Optimal Drainage Area and Surface Pad Positioning for SAGD Development

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Locations of drainage areas and surface pads have a large impact on the production of bitumen in steam assisted gravity drainage process (SAGD). In a SAGD development project, the objective is to access subsurface quality in the best possible way to maximize the recovery of bitumen. Uncertainty in the reservoir properties and complexity in allocating surface pads because of surface obstructions makes optimizing pad orientation a challenging task that includes "optimal allocations" as well as a "space packing" problem. Optimal use of space for SAGD development allows for access to the maximum available resources and optimal allocation of drainage areas maximizes the recovery of bitumen. This paper presents a methodology to optimize pad orientation and determine the optimal positions of drainage areas and surface pads. The presented methodology uses realizations of subsurface reservoir properties to minimize the risk involved in the locations of drainage areas. Instead of working at a level of individual drainage area, this method works on a compact group of non-overlapping drainage areas to insure optimal use of space. A DASP (Drainage Area Surface Pad) tool containing several programs is developed for this purpose. Calculations are done at an individual well pair level and the optimizations algorithm considers surface obstructions and subsurface quality in a single objective function. A heuristic optimization algorithm selects the optimum locations of drainage areas and surface pads by means of 4 optimization steps: rotation, sliding, translation and breaking of individual rows.

1. Introduction

A bitumen deposit is accessed and recovered in SAGD by drilling horizontal well pairs in the deposit. These well pairs are located in the economically recoverable areas of a bitumen deposit. Currently huge deposits of bitumen are being extracted in many SAGD projects such as Surmont, Christina Lake and Sunrise projects in the Athabasca region of Alberta, Canada. Optimizing the positions of a large numbers of well pairs to maximize recovery is challenging because of the inter relationship between adjacent well pairs. Figure 1 shows the inter relationship between the positions of different well pairs for an optimum overall configuration. Optimizing the position of a single well pair does not guarantee maximum recovery across the field. An optimum position for a single well can affect the positions of neighboring wells and may force them to be located in non favorable positions, which does not maximize the recovery over all pairs; the example in Figure 1 highlights this in a simple three pair 2D configuration.

Groups of well pairs are drilled from a single surface facility. A general practice of SAGD well pair placement is shown in Figure 2(a). Several horizontal well pairs are drilled from a single surface facility. All well pairs associated with a single surface facility are generally parallel with each other. It is common to have wells with different lengths or even non parallel well pairs from a single surface facility for small development areas. A regular pattern of parallel wells are used for large development areas. This helps to balance operational simplicity and allow for access to most of deposit. A group of parallel well pairs which are placed side by side and associated with same surface facility is a Drainage Area (DA) and the surface facility used to drill them, inject steam and collect bitumen over the entire period of production is the Surface Pad (SP). The size of a SP depends upon the number of well pairs it is associated with; a large number of well pairs in a DA requires a larger SP. It is possible to have different sizes of DA's in a single development area, but it is generally avoided for large development areas. The use of smaller DA's is more common at the boundaries of the deposit to allow flexible access to the remaining resource. Superheated steam which is injected into the well pairs is produced and maintained at a facility located at surface, the Central Processing Plant (CPF). Steam is transported to many SP's from a single CPF. Different lengths of well pairs require different operating temperature and pressure of steam, and therefore to maintain operating pressure and temperature and minimize operational difficulty, most of the well pairs and DAs are of the same shapes and size. Figure 2(b) shows a simple illustration of SP and DA.

2. Problem

The problem of locating different DA's optimally in a SAGD development area is challenging due to various reasons:

- Increasing the separation between two adjacent DA's in an area of high reservoir quality risks a loss of bitumen. This can be avoided if the spacing between adjacent DA's is minimized. Therefore allocating different DA's in an area of interest is similar to space packing problems where the objective is not only to maximize the accessibility of available resources but also to maximize the volume of recoverable bitumen.
- The nature of the base of continuous bitumen (BCB) (McLennan, Ren, Leuangthong, and Deutsch2006) influences the amount of bitumen that can be recovered from a well pair. The vertical position of a well pair is crucial for effective bitumen recovery and is determined by the elevation of the BCB surface along the length of the well pair. Placement of a well pair below the BCB surface may result in the loss of steam in unproductive regions. And conversely placement of a well pair at a higher elevation may result into the loss of bitumen lying below.Complexity is also added because of surface locations where it is not possible to develop SP's. Surface obstructions such as roads, rivers, hydrology and structures should not be affected by SAGD development projects and restricts the area available for development. It might be possible that there is no surface available for development of SP for a good DA location. If possible, an alternative distance and direction for drilling can be developed (away from any surface restrictions); however, there is a distance limitation between SP's and corresponding DA's. Both surface and subsurface factors must be considered together for a feasible SP and better recovery of bitumen. Considering two different but inter-related objectives makes DA and SP allocation as a multi-objective optimization problem. One part of objective is to find the best positions for surface pads and the other part of objective is to find the best location and orientation of associated DA for maximum recovery of bitumen.
- Uncertainty in reservoir properties adds additional complexity. Selecting optimal locations and positions of well pairs based on a single estimate or realization can be misleading. Geostatistical simulations can be used to generate multiple realizations to determine optimal locations of SP and DA's.

3. Surface and Subsurface variables

The surface area for the development and construction of an SP is selected by filtering out the locations where surface obstructions are present, such as rivers, roads, water etc. The subsurface parameters on which the location of DA depends are:

1. *Region of interest*: A region of interest is a geological boundary within which the placement of DA's are targeted. A DA partially outside the region of interest should be avoided. A better orientation of DA is with minimum number of well pairs intersecting the boundary of region of interest (figure 3(b)).
2. *Volume of available bitumen and reservoir quality*: This is the primary variable considered in the optimization. The overall objective is to maximize the recovery of bitumen. For example, optimization can consider the maximization of the net thickness of continuous bitumen (NCB) over the geological region (figure 3(a)).
3. *BCB*: The base of continuous bitumen affects the vertical depth of a well pair and so it also effects the location of well pairs. The nature of BCB and NCB thickness is combined to calculate the recovery of bitumen for a given location of DA (explained later).
4. *TCB or GCB*: Top continuous bitumen (TCB) provides the top boundary of the deposit. Together, BCB and TCB set the boundary of deposit for the calculation of recoverable bitumen. GCB is thickness of gross continuous bitumen, the difference between elevations of TCB and BCB is equal to GCB value (figure 3(a)).
5. *Thief Zones*: Thief zones are the regions where subsurface water is present. A different kind of operating pressure and temperature is required to operate if a well passes through these regions. Layout of wells should be considered to minimize the total number of wells in thief zones (figure 3(b)).
6. *Size and shape of SP*: Generally SP's are rectangular in shape and size varies with the number of well pairs they are associated with. Circular surface pads are assumed in this paper but considering rectangular ones would not change the methodology. A large SP requires more unrestricted area on surface. If a surface pad overlaps with any of the surface obstructions then it is not considered for development and therefore no contribution is counted for corresponding SP and DA in the objective function calculation.
7. *Distance tolerances for SP*: There exists an ideal position of a SP from its DA. But it is possible to drill from a distance offset from the ideal position. More distance tolerances provide more chance of availability of SP location on surface (figure 7b) but increases the distance along which steam must be injected.

