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Optimization of Paved Drainage Area Configurations for SAGD

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Placement of SAGD surface production pads and subsurface drainage areas in the McMurray formation to maximize the economic potential of an area is a challenging problem. The location of surface pads and drainage areas have a large impact on their production performance due to several factors including variation of bitumen in place, variation of the reservoir base surface, vertical conformance, areal conformance, interaction between different drainage areas and pads, and surface hazards. An optimization algorithm is presented to determine the positions and orientations of surface pads and drainage areas over a reservoir area so that the potential for economically recoverable bitumen is maximized. The optimization considers either a deterministic model of the relevant properties or multiple realizations to account for uncertainty. Optimization considers all drainage areas simultaneously to ensure joint optimality of an entire set. The algorithm is demonstrated using two realistic examples that show a significant improvement in potential recovery. The algorithm executes in a reasonable amount of computation time considering the complexity of the problem.

Introduction

A significant percentage of the McMurray formation oil sands are planned to be recovered using unconventional methods such as steam assisted gravity drainage (SAGD). There are a number of producing projects and more under construction and being proposed in Alberta. Several companies are involved such as Cenovus Energy, ConocoPhillips, Husky Energy, Shell, Statoil and Suncor, among others (ERCB, 2012). SAGD production generally requires three components: a surface pad (SP) that includes the required facilities and from which wells are drilled; a subsurface drainage area (DA) consisting of a set of horizontal well pairs; and the individual well pairs with a steam injector drilled above a producer. The aerial extent of a SAGD project can be extensive, requiring potentially hundreds of DAs to achieve target production rates over the lifetime of the project. Designing the layout of the set of DAs to maximize recovery or net present value (NPV) of an operation is a complex optimization problem that has largely been unexplored. A naïve approach is to use a greedy optimization strategy that finds the aerial position of a DA that maximizes its recovery then proceed to the second best and so on; however, this does not account for the interaction between multiple DAs and will not likely lead to an optimal solution over all DAs involved. For example, the optimal position of the first DA may force the position of the second DA to be unfavourable (Figure 1). Optimization must consider all DAs simultaneously to converge to a global optimal.

Based on the geology of the McMurray formation (Ranger and Gingras, 2003) and the relatively uniform distribution of economically developable reservoir, a compact arrangement of DAs would provide higher recovery than other arrangements due to close areal conformance. This is due to the geometric aspects of the problem where the spatial distribution of bitumen is continuous relative to the dimensions of a DA; therefore, a disjoint configuration of DAs would miss available resource. As the aerial coverage of a project increases, the continuity of bitumen relative to the area decreases and we are likely to observe multiple compact sets of DAs that are disjoint along with more variability in their orientation (Figure 2). This paper focuses on optimizing the configuration of a compact set of DAs to maximize the potential recovery of the set. Clearly uneconomic regions would permit multiple compact sets of DAs to be adjusted separately. There will be many changes over the long lifetime of these SAGD projects; regions deemed uneconomic now may not be uneconomic in the future. Therefore, a compact arrangement of DAs may be the best approach in many situations.

The optimization problem is complex due to its combinatorial nature and is in the class of nondeterministic polynomial time (NP-hard) optimization problems (Papadimitriou and Steiglitz, 1998). Finding the optimal position of a single DA within an area is challenging because the optimal trajectory of wells is a function of the position and orientation of the DA. The problem is also highly multi-modal having many local maxima due to the variation in the base, thickness and quality of the reservoir and due to the spatial constraints from surface culture such as existing infrastructure, lease boundaries, and topographic hazards like escarpments and bodies of water among others. Devising an optimization approach that finds the global maximum of the objective function is non-trivial. In this work, the objective function is expressed in barrels of bitumen. It is calculated as recovered bitumen less capital and operating costs that have been scaled to barrels of bitumen. An adaptive grid search algorithm is used to find the optimal arrangement of DAs. It is possible to optimize the configuration using a single deterministic model of the required properties or using a set of realizations. Two examples involving realistic but synthetic data are provided to demonstrate the effectiveness of the optimization procedure, as well as identify some of its limitations.

Problem Description

DA geometry defines the area, usually rectangular, that will be drained by a set of nearly horizontal well pairs. Wells are drilled from the SP located near the heel of the DA (Figure 3). The optimization problem is to determine the spatial configuration of DA's and SP's and the depth of wells for a field to be produced such that the economic potential is maximized. Three variables that describe the reservoir are required and include a reservoir quality variable, a base surface, and gross thickness. In this work, reservoir quality is summarized using net continuous bitumen (NCB) that is the total thickness of recoverable bitumen above the base surface (Figure 4). Net reservoir is often determined based on facies and cut-offs for porosity, permeability and water saturation. The base surface is a base of continuous bitumen (BCB) that defines the lowest elevation a horizontal well could retain while still being able to recover bitumen from above. Well length below the BCB is considered ineffective, that is, bitumen cannot flow into that length of the well. Gross thickness or gross continuous bitumen (GCB) includes all recoverable net and non-net intervals above the BCB.

The BCB, NCB and GCB surfaces would often be derived from a 3D reservoir model although these variables could be mapped directly. They are deterministic if a single reservoir model is available or stochastic if the reservoir is modeled by a set of realizations. In the latter case, the optimization problem is solved in a probabilistic sense, accounting for the uncertainty that is quantified by the set of realizations. In either case, the objective function of the optimization problem is measured in barrels of bitumen and defines the economic value of a specified SP-DA configuration. Variables involved in calculating the objective of a single DA are: the number of well pairs, m; the elevation of each well, $z_j, j = 1, \dots, m$; and the barrels of bitumen recovered from each well pair, $R_j, j = 1, \dots, m$. R_j is a function of the position of the well relative to the BCB, NCB and GCB surfaces and of z_j and the well spacing defined by Eq. 1, where u and v are coordinates that span the area of influence of the well, θ is an angle that defines the limit of drainage between adjacent well pairs, v_j is the location of the well in the v coordinate, and $z_{TCB} = z_{BCB} + h_{GCB}$ is the top of continuous bitumen:

$$R_j = \iint_{u,v} h_{NCB}(u,v) \cdot \frac{z_{TCB}(u,v) - z_j(u) + |v - v_j| \tan(\theta)}{h_{GCB}(u,v)} dv du \qquad (1)$$

This equation is applicable in areas where $z_j(u) > z_{BCB}(u,v)$. There are two cases where the integrand evaluates to zero: when the GCB is less than a minimum producible thickness and when the injection well intersects the TCB. A case that requires a slightly different integrand is when a segment of the well is ineffective and its length exceeds the limit of steam chamber growth. The stranded volume of bitumen left behind is assumed to be of a similar geometry as that between neighbouring well pairs, where wedge wells are being used to recover it (Jaremko, 2010). If the length of ineffective well is small enough, denoted $l_{\min}$, all of the bitumen above that portion is assumed to drain; however, in longer segments the thermal and pressure gradients to drive flow are assumed inadequate (Figure 5) based on the theory of steam chamber growth proposed by Butler (1991).

