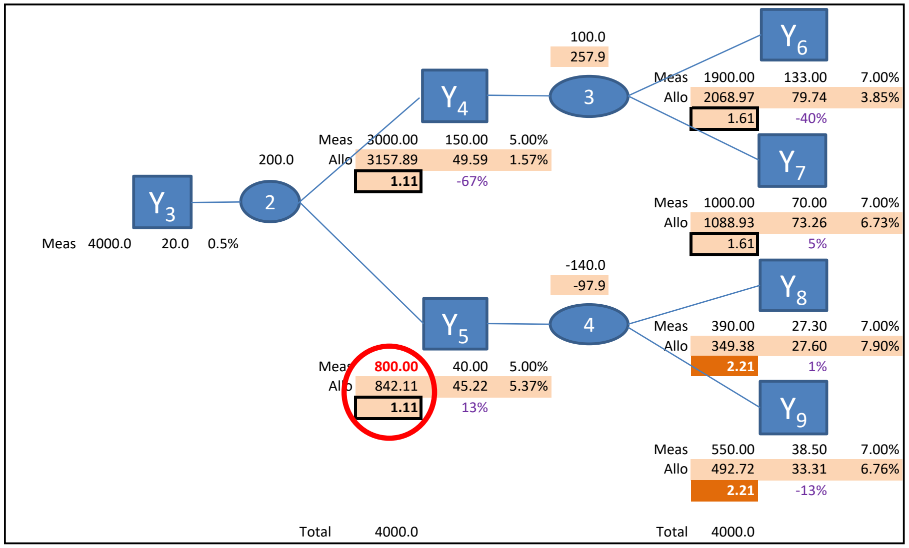
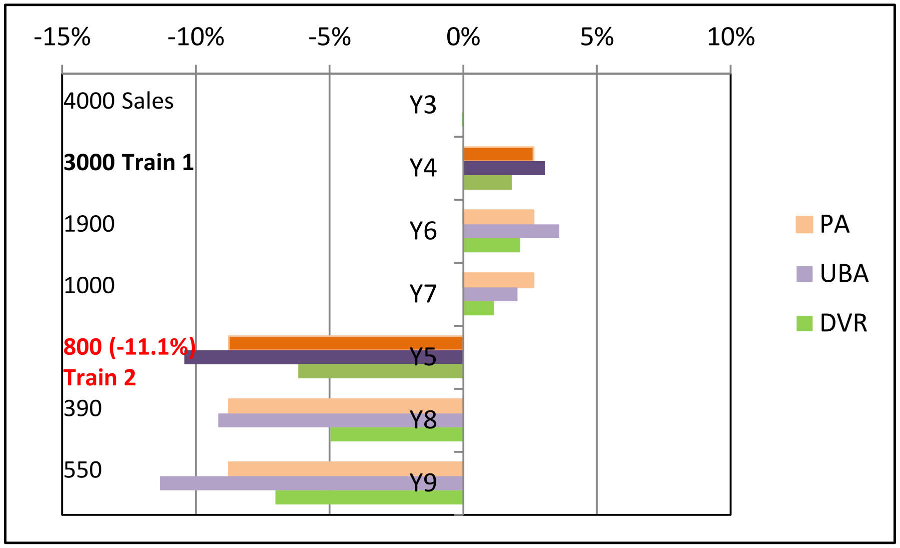


**Figure 9: Comparative analysis - Base case with bias at Y4. Bar chart shows the relative percentage difference between this case and base case allocated quantities**

