DEVELOPMENT OF CAD-SPREADSHEET INTEGRATED SOLUTON TO OPTIMIZING SITE GRADING DESIGN FOR INDUSTRIAL CONSTRUCTION

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ABSTRACT

Industrial construction covers a wide range of construction projects that are essential to our utilities and basic industries, such as petroleum refineries and petrochemical plants, synthetic fuel plants, fossil fuel and nuclear power plants etc. Land formation for an industrial construction site needs to consider many engineering constraints such as (1) ensuring proper drainage, (2) prevention of flood, (3) driving safety, (4) optimizing earthwork by balancing cut and fill, (5) minimizing truck travel distances in earthmoving, and (6) proper equipment matching for achieving high equipment utilization rates. We have developed a computer-based application framework by seamlessly integrating earthwork design in CAD and earthwork optimization in spreadsheet, in order to facilitate the practical application of the proposed framework on site formation for industrial construction. This paper presents an optimization problem formulation in an Excel spreadsheet model based on the least squares method. The *Solver* utility for optimization analysis in Excel provides a cost-effective tool to identify the optimum design surface model satisfying practical constraints on slopes and the highest elevation. A case study is used to demonstrate the effectiveness of the proposed application framework for earthwork optimization based on site formation on an industrial project in Alberta.
Keywords: earthwork, optimization least squares method, cut/fill balance, CAD, Excel Solver,

1. INTRODUCTION

Industrial construction covers a wide range of construction projects that are essential to our utilities and basic industries, such as petroleum refineries and petrochemical plants, synthetic fuel plants, fossil fuel and nuclear power plants etc. Earthwork design for the purpose of land development and site formation in the context of industrial construction intends to shape the existing ground surface to fit its designed usage such as buildings, roads, plants, irrigations etc. To reduce cost, earthworks demands careful assessment of the cut / fill balance, balancing the cut / fill earthwork or minimizing the quantity of surplus / borrowing material, at the same time, maintaining grading design to prevent erosion and flooding while providing a safe driving environment. Earthwork optimization based the least squares method is the most popular technique for such applications. Nonetheless, previous attempts of utilizing the least squares method encountered many challenges including: (1) the oversimplified problem definition overlooking practical constraints (2) the complexity of the mathematical formulation and optimization (3) the difficulty in finding the optimum solutions from mathematical models. This paper will present a modification of the least squares method to overcome these challenges. Additionally, we have developed a computer-based application framework by seamlessly integrating earthwork design in CAD and earthwork optimization in Excel, in order to facilitate the practical application of the proposed framework on industrial construction site formation.

2. EARTHWORK OPTIMIZATION

Traditionally, experienced civil engineers manually perform site formation design by the cell grid method, the end section method or other methods. Usually several solutions will be created from the manual process, and the best one will then be chosen. Because the intensive earthwork design and calculation relies heavily on human expertise, the site formation design can be time-consuming, tedious and expensive. In the past few decades, researchers have tried to devise mathematical methods enabling the generation of the best design plane for grading design on a particular site. Those methods include "least squares" methods (Givan 1940, Chugg 1947, Scaloppi and Willardson 1986, Reddy et. al 1996), the fixed center method (Raju 1960), the warped-surface method (Harris et al., 1966), the residual method (Shih and Kriz 1971, 1973), the linear programming (Semerdon et al., 1966), the non-linear programming (Hamad et. al., 1990, Reddy et. al., 1996), and the weighted average method (Reza 2004). Despite different methods developed for earthwork optimization, the "least squares" method is still considered the most accurate and most widely applied (Gebre-Selssie 1991).

Scaloppi and Willardson (1986) presented a hand calculation solution that applies the least squares method to find the minimum cut and fill plane. The sample data from Chugg (1947) are used to illustrate the procedure for finding the plane surface, which fits best for the existing surface of an irregularly shaped field and to illustrate the use of the least squares plane in land grading design. The relative elevations of the field surface are given in the Figure 1. Note Figure 1 also shows the rectangular grid system used in the computations along with the area weighing factors defined for the determination of cut or fill volumes on each cell.