Theoretically, it is possible to drain the stranded bitumen in both cases shown in Figure 5; however, as the height of the volume of stranded bitumen above the producer decreases with time, the flow rate also decreases, eventually to a point where it is uneconomic to sustain (Butler, 1994). This type of behaviour is difficult to incorporate into Eq. 1 analytically. Numerically, the stranded oil volume due to ineffective well length can be approximated using a cone emanating from the point of intersection between the production well and the BCB surface. The angle of the cone relates to the time a DA has been producing, with high angles being representative of early production and low angles of late production. Assuming such a point exists along a well, the recovery equation is modified to involve a distance function, $d(u,v)$, in Eq. 2. Along effective length of a producer, $d(u,v) = |v - v_j|$, and along ineffective length $> l_{\min}$, it is the distance to the nearest effective portion.

$$R_j = \iint_{u,v} h_{NCB}(u,v) \cdot \frac{z_{TCB}(u,v) - z_j(u) + d(u,v)\tan(\theta)}{h_{GCB}(u,v)} dvdu \quad (2)$$

The efficiency of recovery is also affected by irregularity in the height of the DA in cross section along a well pair. Under ideal conditions, the steam chamber should rise uniformly along an injection well, assuming injection rates are uniform along the entire length; therefore, the recovery rate could be decomposed into the product of recovery in a cross section perpendicular to the well with the length of the well. If the DA is non-uniform, the shape of the steam chamber and DA will not conform, thus having some negative influence on recovery rates. To account for this activity in DA optimization, the potential recoverable volume of bitumen above a well pair is augmented based on the distribution function, $F(h)$, of the thickness, h, between the producer and the TCB (Figure 6). In Eq. 2, z_{TCB} is replaced by z'_{TCB} that is defined by Eq. 3, where $h(q)$ is the thickness as a function of the probability, q, such that $F\big(h(q)\big) = q$.

$$z'_{TCB}(u,v) = \min\left(z_{TCB}(u,v), h(q) + z_j(u)\right) \quad (3)$$

Selecting a low value for q will lead to a potential recovery that is closer to the thin portions of a DA. As q increases, potential recovery increases. The more uniform the thickness is above a well, the less impact the choice of q has on results.

Recovery of a DA is approximated by the sum of the recovery of the set of m wells. To evaluate Eq. 2, the trajectory of the horizontal portion of the producer well, $z_j(u)$, must be defined. Solving for the trajectory is another optimization problem, related to but independent of the DA configuration optimization problem, that is applied to each well pair in a DA. In this work, horizontal wells are used so that $z_j(u) = z_j$; however, the final well trajectory will be permitted to vary along u within some design constraints. For the purpose of DA optimization it is reasonable to use horizontal wells. Solving for z_j is straightforward and is accomplished using a line search algorithm. Minimum and maximum values for z_j are equal to the corresponding elevations of the BCB surface along the producer. The optimal producer elevation exists somewhere in between.

Using wells that are exactly horizontal was chosen for simplicity, but also because their potential recovery will be dependent on the BCB geometry along it. If the base is very non-uniform relative to the producer, the well is placed higher to minimize stranded oil due to ineffective length, leading to increased stranded oil below the well in effective portions. At a different orientation, if the BCB is nearly horizontal, losses due to stranded oil are minimal. The dependency between horizontal wells and BCB uniformity will influence the SP – DA optimization process so that DAs are generally oriented where base conformance is good.

The objective function for optimization also accounts for costs, including: fixed capital costs for items such as surface facilities and land; supply costs that also included operating costs and royalties; and costs associated with horizontal wells that are not of a target design length (Fisher and Gill, 1999). The last cost assumes that if wells are too long or short, surface facilities or operating practices result in additional cost compared to wells that are approximately of the designed length. Capital cost is assumed to be a function of the number of well pairs in a DA in addition to a base cost and supply costs are expressed as a function of recoverable bitumen. The objective function is expressed by Eq. 4, where c_j is the cost associated with unordinary well length, $C(m)$ is the capital cost varying by the number of well pairs, and S is the supply cost.

$$F = \sum_{j=1}^{m} \left(R_j (1 - S) - c_j \right) - C(m) \quad (4)$$

Capital cost is expressed as Eq. 5, where C_0 is a base cost incurred independent of the number of well pairs, and C_j is the cost of a well pair (different from c_j):

$$C(m) = m \cdot C_j + C_0 \quad (5)$$

Units of recovery and costs are in barrels of bitumen, except for supply cost that is in barrels per barrel of bitumen recovered. The sum of the objective of all DAs in a set is the function used in the optimization problem given by Eq. 6, where n is the number of DAs.

$$P = \sum_{k=1}^{n} F_k \quad (6)$$

In the case of multiple realizations, the objective is the expected recovery over all realizations from a DA configuration defined by Eq. 7, where L is the number of realizations:

$$\overline{P} = \frac{1}{L} \sum_{l=1}^{L} \sum_{k=1}^{n} F_{lk} \quad (7)$$

For optimizing the DA configuration, evaluating the recovery of all well pairs within each DA must be efficient and fast computationally as it will be done potentially thousands of times for tens to hundreds of DAs involved in a configuration.

Optimization Strategy

Optimizing a configuration of DAs involves searching for the layout of DA locations, orientations, and sizes that maximizes economic value. The objective function described previously is intended to provide a measure of potential economic value in barrels of bitumen based solely on the geometric attributes of the problem; therefore it is dependent on the location and orientation of each DA. The objective function will ensure that good DA configurations are found, where our concept of goodness is based on specific properties of each DA. One of the properties is base conformance. Because horizontal wells are involved, recovery will tend to be higher in orientations where the base is flat or dipping perpendicular to the well pair orientation, with flatness measured on a length scale larger than $l_{\min}$. In such orientations, the volume of stranded oil is less. Another property is steam chamber uniformity for low choices of q from the thickness distribution function. Recovery will tend to be higher in locations and orientations where the volume for steam chamber expansion is uniform.

The optimization algorithm assumes that the set of DAs is compact and the well pairs within each DA are parallel. Such properties of DA configurations are evident in Figure 2 and in other published examples (ERCB, 2012). Other important features include:

1. DAs tend to conform to the geometry of the high quality reservoir by taking on a variety of orientations.
2. Well length is permitted to vary within some design constraints to provide aerial conformance when DAs are oblique to a boundary or high quality contour.
3. The number of well pairs within each DA is permitted to vary between some minimum and maximum number, with well pairs separated by some fixed distance.
4. Along any particular line of sight, the SPs appear to be on the same side of each DA, relative to one another.
5. The occurrence of SPs on adjacent sides of DAs is minimal. In other words, DAs are rarely in line connected heel to heel with wells facing opposite directions.
6. DAs that are in line (heel to toe) are staggered so that the toe positions of well pairs from one DA do not interfere with the heel positions of the wells from the adjacent DA.