8. *Number of well pairs (n_{well})* present in a DA. The relative positions of individual well pairs in a DA are fixed. Figure 4a shows the relative position of wells for a DA with 5 well pairs. Well spacing can be easily determined for a given size of DA and number of well pairs (figure 4a):

$$WS = \frac{W_{DA}}{n_{well}},$$

WS =well spacing: distance between two adjacent well pairs of a DA.

n_{well} =Number of well pairs in a DA.

W_{DA} =Width of a DA.

4. Objective function

After combining different variables and constraints, the overall objective function for optimization is expressed in terms of recoverable bitumen. Different constraints are penalized as per the amount of their effect on the recovery of bitumen. Mathematically, the objective function is expressed as:

$$f_{obj} = \sum_{i=1}^{N_{DA}} \left[R_{aval}^{i} \cdot Pen_{base}^{i} \cdot Pen_{tz}^{i} \cdot Pen_{SP}^{i} \right] \tag{1}$$

R_{aval}^{i} =Available resource at i^{th} DA location.

Pen_{base}^{i}, Pen_{tz}^{i}, Pen_{SP}^{i} =Penalty factors for BCB surface, Thief zone and SP respectively for i^{th} DA.

N_{DA} =Total number of DA for optimization.

The objective function f_{obj} is a sum of N_{DA} DA's objective functions f_{obj}^{i}. R_{aval}^{i} is the average thickness of resource (NCB) at the i^{th} DA and It represents the quality of the reservoir. Different penalty factors are introduced to guide the objective function to allocate DA's in areas where constraints minimum. The base penalty indicates the amount of roughness of BCB surface enclosed inside DA. More resource is lost in an area of rough BCB surface. Higher penalty is given for an irregular and curvy BCB surface. Thief zone penalty is assigned based on the number of well pairs affected inside a DA because of passing through a thief zone area. Surface penalty indicates the availability of SP, it is either 0 or 1. 0 being the case where it is not possible to locate a SP for corresponding DA and therefore making the objective function value 0. Use of a compact and non overlapping group of DA's guarantees the maximum number of DA's and access to almost all R_{aval} in the area. The goal is to maximize the objective function by reducing the penalty values of each DA. It should be noted that the sum of all available resource over the area of interest is constant but the penalty values change as different orientations of DAs are tested. All penalty factors in the objective function equation are scaled to range between 0 and 1.

A better way to express objective function is by eliminating the base penalty factor from objective function equation. An improper choice of base penalty value might be misleading in the optimization process. A high penalty will force the objective function to allocate DAs in an orientation which has a smoother BCB surface which is not ideal for an area with high resources but a rough base. Similarly, a smooth BCB surface in a low R_{aval} area will have more objective function value. This can be misleading in the optimization process if a low reservoir quality is selected over a higher one. Implementation of other penalty factors: pen_{tz}^{i} and pen_{SP}^{i} are straight forward. pen_{SP}^{i} is either 0 or 1 in most of the cases. The thief zone penalty is selected based on the number of affected well pairs. A high penalty for thief zone violations ensures the minimum number of affected wells irrespective of available resource. Also, thief zones are not present everywhere in the area.

The base penalty factor it is difficult to determine. Removal of base penalty can be done by not considering the available resource at DA location but taking account of recoverable resource of each well pair in a DA. But one benefit of using base penalty is the calculation time. Calculation of recoverable reserve takes more time than calculating the base penalty, also recoverable reserve is calculated for each well pair but base penalty is for whole DA. Calculation of recoverable reserve for a well pair is done by placing the well at maximum BCB elevation. This maximum BCB elevation is calculated from the elevation of BCB surface along the well pair. The new way of expressing the objective function is:

$$f_{obj} = \sum_{i=1}^{N_{DA}} \left[R^i_{recov} \cdot Pen^i_{tz} \cdot Pen^i_{SP} \right] \tag{2}$$

R^i_{recov} =Amount of recoverable resource for ith DA.

$$R^i_{recov} = \frac{1}{n_{well}} \sum_{j=1}^{n_{well}} r^i_j \tag{3}$$

r^i_j =Amount of recoverable resource by jth well of ith DA, when well is placed at maximum BCB elevation.

All the factors included in the objective function are functions of location and orientation of DAs. The optimization problem can be expressed as an unconstrained optimization by means of penalty functions.

$$\begin{aligned} &Find\ (X_i, Y_i, \theta_i)\ , i = 1, ...N_{DA} \\ &to\ Maximize:\ \sum_{i=1}^{N_{DA}} f^i_{obj}(X_i, Y_i, \theta_i), \\ &where,\ f^i_{obj}(X_i, Y_i, \theta_i) = R^i_{reaov} \cdot Pen^i_{tz} \cdot Pen^i_{SP} \end{aligned} \tag{4}$$

(X_i, Y_i) is location, θ_i is the orientation of ith DA.

N_{DA} is the total number of DAs for optimization.