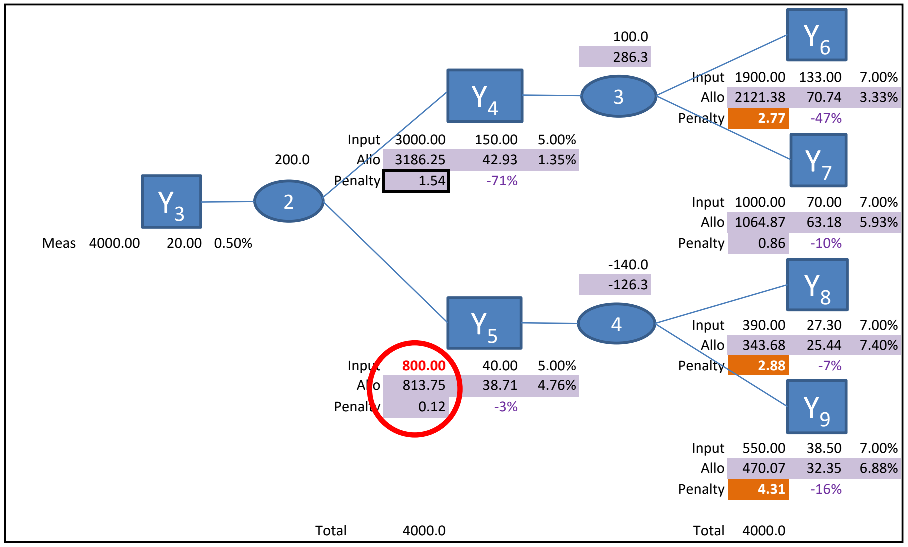
Proportional Allocation



Relative deviation from base case



Uncertainty-based Allocation



DVR-based Allocation

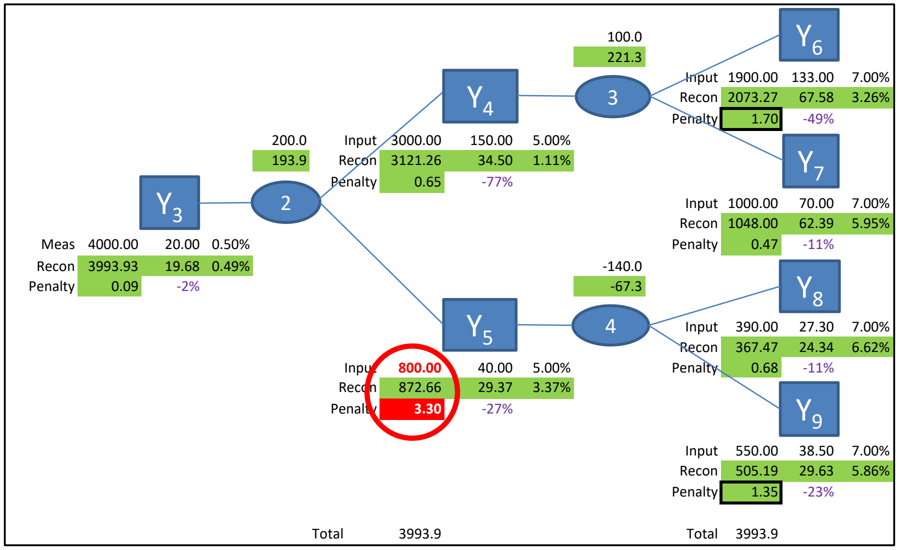
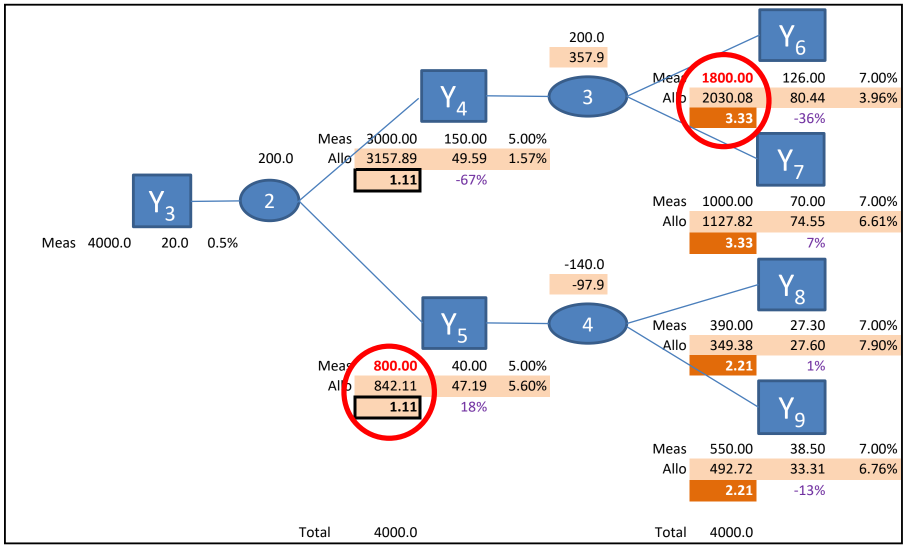
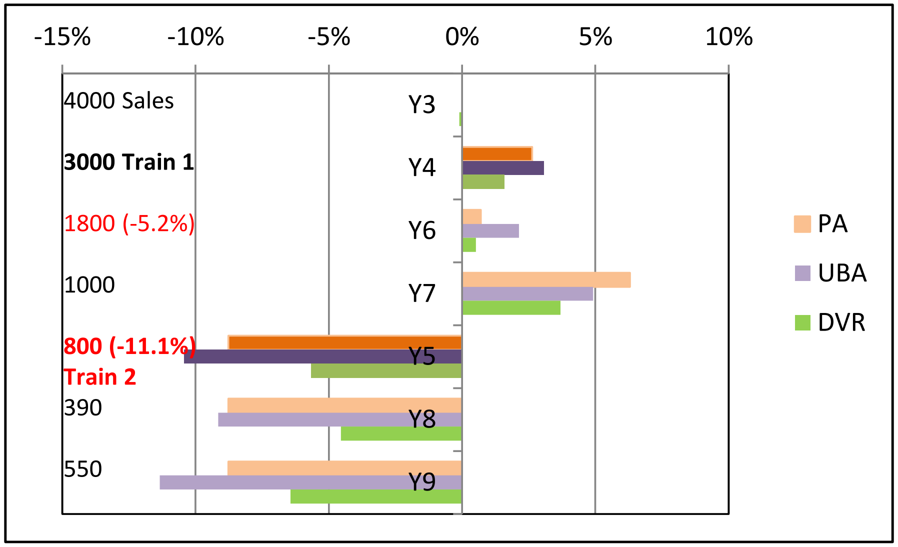