Points 1, 2 and 3 can be explained from a recovery perspective, where obtaining better conformance to net reservoir leads to higher recoverable reserves. Point 4 is an economic factor, where a good arrangement of SPs minimizes surface facility costs, for example, two DAs joined toe to heel with SPs on the same side requires half as much road and pipeline as the same two DAs with SPs on opposite sides. Points 5 and 6 are related to minimizing well collisions during drilling.

To accommodate these assumptions and features, DAs are defined as quadrilateral areas with two sides that must remain parallel. The heel and toe edges can vary in their position and orientation and only loosely guide the position of the well pairs (Figure 7). Heel and toe edges are primarily in place for locating SPs and adjacent DAs. Parallel DA sides are separated by a distance, e, that is divisible by the well spacing, s, so that $e/s = m$ is the number of well pairs in the DA. The value e is the DA width. Another factor to consider in the optimization problem is the presence of topographical hazards, such as existing infrastructure, marshlands, and bodies of water such as rivers and lakes. If it is not feasible to develop a surface pad for a particular DA design, then such a design is suboptimal: well pairs for that DA cannot be drilled and operated.

Maintaining a compact configuration of DAs and parallel wells during optimization is accomplished by defining a fixed set of geometric transformations that can be applied to a DA configuration. First, a configuration is defined as a set of DAs that are stitched together in some area of interest that could be the limit of a reservoir or a lease boundary, see Figure 8, that also shows arbitrary surface culture and an NCB realization. DAs in the configuration are linked together into columns (DAs connected along sides) and columns are connected across tie-lines, also identified in Figure 8. The configuration is then manipulated in several predefined ways in search of an optimal configuration. Four geometric transformations are defined: global rotation; global translation; column rotation, and; column translation (Figure 9).

After each transformation, the DA configuration is updated in the following ways if the objective function increases: new columns are added, or existing non-profitable ones removed; new DAs are added to the ends of columns, or existing ones are removed; well pairs are added or removed from existing DAs, and; positions of toe and heel ends are adjusted to accommodate the producible length of wells. Also, columns are staggered to minimize the occurrence of well collision for DAs that are joined heel to toe or likewise. Staggering does not have a significant impact on the objective since the maximum possible distance a column is translated is equal to half the well spacing. Lastly, an attempt to create SPs for each DA is made. If an SP cannot be created on either end of a DA due to surface constraints, the DA is deleted. These updates ensure the objective function is maximized for a given configuration and are visible in Figure 8.

Maximizing the objective over all possible configurations is accomplished using an adaptive grid search approach (Zabinsky, 2003). The grid parameters are the global rotation angle, α, of the DA configuration and the global translation position, t. The rotation angle is searched in uniform sets of five between specified minimum and maximum rotation angles, α_0 and α_4 respectively. The grid step is equal to $d\alpha = (\alpha_4 - \alpha_0)/4$ and the set of angles is $\alpha_j = \alpha_0 + jd\alpha, j = 0, \dots, 4$. Global translation is also searched in uniform sets of five. It is applied in the direction of the current orientation, α_j, with minimum and maximum limits on the magnitude of translation, t_0 and t_4 respectively, being limited by the targeted well length, w, for the initial grid: $t_0 = -w, t_4 = w$. Translation of a configuration beyond these limits will result in repetition of the pattern of DAs because of the update processes discussed previously. After all 25 parameter sets are visited in search of an optimal, the grid search parameters are adapted so that the search space is reduced around the optimal set, denoted $(\alpha^*, t^*)^k$, where k is the iteration number. Adapting the grid is done by selecting a new centre point and step size for each parameter; however, this must be done in such a way that no set of parameters is visited more than once. For example, if the new grid was centred at the previous optimal, we would be re-visiting the previous optimal position and this does not add value to the optimization process.

For the next iteration in the grid search, the central rotation angle parameter is defined by Eq. 8, where $\alpha_j^{k-1} = \alpha^*$ and $\phi = (3 - \sqrt{5})/2 \cong 0.38197$ is derived from the golden ratio. The adapted translation parameters are determined similarly.

$$\alpha_2^k = \begin{cases} \alpha_j^{k-1} - \phi\left(\alpha_j^{k-1} - \alpha_{j-1}^{k-1}\right) & \text{if } \mathrm{P}\left(\alpha_{j-1}^{k-1}\right) \geq P\left(\alpha_{j+1}^{k-1}\right) \\ \alpha_j^{k-1} - \phi\left(\alpha_{j+1}^{k-1} - \alpha_j^{k-1}\right) & \text{if } \mathrm{P}\left(\alpha_{j-1}^{k-1}\right) < P\left(\alpha_{j+1}^{k-1}\right) \end{cases} \quad (8)$$

The new search range and step are then defined by Eq. 9:

$$\begin{aligned} \alpha_0^k &= \alpha_2^k - d\alpha^{k-1} \\ \alpha_4^k &= \alpha_2^k + d\alpha^{k-1} \\ d\alpha^k &= (\alpha_4^k - \alpha_0^k)/4 \end{aligned} \tag{9}$$

When the grid step becomes small enough, $d\alpha^k/d\alpha^0 + dt^k/dt^0 < \varepsilon$, where ε is a user defined bound, the last DA configuration with maximum recovery is considered optimal. An area of future work is to ensure that the solution is a global optimum within the initial grid search space. For each set of parameters in the grid, the configuration is manipulated via the other transformations to maximize the objective.

A line search (Scales, 1985; Sun and Yuan, 2010) is used for column translation that is applied in a direction perpendicular to α_j. The maximum column translation distance cannot exceed the maximum allowable DA width, $e_{\max}$, since the pattern of DAs in the column would begin to repeat afterwards due to the updating processes. To maintain good staggering of columns, translation is applied in whole increments of the well spacing. Optimizing column rotation is also done using a line search where the minimum and maximum possible angles for rotation are limited by the maximum allowable well length.
Column rotation and column translation are applied independently in the current version of the optimization algorithm. They are intended to find optimal positions, for a given global rotation and global translation, that maximize recovery in the presence of surface culture and find local DA orientations that result in better base conformance and more uniform steam chambers. The decision to apply these transformations independently is based on the assumption that the automatic updating operations provide a good initial approximation to the optimal objective after applying each of the transformations, and that interactions between them will not lead to a significantly higher recovery. Column translation and column rotation are applied in an iterative process: the algorithm cycles through optimizing translation and rotation until neither results in an increase in the objective function. An area for future work is to combine the optimization stages into a joint optimization algorithm for cases where the assumptions for independent optimization are invalid.