5. Comment on general Optimization Algorithms:

Even though the objective function is expressed as an unconstrained optimization problem, it is difficult to apply any general optimization algorithms because of the large dimensionality of the solution space and the highly convex, multimodal nature of the objective function. The dimension of solution space is the size of vectors $\mathbf{X} = [X_1, X_2, ...X_{N_{DA}}]$, $\mathbf{Y} = [Y_1, Y_2, ...Y_{N_{DA}}$, $\boldsymbol{\theta} = [\theta_1, \theta_2, ...\theta_{N_{DA}}]$. Therefore dimensionality of problem increases as the number of DA's considered for optimization increases. Even if the dimensionality is traceable, it is the multimodal nature of objective function which makes it very difficult to solve by any gradient or direct search algorithms. The multimodal nature of objective function is explained with the help of a very simple example (Figure 5). The simple to visualize the multimodal nature by considering just one DA with fixed orientation. It is simplified more by moving DA in only x direction. Figure 12 shows two different positions of local maxima. There can be several maxima of objective function just for the movement in x direction. Same way there are several local maxima for y-coordinate and orientation. For this example the reservoir quality is smooth and there is continuous increase or decrease in it. A long list of literature is available on optimal polygon packing problems. Such as Dowsland, Vaid, and Dowsland (2002), Babu and Babu (2001), describes the use of a bottom left strategy, no fit polygon and genetic algorithms to pack a given area optimally using polygons. The main limitations of these approaches are that they either work on rectangular regions (Dowsland, Vida and Dowsland) or have a very high CPU time (Babu and Babu) and are specially designed only for space packing. The objective with maximum volume recovery is another complexity for evolutionary algorithms.

6. Methodology

To avoid searching in a high dimensional solution space, a compact pattern of DA's are considered for optimization (figure 6). Only rectangular shaped DA's are considered, which results in no gapping between adjacent DA's. Figure 6 illustrates the nature of the problem and a compact pattern of DA's. The surface obstructions for SP allocation are shown in gray as hydrology and roads. The boundary within which DA placement is required (region of interest) is shown with a green colored polygon. This region is colored by NCB thickness. Green circles represent SPs. Any

DA with cross over it indicates the unavailability of SP (overlapping of SP with surface obstructions) for that location of DA.

The optimization methodology is a 5 step processes: (1) simulate geological variables to generate realizations of reservoir properties such as NCB, BCB, GCB, and thief zones. (2) Model surface obstructions. (3) Generate an initial compact arrangement of DAs as an input for the optimization. (4) Optimize by rotating and translating the group of DAs within the model area and sliding the individual rows of DAs. (5) Slide and break rows of DA to look for the possibility to develop any DA on this row which is not developable due to surface constraints. The decision variables considered in the optimization process are location and orientation of DA's. Figure 7 explains the decision variable of a single DA. (x_i, y_i) is the location of the centre of i^{th} DA and θ_i is the angle of centre line of DA measured in counter clockwise direction from x-axis.

Simulating geological realizations: Simulation of geological realizations is done with any standard geostatistical simulation methods such as Sequential Gaussian Simulation (SGS). All realizations are used to calculate a single value of objective function. Objective function values over all realizations are averaged to get a single value of objective function. All realizations are generated on a 2D grid. For example NCB realization indicates the value of thickness of reserve at each grid cell. Any cell outside the region of interest is assigned NAN (not a number). Similarly, BCB, GCB and thief zones realizations are generated.

Modeling surface data: Surface data is transferred over a grid to indicate each cell with a surface penalty. The penalty value indicates if it is possible to place an SP over this grid or not? Any cell having a surface obstruction is assigned a penalty value of 0 and all other regions available for surface pads placement are assigned with 1. Any region over which placement of SP's is expensive or require additional approval from government can be penalized with a value between 0 and 1. A program `SETPEN` is developed to transfer surface penalties to a grid. Generally a high resolution grid is considered for surface penalty map because there is no uncertainty associated with surface data. A high resolution map of subsurface quality is not possible for computational reasons.

Initial Configuration: To start the optimization an initial configuration of paved and compact arrangements of DA's is required. `DApave` is developed to generate an initial guess for optimization. It is possible to include any paved arrangement of DA's as input. The result of the optimization can be used again as an input to run the optimization a second time.

Optimization: The optimization method is a heuristic method. The value of the objective function is calculated by changing the pattern of DA's. At each iteration, the best solution is selected. A program `DASPopt` is developed to perform the optimization by changing the arrangement of DA's by means of one or all 4 movement pattern: (i) by rotating entire group of DA's at its centre of mass, (ii) Translating entire group, (iii) Sliding individual rows of DA's, and (iv) breaking individual rows. These optimization processes are either user specified or automated. One example of user specified option $R^{opt}_{-45\ to\ 45} - T^{opt} - S^{opt}$ is a 3 step optimization step: (i) Rotate initial configuration of entire group of DA between angles of -45 to 45 degrees and determine the optimal rotation which gives the maximum value of objective function, (ii) Translate entire group of the optimal arrangement obtained from previous step (rotation) and find the optimal translation value, (iii) After finding the optimal from 2nd step slide individual rows to maximize the objective function. The problem with user specified optimization step is that it is hard to know a pattern of optimization option which results in the global maxima. Suppose 7 degrees is the optimum angle of rotation for the first step of $R^{opt}_{-45\ to\ 45} - T^{opt} - S^{opt}$ pattern. After 7 degrees of rotation translation and sliding optimization is done which increases the value of objective function further. But it is possible that a global maximum exists for a pattern with a different degree of rotation, translation and sliding. This can be illustrated as below:

	Initial Guess	-	$R^{opt=07}_{-45\ to\ 45}$	–	T^{opt}	–	S^{opt}
Obj. fun. =	100	-	110	-	115	-	120

	Initial Guess	-	R_{30}	–	T^{opt}	–	S^{opt}
Obj. fun. =	100	-	105	-	110	-	125

The option of automatic optimization enforces the program to do calculation for all possible orientations and for all possible permutations of rotation (R), sliding (S), and Translation (T) steps. It checks for all possible rotations from 1 to 180 degrees. There are total 3x2x2=12 arrangements of T (translation), S (sliding), and R (rotation) with no consecutive repetitions of T, S or R. one T is achieved in only one way (selecting only optional translation for entire group) and similarly one S can be achieved in one way (selecting optimum sliding for each row). R can have 180 values (1 to 180 degrees of rotation option). A simple permutation calculation gives a total of 66,242 patterns of optimization involving 3 steps. For example one such pattern can be $T^{opt} - R_7 - S^{opt}$ i.e. first translate the entire group and find the optimum translation, then rotate the entire group by 7 degrees (in counter clockwise direction) and then slide individual rows and find the optimal sliding for each rows. A global maximum is selected after testing against all the optimization patterns. Another benefit of testing against all possible permutations is that all permutations can be sorted as per their objective function value and top patterns can be analyzed. Then it is possible to select an angle which is more favorable in technical terms and have local maximum value or close to the global maximum.