O	X_1	X_2	X_3	X_4	X_5	X_6	X_7
Y_1	0.65 6.6	1.00 6.1	1.00 6.7	0.55 6.7	0.0	0.0	0.0
Y_2	0.80 5.7	1.00 5.4	1.00 5.9	0.80 6.0	0.0	0.0	0.0
Y_3	0.85 4.7	1.00 4.4	1.00 5.0	1.40 5.4	0.0	0.0	0.0
Y_4	1.20 4.0	1.00 3.8	1.00 4.2	1.00 4.4	1.00 4.2	1.30 3.9	0.75 3.8
Y_5	1.20 3.4	1.00 3.1	1.00 3.5	1.00 3.4	1.00 3.6	1.00 3.2	1.10 2.9
Y_6	0.80 2.7	1.00 2.2	1.00 3.2	1.00 2.6	1.00 2.4	1.00 2.3	1.30 2.2
Y_7	0.0	1.35 1.5	1.00 2.0	1.00 1.6	1.00 1.8	1.00 1.7	1.00 1.5
Y_8	0.0	0.80 0.7	1.20 1.2	1.25 0.7	1.25 1.0	1.12 1.0	0.55 0.9

Area assigned to a grid point

W_{ij} ← Area weighting factor
H_{ij} ← Elevation at grid point

Figure 1. Sample for illustrating the use of the least squares plane in land grading design

The computation is performed by considering the unit distance and the unit area of the grid according to the proposed procedure. At the end of the computation, the appropriate actual field dimensions can be used to compute the volumes of cuts and fills. The field and office procedure is outlined as follows:

- Stake the field in a regular grid pattern. Measure the distance from the last grid point in each line to the edge of the field in both directions in order to define the field boundaries.
- Determine the elevation of each grid point and the elevation of the soil surface at the end of each grid line projected to the edge of the field. This latter information is not used in the computations but is needed to mark cuts and fills at the edges of the field for the benefit of the machine operators when the actual grading is done.

- Draw a plan map of the field and sketch the field boundaries.
- At each grid point, write the elevation.
- Write a weighting number for each grid point above the elevation of the grid point to indicate the area weighting factor for that grid point. Interior regular grid points have a weighting factor of 1.00. Grid points on the boundary will have area weighting factors greater or less than 1.00 depending on the size of surface area represented by the grid. For an area outside regular grid dimensions that could be represented by more than one grid point, add the extra area to the grid point in the direction of least slope.
- Assign zero elevations for grid points that fall outside the field boundaries.
- Using the least squares method, compute the equation of the least squares plane, and the coordinates and elevation of the centroid. Any grid point with a zero elevation is not included in the calculation.

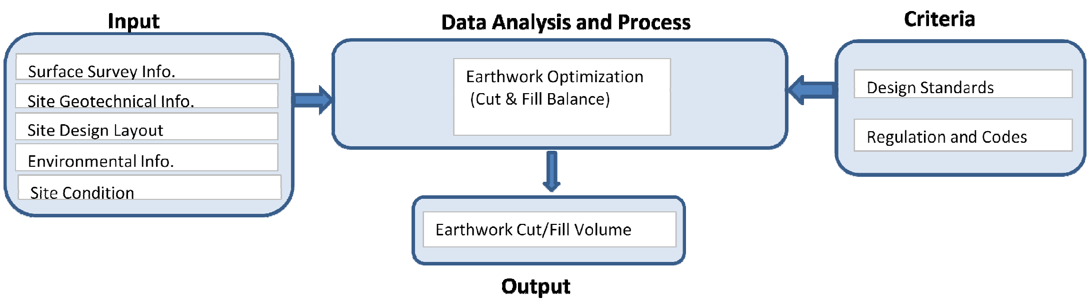

Figure 2. proposed methodology for minimizing the cut and fill volumes at a particular site