Not all geometric transformations must be applied for each optimization problem. It is possible to only consider global rotation, or only global translation and column rotation, or some other combination of the available transformations. The overall optimization process is as follows:

Algorithm OptimizeDrainareas
Input. An initial DA configuration, well spacing, target well length, minimum and maximum well length, minimum and maximum number of well pairs per DA, SP geometry, NCB, BCB, GCB surfaces, economic parameters, surface culture, lease boundary, permitted geometric transforms, initial global rotation angle range, stopping criteria.
Output. An optimal DA-SP configuration.

1. Initialize the 5×5 grid of global rotation and global translation parameters.
2. **While** $d\alpha^k/d\alpha^0 + dt^k/dt^0 > \varepsilon$
3.   **For** each set of parameters, $(\alpha_j, t_k), jk = 0, \ldots, 4$:
4.   **For** each column of DAs:
5.   **While** $\Delta P_i > 0$, where P_i is the objective function of column i:
6.   Optimize column translation.
7.   Optimize column rotation.
8.   Compute objective function $P(\alpha_j, t_k) = \sum P_i$
9.   **If** $P(\alpha_j, t_k) > P^k$, let $P^k = P(\alpha_j, t_k)$ and save the DA configuration.
10.   **If** $P^k > P^{k-1}$, save the corresponding (α_j, t_k)
11.   Update global rotation and global translation grid parameters.

Another assumption utilized for development of this optimization strategy is that the bitumen resource varies somewhat smoothly so that recovery is maximized for a DA configuration with the orientation of

DAs varying smoothly as well. Although column rotation allows some variation in DA orientation, abrupt changes such as DAs from one column being oriented at 90 degrees from an adjacent column are not possible. Such changes are observed in Figure 2.

Example

Synthetic surfaces were generated for demonstrating the optimization algorithm. They represent a massive fluvial or estuarine channel complex that has resulted in a high quality reservoir. Surface culture in the form of a river and a small lake are present. An arbitrary lease boundary is used as an area of interest (Figure 10). DA geometry was chosen to be nominally 2000 m length by 1400 m width with a well spacing of 200 m. The target well length was 2000 m and minimum and maximum allowable well lengths were 1000 m and 2500 m respectively. This target length is admittedly larger than many current development plans; however, it is simply an input parameter to the optimization and could be changed. Minimum, maximum, and target number of well pairs for each DA was three, ten and seven, respectively. Surfaces were defined on a grid that was 600 by 500 cells in x and y respectively, with a cell size of 50 m by 50 m. Only one realization was generated for this example. For global rotation, minimum and maximum rotation angles were set to 0 and 90 degrees respectively. Stopping criteria for the grid search was 0.1.

The initial DA configuration is shown in Figure 10 and it has a value of 339.54 million barrels of bitumen. Good conformance and a significantly higher value was achieved by using all geometric transformation processes during optimization: global rotation finds the overall orientation of highest quality reservoir; global translation obtains conformance with the lease boundary in the same orientation and prevents some losses due to surface hazards; column rotation finds the local orientation of the high quality reservoir, and; column translation avoids surface hazards and centres the columns of DAs over the channels (Figure 11). Optimization took 20 minutes on a single 2.13 GHz processor and resulted in a value of 626.05 million barrels, an increase of 130 %.

Optimization resulted in the majority of DAs being aligned with the local orientation of the channel. In this direction the BCB and TCB are more uniform, resulting in horizontal wells with better base conformance and more uniform steam chambers. A cross section of a DA that is oriented roughly perpendicular to the channel prior to optimization and another in the same area oriented parallel to the channel after optimization is shown in Figure 12. The resulting arrangement of DAs has also avoided positions where the SPs conflict with surface hazards. Around the lake, DAs are arranged to maximize recovery from beneath it in the high quality zone.

There are four cases where SPs are positioned on adjacent DAs that result in a probability of well collision. This is caused by some SPs being swapped from one end of a DA to the other when there was interference with a surface hazard. In the event such a change leads to two conflicting SPs, swapping would have to be cascaded through DAs to minimize their occurrence. Some limitations of the compact arrangement are also evident. For example, a profitable DA could likely be placed at a few points identified in Figure 11; however, the column structure and orientation near those areas prevents their creation.

The optimization algorithm could be applied in subareas with separate compact sets. Individual DAs in stranded areas could also be introduced. A second example is used to demonstrate optimization in subareas within the same lease. Synthetic surfaces and the lease boundary are shown in Figure 13. Surfaces were defined on a 400 by 400 cell grid with 20 by 20 m cells. Surface culture consists of rivers and isolated pools that were placed to interfere with high pay regions. Surface culture polygons were generated with a setback of 100 m from the actual rivers. The lease is broken into three subareas labelled A, B and C. Wells were given a target length of 1000 m and a spacing of 100 m. Minimum and maximum well length was 500 m and 1500 m respectively. The target number of wells was 7 and this was permitted to range from 3 to 8. Optimization was applied using global rotation and column translation to the whole area together and then to each subarea independently.

Optimization over the whole area took 167 seconds and resulted in an increase in value from 124 M barrels for an initial configuration with all DAs facing north-south to 139 M barrels for the configuration shown in Figure 14. Optimization of the subareas took 196 seconds and resulted in an increase from 114 M barrels to 140 M barrels for the configuration shown in Figure 15. The difference in the values of these configurations is small; however, larger differences are observed for other factors including total bitumen recovered and aerial and vertical conformance (Table 1). Aerial conformance was calculated as the ratio of the area of the 10 m NCB thickness contour inside DAs to the total area of the same contour. Vertical conformance was calculated as the ratio of NCB above production wells to total NCB along the wells. By considering subareas, optimization results in more recovery and better conformance.

Table 1 — Optimization results for example 2

Region	No. DAs	Initial Value M bbl	Final Value M bbl	Recovery M bbl	Aerial Conformance %	Vertical Conformance %
A+B+C	40	124	139	334	87.2	91.8
A	16	36.7	50.5	128	88.9	92.5
B	9	25.7	31.5	75	92.6	91.8
C	17	51.5	58.3	143	90.2	92.6
Total	42	114	140	346	90.1	92.4

Conclusions

Optimization can be utilized to automatically design the preliminary layout of drainage areas and surface pads for SAGD applications. Optimization is done to maximize the economic potential or recovery from a set of drainage areas for deterministic models or multiple realizations. The optimization problem was defined with an objective function and set of rules so that viable DA configurations are found. Resulting configurations were shown to yield significantly higher values than naive configurations. Considering the complexity of the problem, optimization executes in a reasonable amount of time; however, a deterministic model was used in the examples and longer times are incurred with multiple realizations. As problem complexity increases, the optimal configuration will not be intuitive and optimization techniques will provide a much more in depth search of the parameter space. Additional rules and constraints are needed in the presented algorithm for more complex cases as well.