7. Calculations

Calculating Surface pad penalty (pen^i_{SP}): SP penalty for a DA is either 0 (not possible to develop a SP) or 1 (possible to develop a SP) or in between 0 and 1 (possible to develop SP but at additional cost). There are 4 main parameters used for checking the possibility of SP. (i) radius of SP (r_{SP}). (ii) Ideal distance of SP from its DA (d_{ideal}). (iii) Search direction of SP: There can be 1, 2, 3, or 4 search directions. For a rectangular DA it can be either direction 1 or 2 and for a square shaped DA it can be maximum up to 4 (figure-8 (a)), SP can be located in any one of these directions. (iv) Distance tolerances (`dis1, dis2`): are the values of distance tolerances in the direction of DA (`dis1`) and in the perpendicular direction (`dis2`) (figure 8(b)). All the directions specified for search are checked for the possibility of SP. Checking the possibility of SP at one direction (direction -1) is shown in figure 8(c). First SP is placed at its ideal position. This ideal position is assumed to be the centre of the cell of the surface penalty map which falls at a distance d_{ideal} from DA. If it is not possible to place SP at its ideal cell's centre, then the next nearest cell is checked for the possibility of SP. This way the checking process continues until all cells inside rectangle ABCD are used or a cell is found for SP location. Surface penalty value is assigned for all search directions. In case of 4 search direction 4 different pen^i_{SP} values are calculated. If all 4 positions are available for SP then one is selected which gives the maximum value of objective function. It should be noted that there are 2 different values of R^i_{recov} for a DA when using equation (2) of the objective function. One value is when wells are drilled either from directions 1 or 2 and other is when wells are drilled either from directions 3 or 4.

Calculating base penalty (pen^i_{pen}): The option of including base penalty and available resource instead of calculating recoverable reserve is helpful in saving calculation time or when no data is available for GCB. When equation (1) is used for objective function calculation the base penalty must be calculated. To calculate base penalty, first all cells inside DA are determined. Then mean BCB $mean_{BCB}$ is calculated. Then, mean of absolute difference between BCB values and $mean_{BCB}$ is calculated from all cells inside DA. A penalty function is used to scale this value between 0 and 1.

Calculating available resource thickness (R^i_{aval}): The mean of the thickness value calculated from cells inside DA. The fractional area of cells is considered in this calculation. Mathematically:

$$R^i_{aval} = \sum_{j \in cell\, inside\, DA} Ar_j * NCB_j,$$

$$where\ Ar_j \text{ is the fraction of area of j}^{\text{th}} \text{ cell inside i}^{\text{th}} \text{ DA}$$

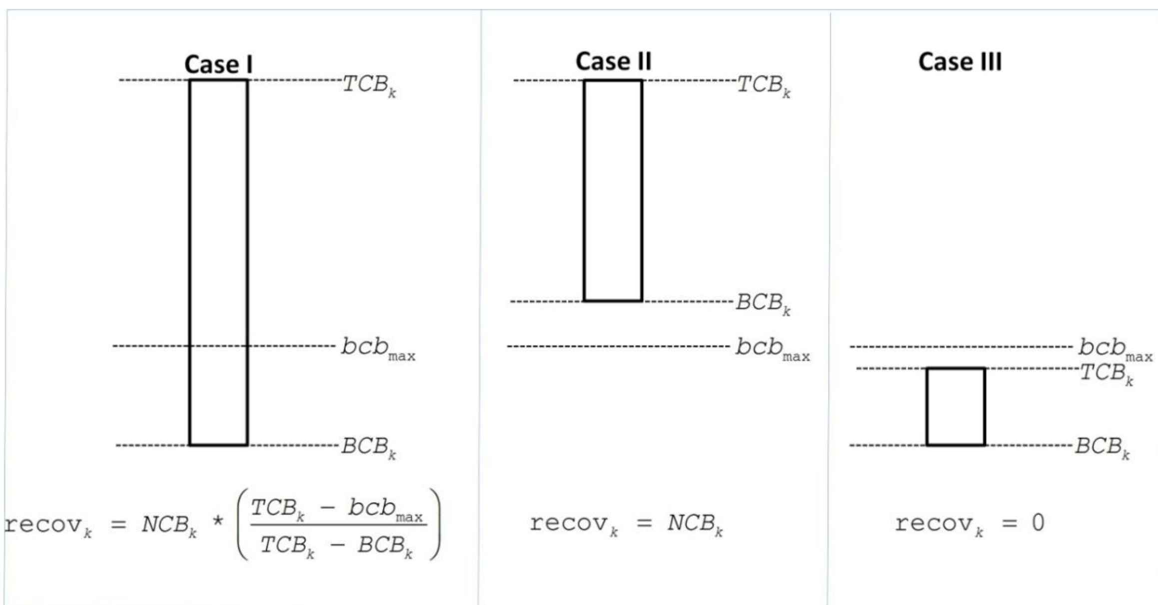
Calculating recoverable resource (R^i_{recov}): Recoverable resource of a DA is the mean of all resource recoverable by individual well pairs (r^i_j). r^i_j is the thickness of recoverable reserve by j^{th} well of i^{th} DA. To calculate the recoverable resource of a well pair: first a well pair polygon ABCD (figure 9) is established. Sides AB and CD are parallel to well pairs and points A and B are at a midpoint between wells 3 and 4. Similarly points C and D are in middle of wells 2 and 3. A maximum BCB elevation value $bcb_{\max}$ is determined from all the cells located along well 3. For the calculation of recoverable reserves, well 3 is assumed to be placed at $bcb_{\max}$ elevation. Value of r^i_j is calculated from all the cells inside polygon ABCD as:

$$r^i_j = \left(\frac{\sum_{k \in inside\, ABCD} \text{recov}_k * \text{Ar}_k}{\sum_{k \in inside\, ABCD} \text{Ar}_k} \right)$$

$$\text{where recov}_k \text{ is recovery form k}^{\text{th}} \text{ cell.}$$

$$\text{Ar}_k \text{ is fraction of area of cell 'k' inside polygon ABCD}$$

recov_k is calculated as:



There are 3 possibilities for a cell 'k' which is inside well pair polygon ABCD. Case I is typical. Case II is the situation when elevation of well is less than the BCB surface elevation at k^{th} cell. Note that this k^{th} cell of case II will never lie along well pair, because for any cell along the well the value of BCB is less than $bcb_{\max}$. For case II all the resource at k^{th} cell is recoverable. Case III is a rare case when the thickness of a bitumen deposit is so low at k^{th} cell that it doesn't even crosses the well pair elevation.