As illustrated in Figure 2, the proposed methodology is aimed to balance or minimize the cut and fill volumes at a particular site; at the same time, it also produces workable drainage patterns on the site. To materialize this methodology, an algorithm is introduced in this research: First, the ground grid cell system is generated. Note the grid's distance cannot be too large; otherwise, the calculation will not be accurate; the grid's distance cannot be too small either, because the too trivial cut/fill cubes will be generated from those grids for the existing land surface, rendering the ensuing optimization analysis to be intractable. Then, the CAD export function can be used to export the geometric information of the existing land surface model to Excel. Based on the site-grading requirement, a site type is chosen to create the initial land formation design model prior to optimization (site type specifies the highest point on the site along with the directions of the desired slopes.) Then, the least square method is applied on an automatically generated spreadsheet formulation in Excel and the 'Solver' function is invoked to arrive at the optimum grading elevations and slopes. The proposed solution has been thoroughly evaluated on multiple practical cases, producing promising results for all the cases tested. Figures 3 and 4 shows the workflow on how to generate a grid and transfer geometric design information from AutoCAD to an Excel optimization model.

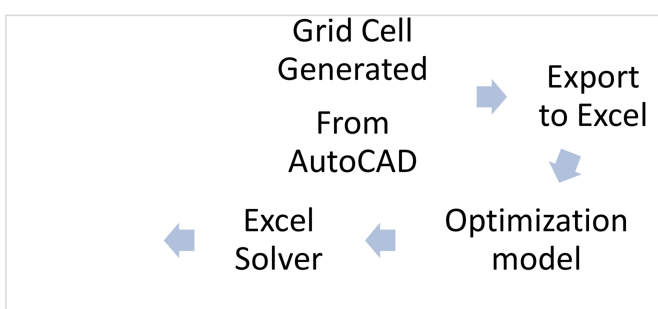

Figure 3: Workflow on how to generate a grid and transfer geometric design information from AutoCAD to an Excel optimization model