Research and development in this area is ongoing. The version presented is somewhat limited because the optimal configuration may not consist of a paved set of DAs. It was shown that an area can be broken up into subareas to achieve a more disjoint configuration; however, such a partitioning may not be immediately obvious. Further research in this area includes development of an algorithm that works with loose DA configurations, that is, DAs are not joined with columns and tie-lines. This will allow the optimization algorithm to discover locally where different orientations are needed to obtain better conformance, avoid surface hazards, and obtain a better optimum. Another area of development involves the configuration of SPs. The current version places them wherever possible without considering the impact on surface facility costs. Instead, SPs will be positioned to minimize surface facility costs and this may also have an impact on the optimal DA configuration in situations where facility costs are excessive.

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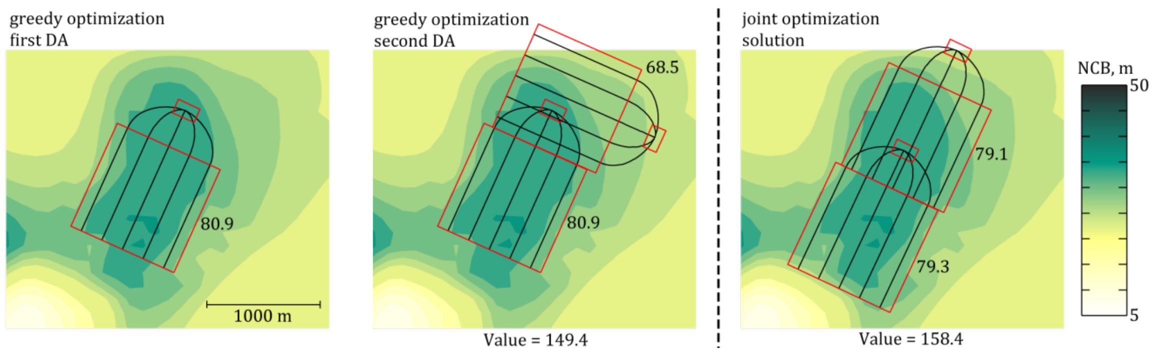

Figure 1: Greedy versus joint optimization techniques for maximizing recovery. Values are relative and were calculated by integrating the area of contour polygons inside the DAs.

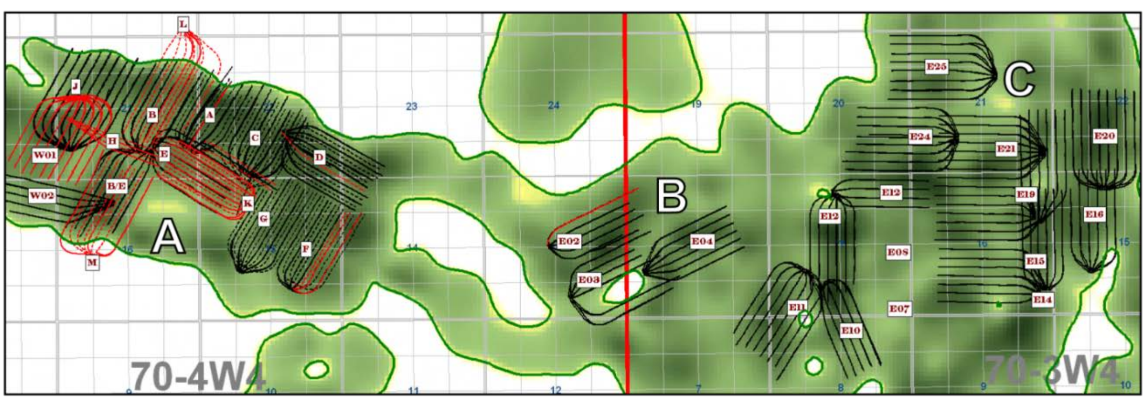

Figure 2: Aerial view of three compact sets of DAs (marked A, B, C) in the Cenovus Foster Creek area (Cenovus Energy, 2011, page 38). Black lines indicate well trajectories. The lower left portion of set C appears more disconnected.

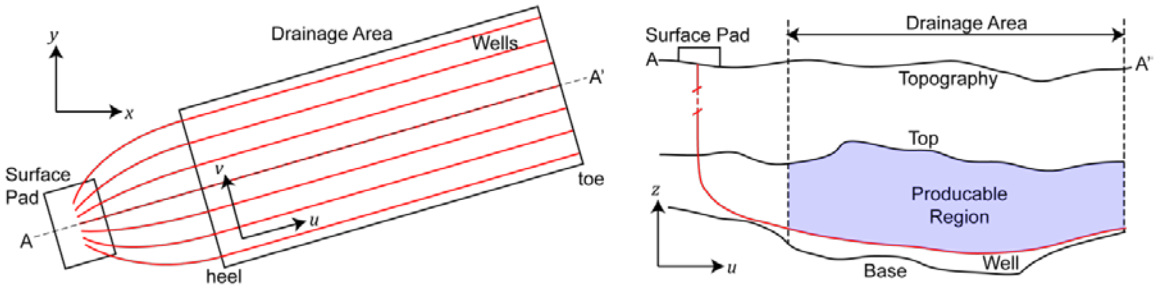

Figure 3: Top view of DA and SP layout (left) and cross section showing deviated well and producible region (right). Steam injector not shown.

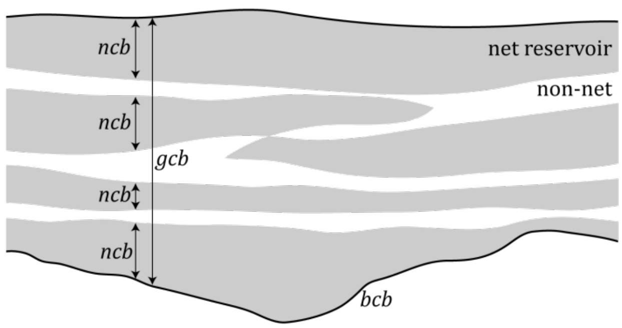

Figure 4: Schematic of NCB, BCB and GCB.

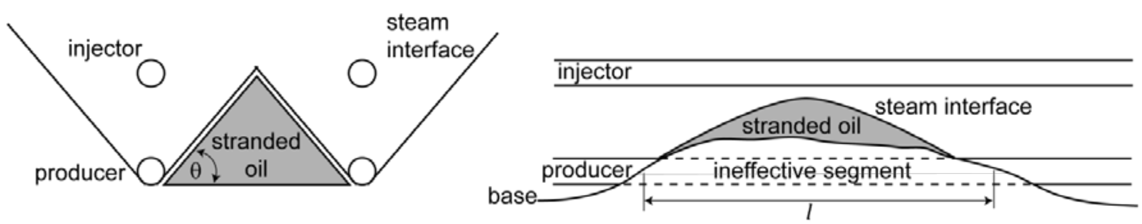

Figure 5: Idealized cases of stranded oil (bitumen) between neighbouring well pairs (left) and above a length, l, of ineffective production well. When l is small enough, the stranded oil is assumed zero.