Calculating thief zone penalty (pen^i_{tz}): This penalty value indicates the number of wells pairs inside a DA that are affected by thief zones (figure 10). The number of affected well pairs is determined and a penalty function is used to transfer number of affected well pairs between 0 and 1.

8. Implementation

An area of size 10km x 10km is selected for the optimization of DA and surface pad locations. A grid size of 100m x 100m is used for modeling the sub surface variables: NCB, BCB, and GCB. 10 realizations of reservoir variables were generated using sequential Gaussian simulation. The surface penalty is calculated on a 25m x 25m grid to facilitate a more precise calculation for SP locations. The step by step process of optimization is shown in figure 11. First the region of interest is defined by a polygon. DAs of size 1000m x 800m are used for this example. A well spacing of 160m (total 5 wells) were considered inside a DA. 350m of ideal distance of SP from DA was used with a distance tolerance of dist1 = 50m and dist2= 50m. Circular surface pads of radius 100m were used. Search for surface pad was done in only two directions: direction 1 and 2. First an initial guess of paved DA's was made using `DApave` program. Automatic optimization option was selected for completeness. The objective function of equation (2) is used instead of penalizing the base. All possible combinations of 3 optimization steps are considered. The value of the objective function improved from 515m (initial) to 722m (optimized). The global optimization step was R96-T-S. Therefore a 6 degrees orientation of entire group of DA is the optimum orientation. The value of objective function is improved to 734m by breaking the individual rows. Figure 1 shows the optimum value of objective function for every orientation.

9. Conclusions

A methodology of finding the optimal location of drainage areas and surface pads for SAGD is very robust and finds a global optima by checking all possible arrangements of DA's. Working on different grid resolutions for surface and subsurface variables provides a good precision for surface pad allocation (fine resolution grid) while balancing the CPU requirements of subsurface resource calculation. Tracking all the optimal arrangements for every orientation improves optimization.

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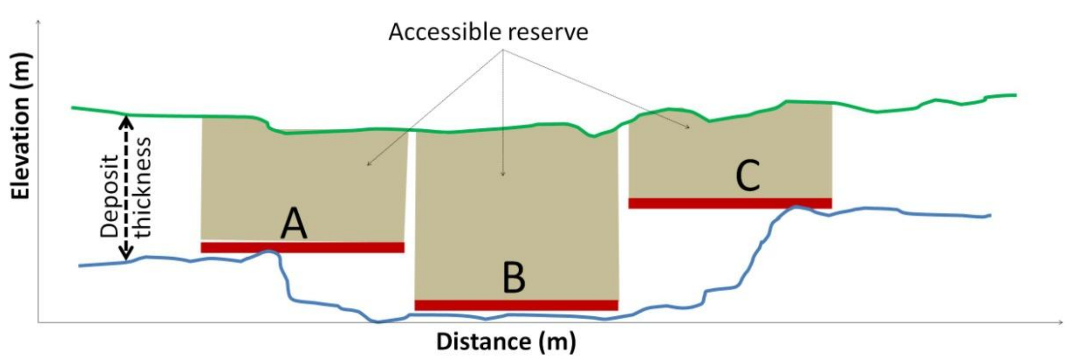

Figure 1(a): Well pair B is located at its optimal position. The individual recovery from well B is maximum, but the overall recovery from all the wells A, B and C together is not maximized. There is chance to increase the recovery from wells A or C by changing the position of well B.

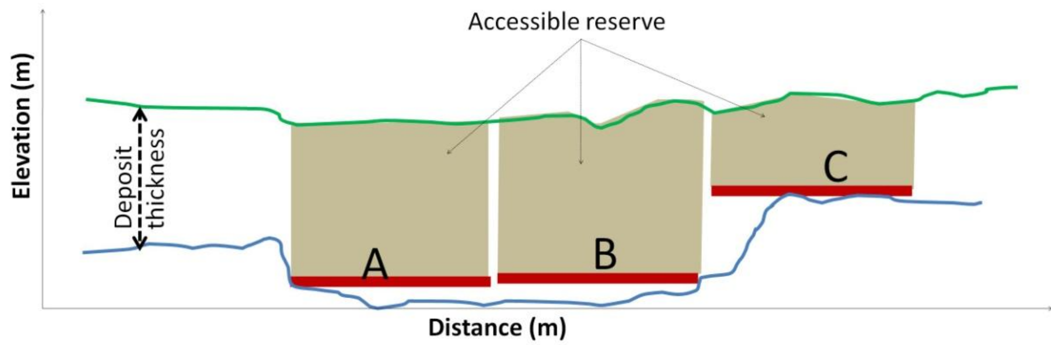

Figure 1(b): Not an optimal position for well B, but recovery from all wells together is increased.

Figure 1: An optimum position for an individual well pair doesn't guarantee its best position for overall recovery.

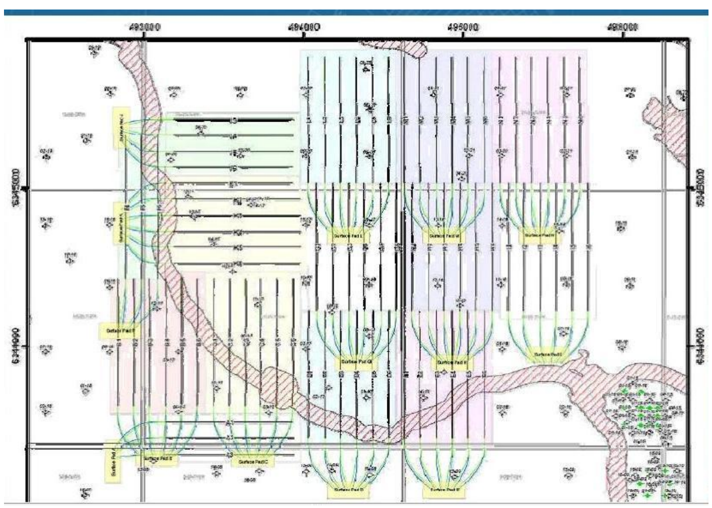

Figure 2(a): A common practice for SAGD development. Taken from RMR report, Sunrise project, Husky Energy, 2006.