**Figure 10: Comparative analysis - Base case with bias at Y5. Bar chart shows the relative percentage difference between this case and base case allocated quantities**

Proportional Allocation



Relative deviation from base case



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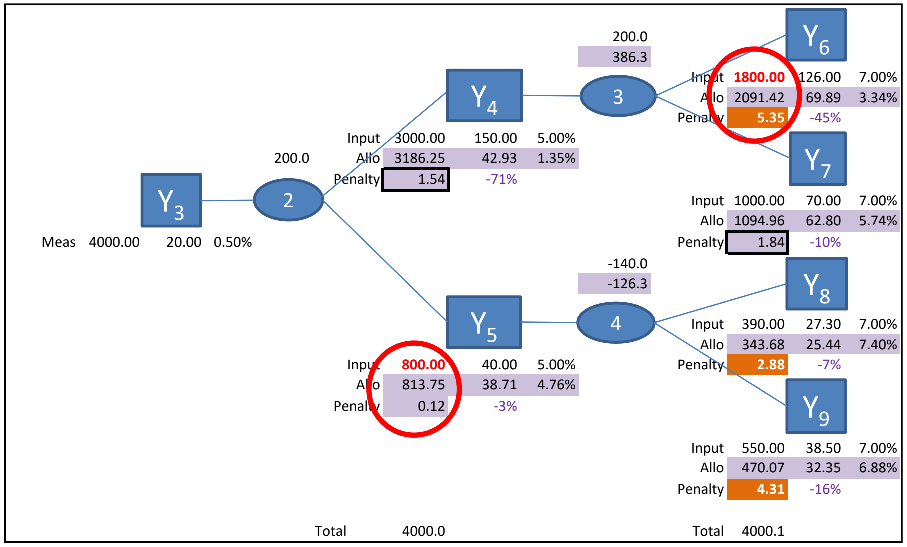

DVR-based Allocation

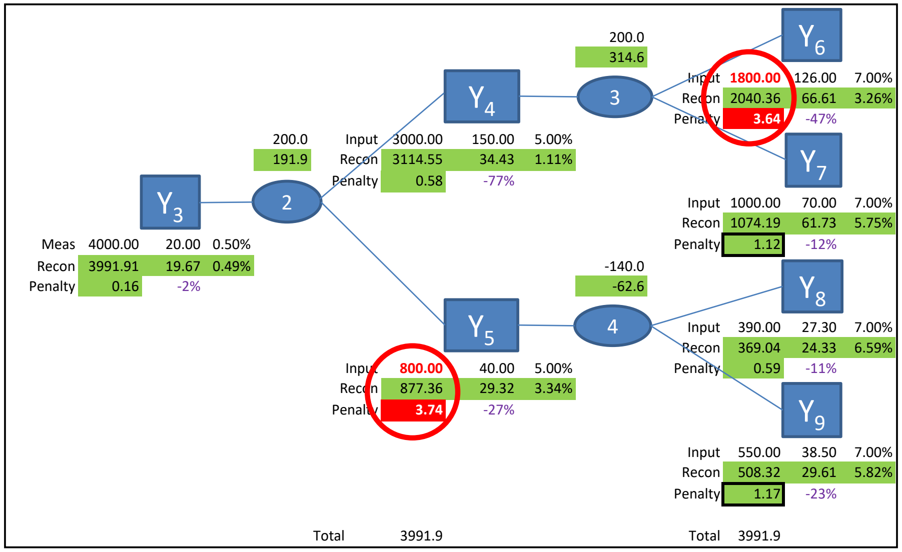

**Figure 11: Comparative analysis - Base case with bias at Y4 and Y6. Bar chart shows the relative percentage difference between this case and base case allocated quantities**