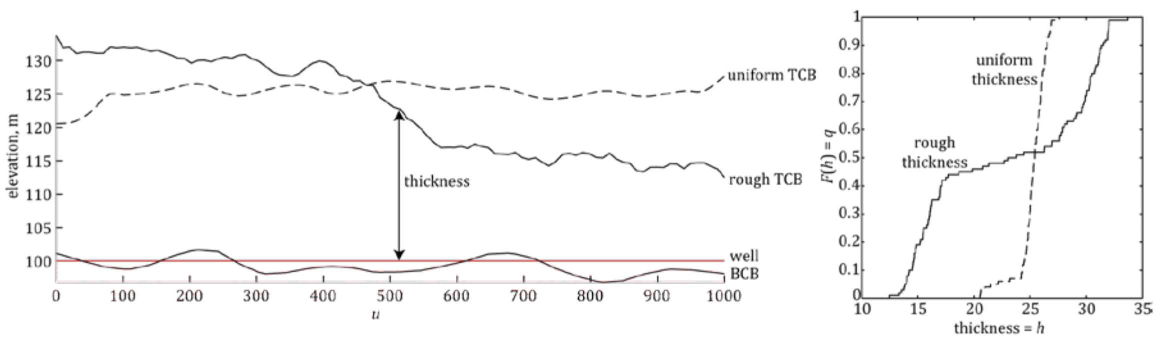

Figure 6: Examples of distribution functions of thickness for a rough TCB and uniform TCB used to augment recovery for a DA.

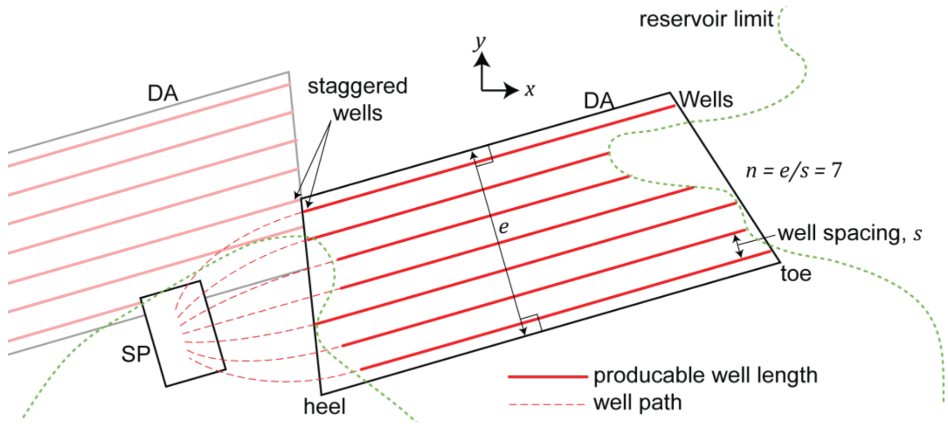

Figure 7: DA geometry, also showing well spacing, variable well length and staggered wells for DAs joined from toe to heel.

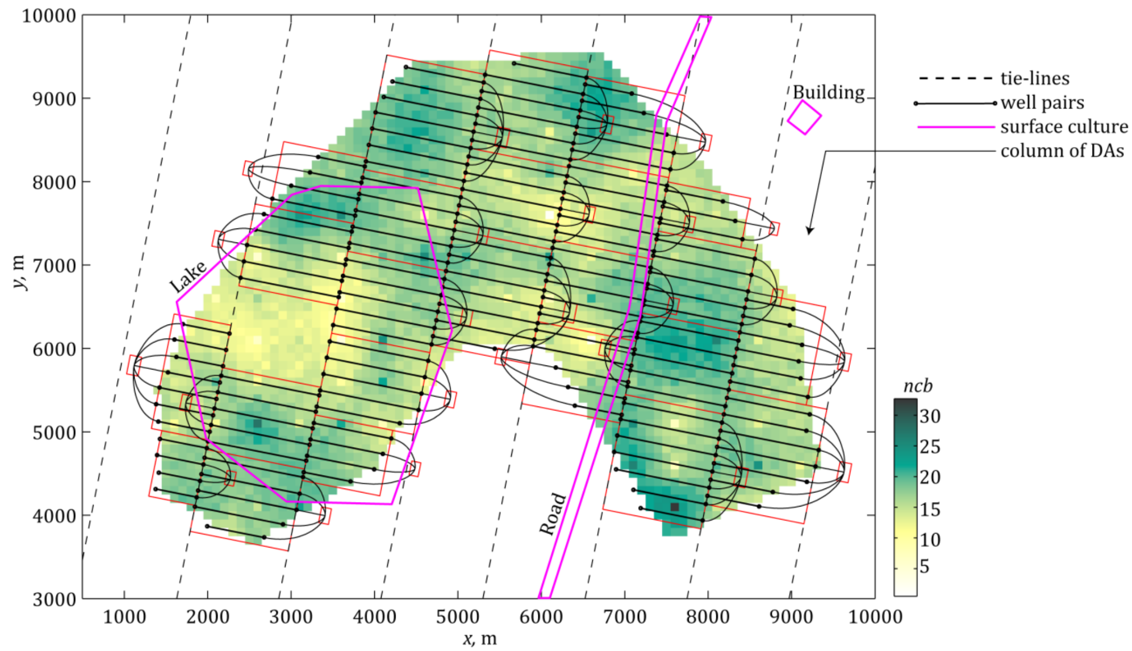

Figure 8: Example of a compact DA configuration, also showing surface culture and organization of DAs into columns separated by tie-lines.

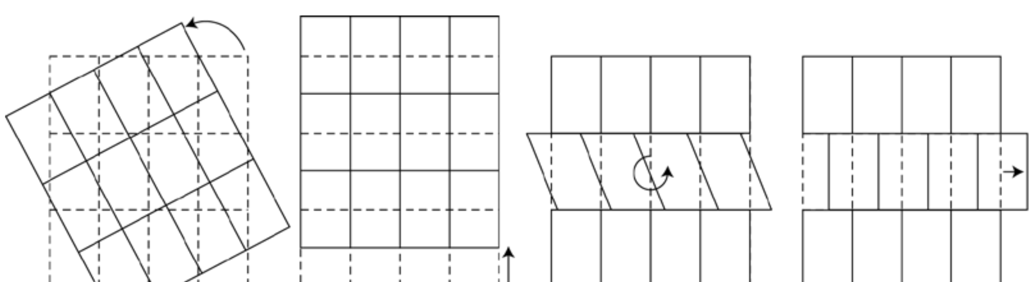

Figure 9: Operations used in DA optimization, from left to right: global rotation, global translation, column rotation, and column translation. Dashed lines indicate the initial configuration.