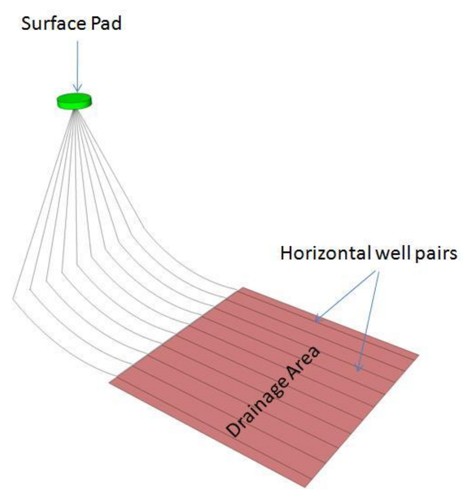

Figure 2(b): Surface Pad (SP) and Drainage Area (DA).

Figure 2: Layout of Surface pads and Drainage areas in a SAGD project

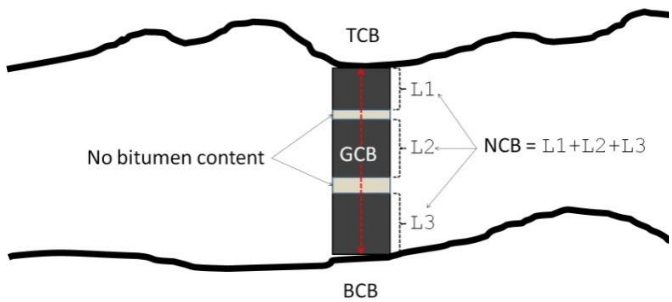

Figure 3(a): Reservoir variables: BCB, GCB, TCB, and NCB.

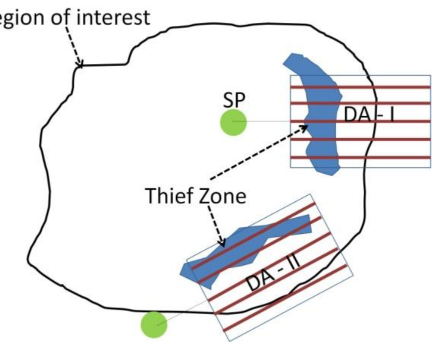

Figure 3(b): Comparison between different arrangements of DA.

Figure 3: Variables which affect the location of a DA. (a) Reservoir variables used in the calculation of recoverable reserve. (b) Comparison between two different arrangements of a DA. DA-I is not favourable because all the well pairs are intersecting the region of interest and also all well pairs are affected by thief zone. DA-II is more favourable because only one well is outside the region of interest and only two wells are affected by thief zone.

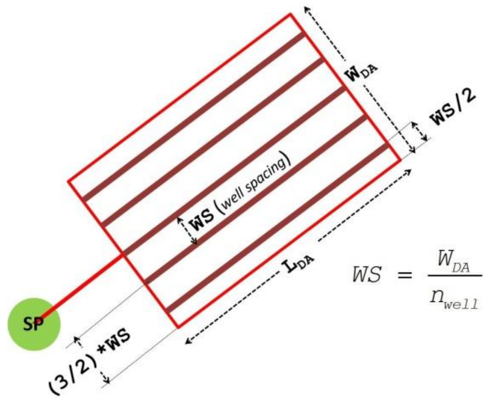

Figure 4(a): Relative positions of well pairs are fixed with respect to DA.

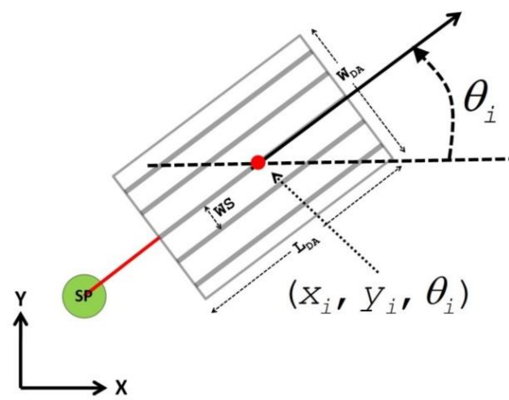

Figure 4(b): Decision variable of a DA. Orientation of DA is measured in counter clockwise direction with respect to x-axis.

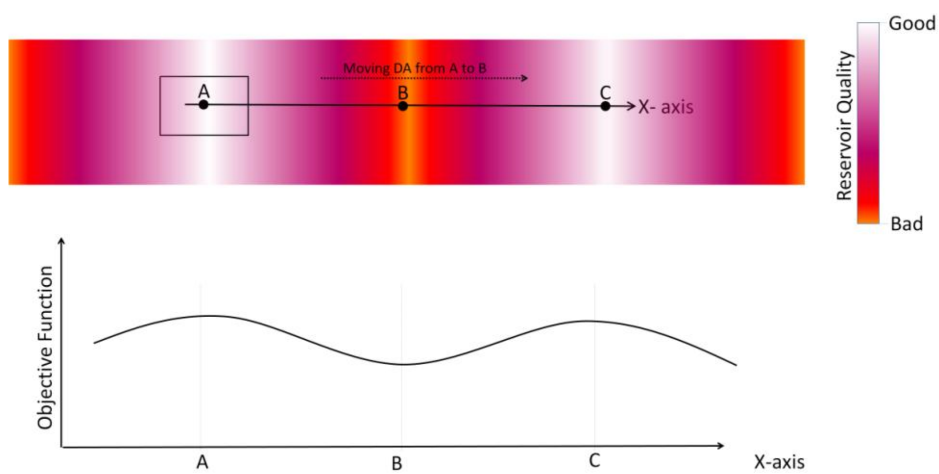

Figure 5: Example showing multimodal nature of objective function. Reservoir quality map (top). Objective function (bottom)

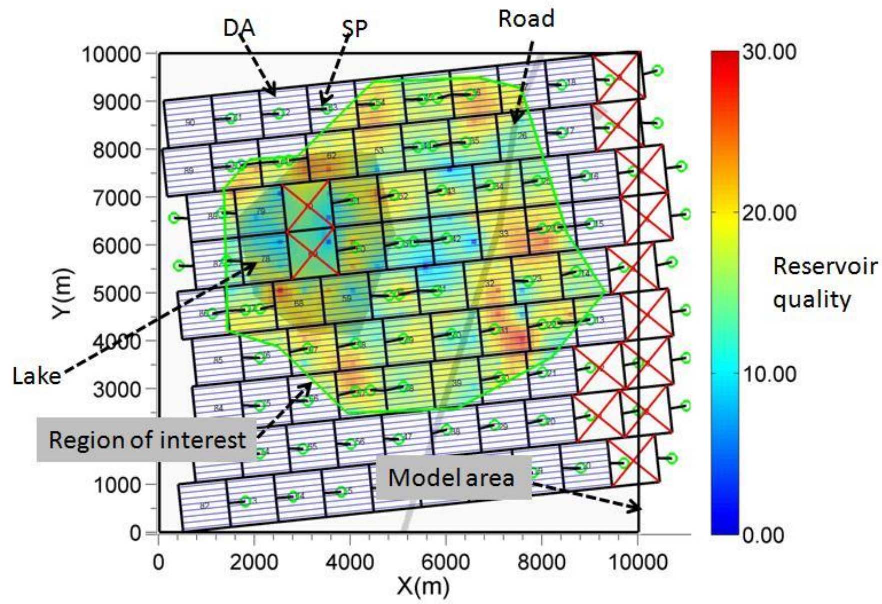

Figure 6: A compact arrangement of DAs guarantees the maximum space utilization. Any DA outside the region of interest makes no contribution in the objective function and therefore considered as imaginary DAs.