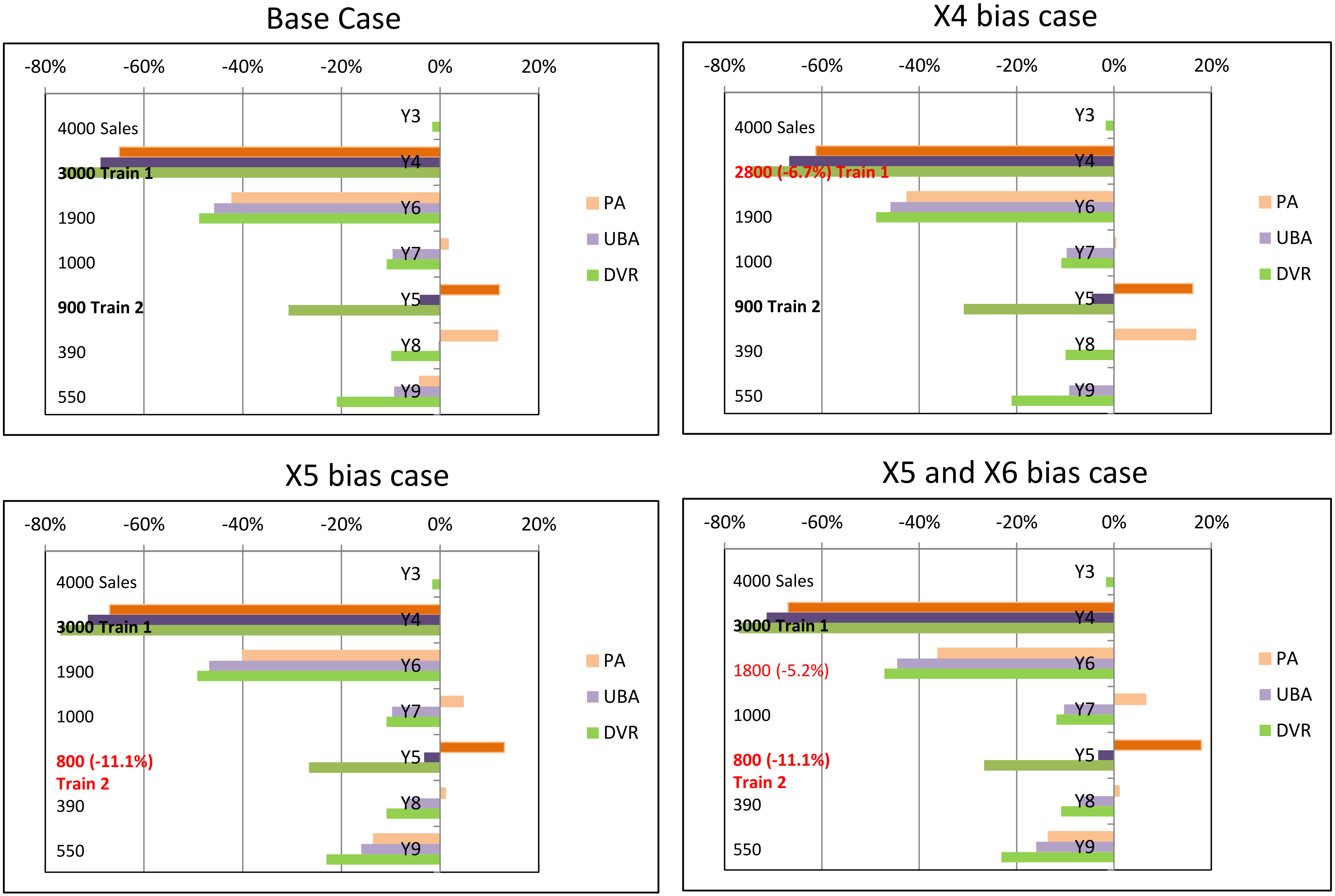

**Figure 12: Comparative analysis - Relative percentage difference measurement and allocated absolute uncertainties. UBA and DVR show consistent uncertainty improvement**