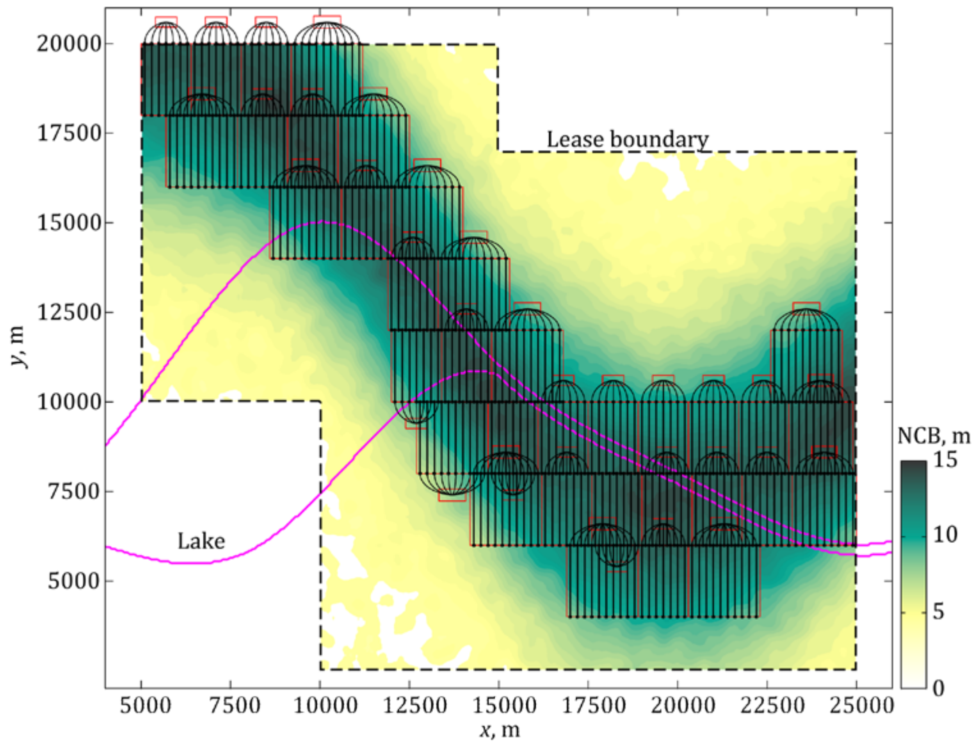

Figure 10: Initial DA configuration from example.

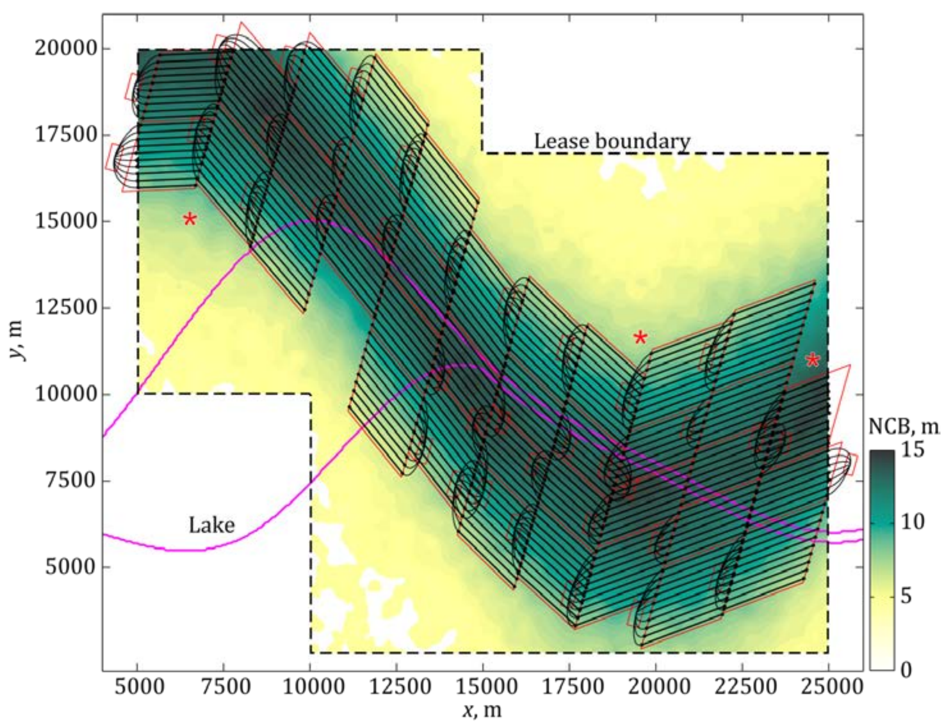

Figure 11: Final DA configuration from example. Asterisks indicate possible recoverable areas that optimization was unable to position a DA.

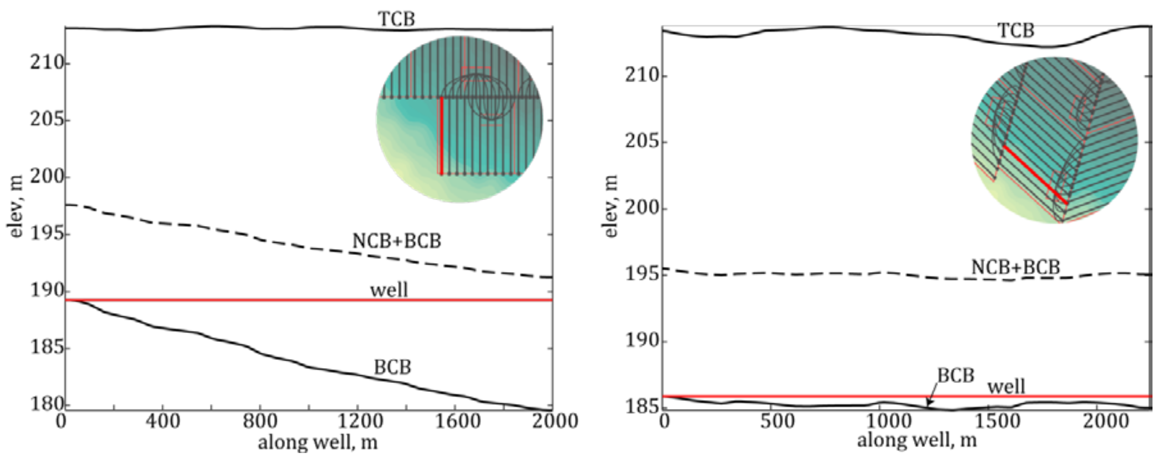

Figure 12: Wells from a DA from the initial configuration (left) and optimal configuration (right) in approximately the same locations. Insets indicate well shown in each cross section, roughly at $x = 17{,}500\ m$ and $y = 4{,}000\ m$.