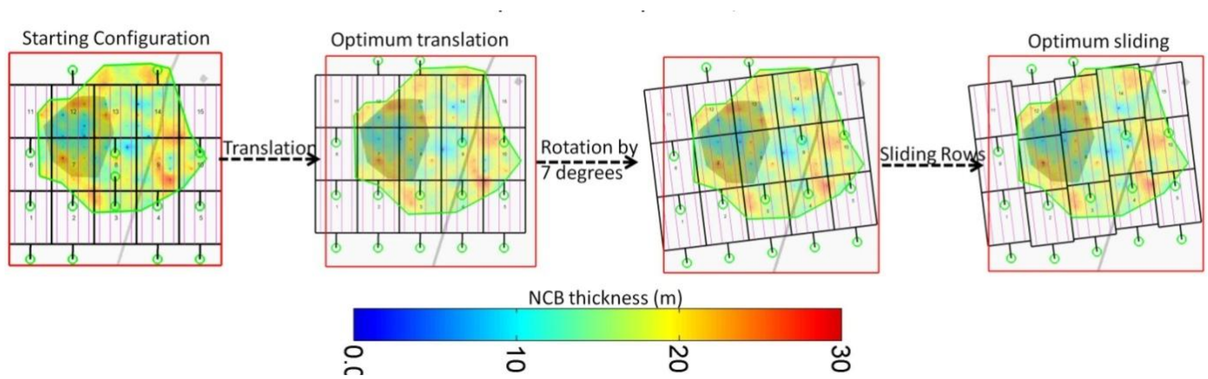

Figure 7: Objective function calculation for one optimization sequence: T-R7-S: Optimum translation, rotation by 7 degrees, and optimum sliding

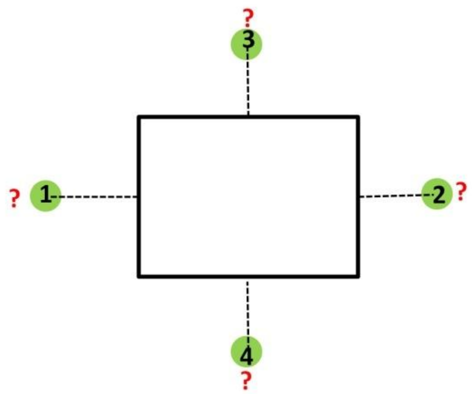

Figure 8(a)

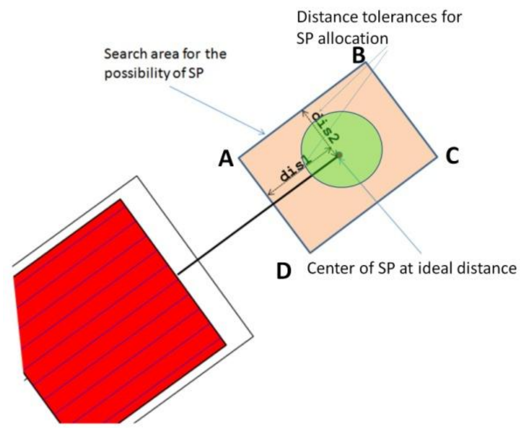

Figure 8(b)

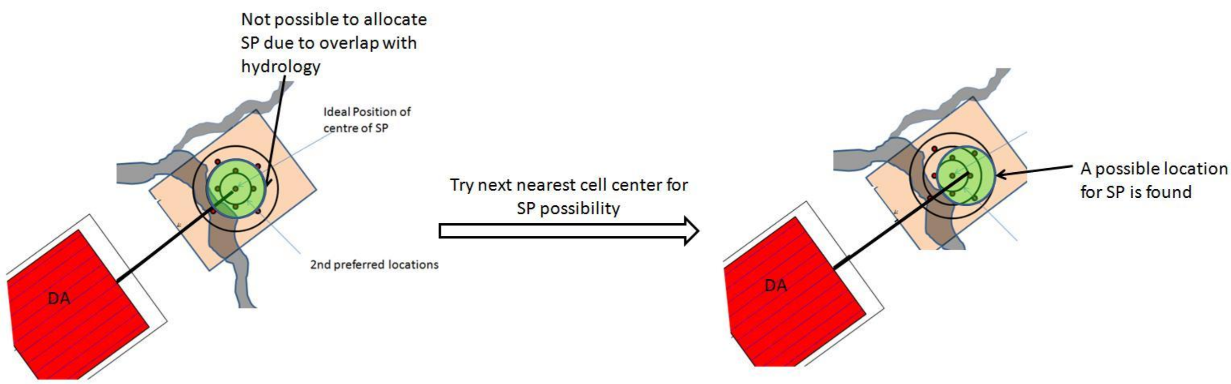

Figure 8(c)

Figure 8: (a) Search direction for SP: maximum 4 search direction. (b) Distance tolerances in search for SP. (c) Searching of SP location by gradually moving away from the ideal position of SP.

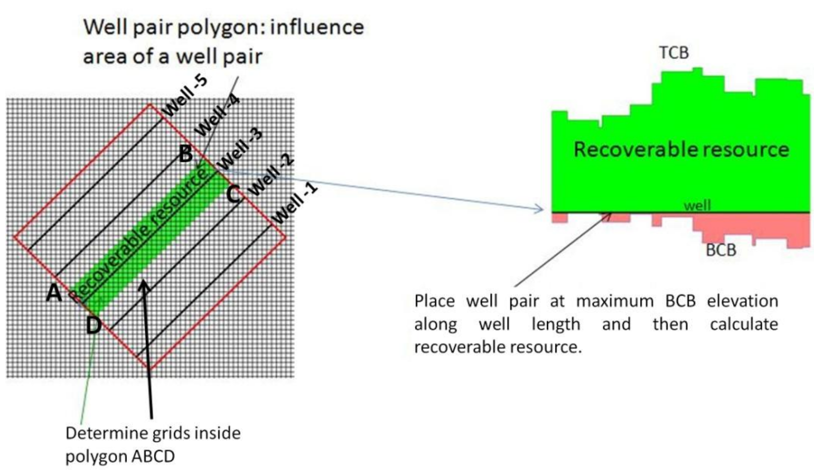

Figure 9: Calculation of recoverable resource of a well pair.