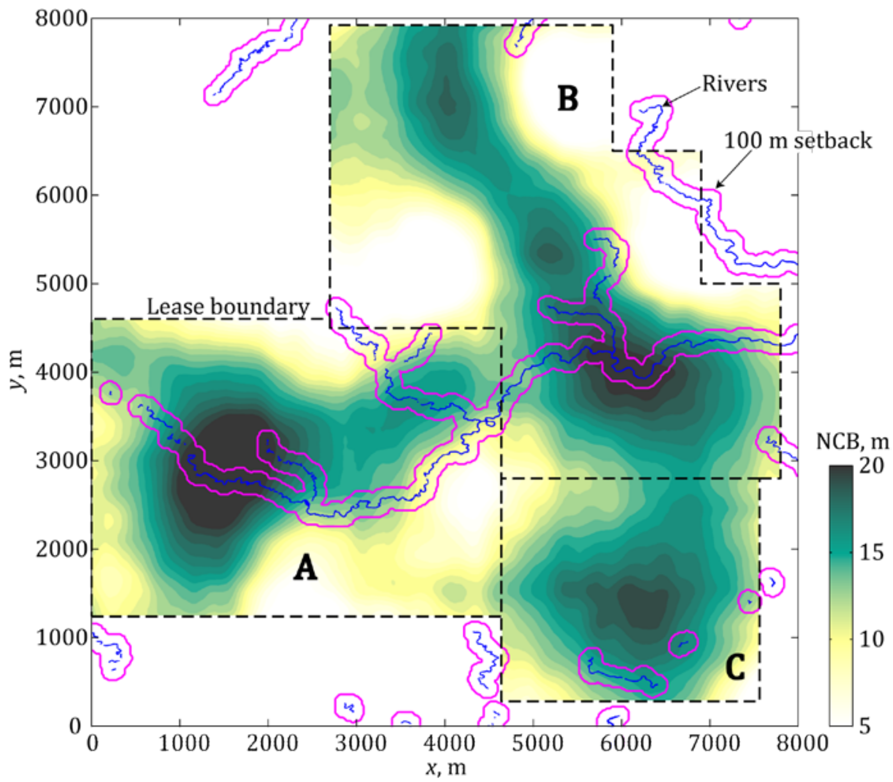

Figure 13: NCB, surface culture, and subareas A, B and C for example 2.

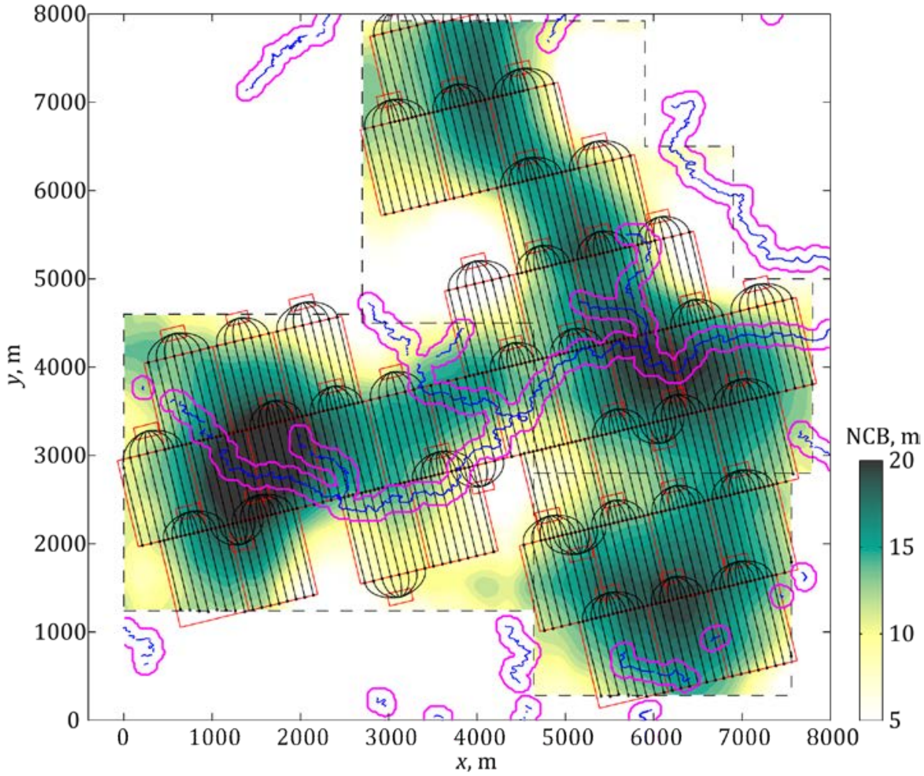

Figure 14: DA configuration from optimization over the entire area.

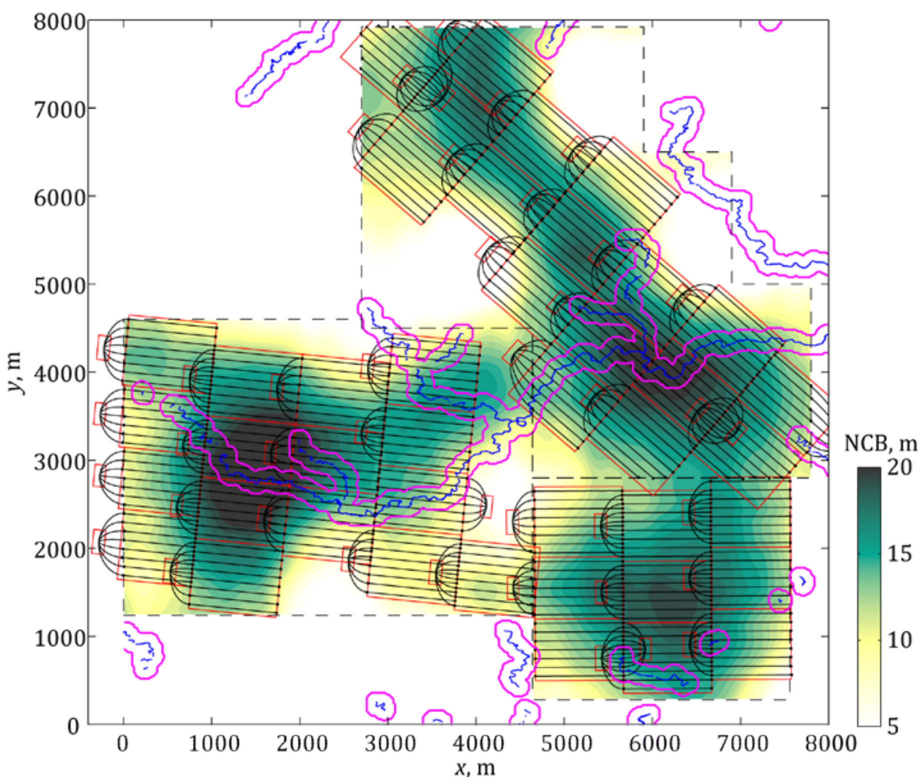

Figure 15: DA configuration from optimizing regions A, B and C (see Figure 13) independently.