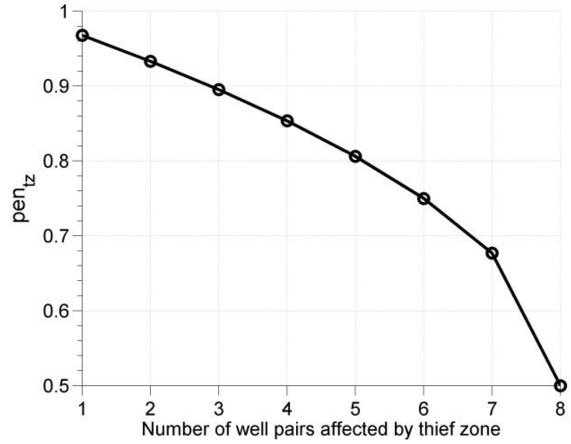

Figure 10- Thief Zone penalty as number of well pairs affected by thief zone

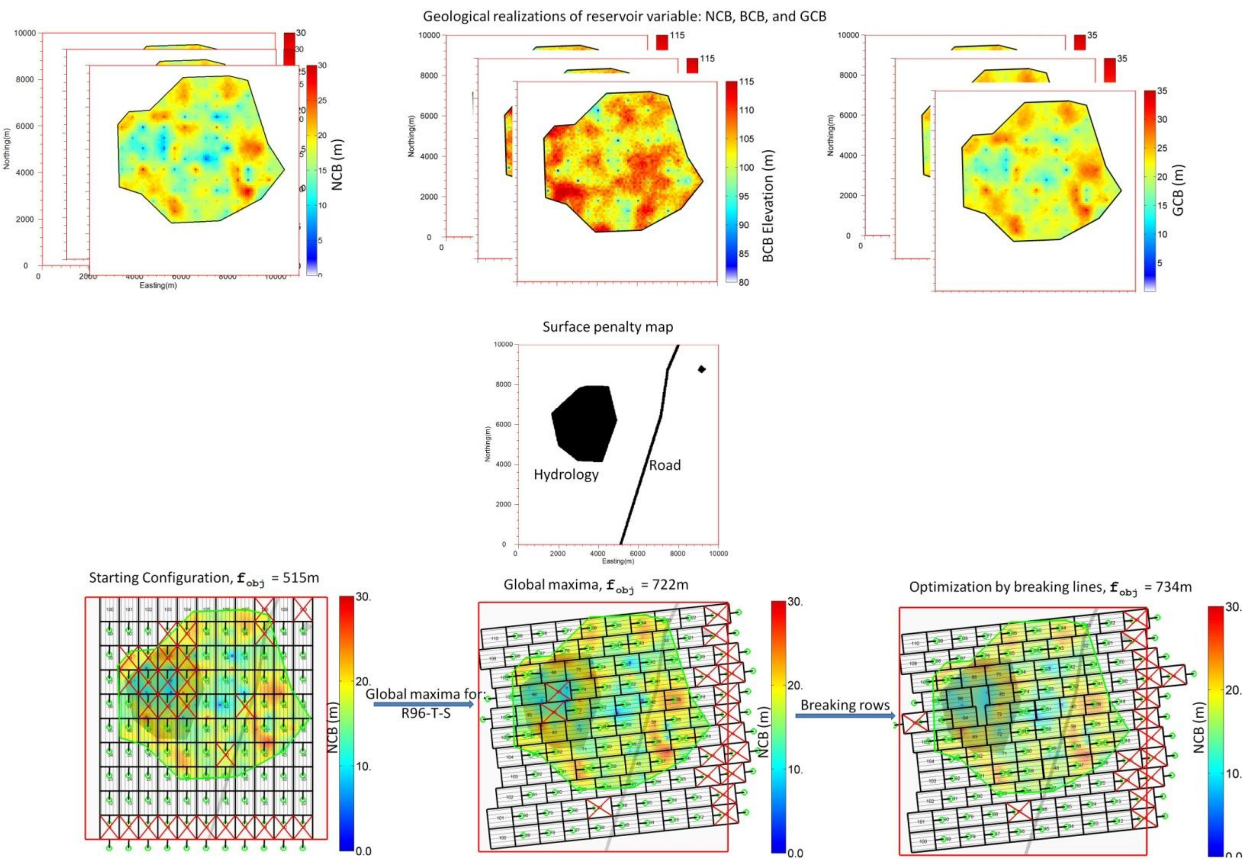

Figure 11- Geological realizations of NCB, BCB and GCB (top). Surface penalty map (middle): black areas are not available for SP placement. Optimization sequence (bottom): starts with a paved DA arrangement. All oriented in North. After running the optimization a global maxima is located at R96-T-S. An orientation of 6 degrees (counter clockwise from x axis) has the optimal arrangement of DAs. Next optimization is done by breaking individual rows.

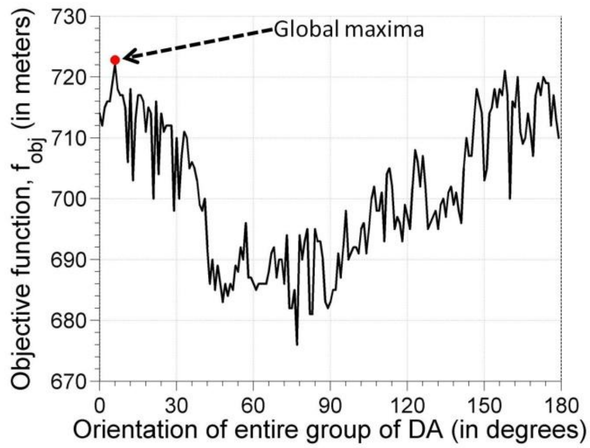

Figure 12- Value of objective function against the optimum arrangement of DA's for every orientation. The global maximum is at 6 degrees.