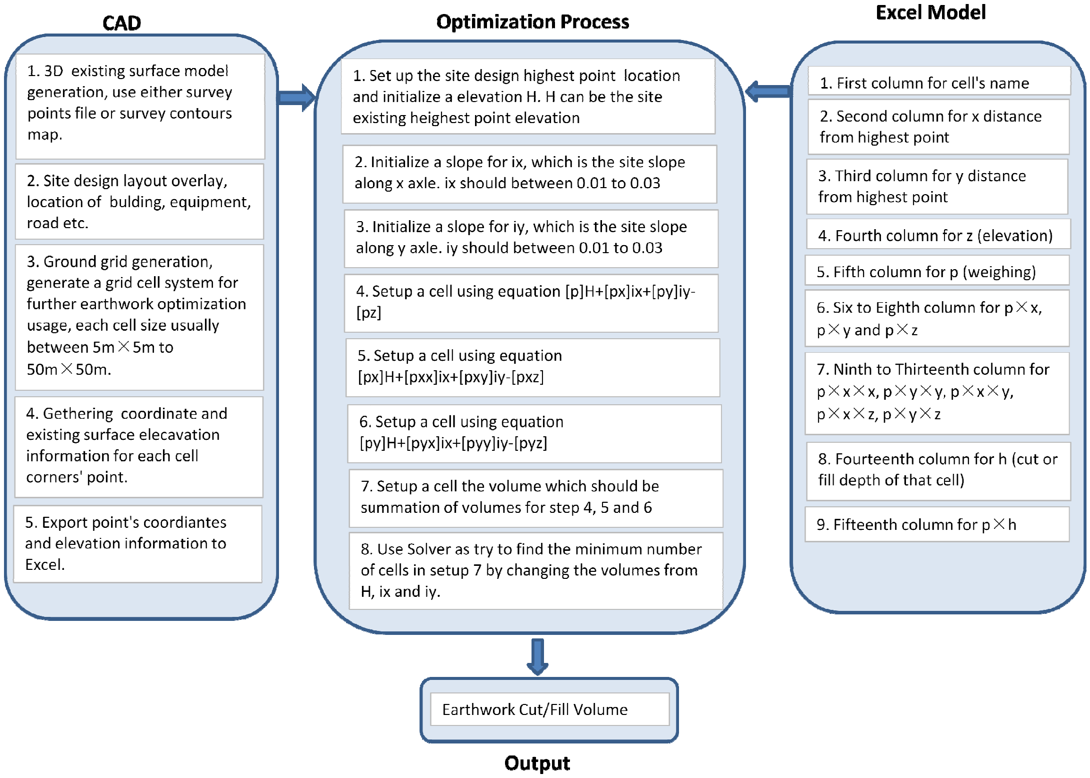

Figure 4: Optimization Model Using Least Squares Method

Modification of least squares method for earthwork optimization

The basic theory of the "least squares" method is reviewed in order to find a new way to model and solve the problem by taking full advantage of computer power. The "least squares" method being applied can be illustrated with the following figure.

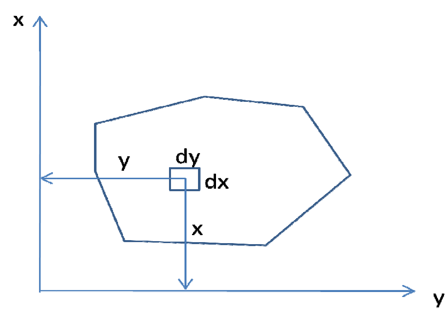

Figure 5: Least squares method illustration

dv	the earthwork volume at dxdy
H	the highest design point's elevation
ix	grading slope along x axis
iy	grading slope along y axis
x,y	the distance from dxdy to x axis and y axis
z	the existing elevation at dxdy

Base on the least squares method, the objective is to find the minimum earthwork volume as defined in Eq. 1:

$\text{Min} \sum_{i=1}^{n} dV^2 = \text{Min} \sum_{i=1}^{n} (H + ixX + iyY - z)^2 dxdy$ Eq.1

Subject to a set of constrains on practical ranges of slopes as:
$0.01 \leq ix \leq 0.03$
$0.01 \leq iy \leq 0.03$

Taking the partial differentiation along H, ix and iy directions, and let them equal to 0, giving the following equations:

$\sum_{i=1}^{n} (H + ixX + iyY - z)dxdy = 0$ Eq.2
$\sum_{i=1}^{n} X(H + ixX + iyY - z)dxdy = 0$ Eq.3
$\sum_{i=1}^{n} Y(H + ixX + iyY - z)dxdy = 0$ Eq.4

To describe it with double integral, we have
$\int^{x} \int^{y} (H + ixX + iyY)\, dxdy$ Eq.5
$\int^{x} \int^{y} X(H + ixX + iyY)\, dxdy$ Eq.6
$\int^{x} \int^{y} Y(H + ixX + iyY)\, dxdy$ Eq.7

If Gauss function ([x], x is integer) is used instead of double integral, then we have a group of criterion formulas as
[H]+[x]ix+[y]iy-[z]=0 Eq.8
[x]H+[xx]ix+[xy]iy-[xz]=0 Eq.9
[y]H+[yx]ix+[yy]iy-[yz]=0 Eq.10

Then we take the weighting factor p into consideration, the group of formulas will change to
[p]H+[px]ix+[py]iy-[pz]=0 Eq.11
[px]H+[pxx]ix+[pxy]iy-[pxz]=0 Eq.12
[py]H+[pyx]ix+[pyy]iy-[pyz]=0 Eq.13

Then
[ph]=0; Eq.14
h= H + ixX + iyY – Z Eq.15

h is the design elevation.

Numerous research efforts have successfully demonstrated how to effectively formalize spreadsheet solutions to complicated problems in construction engineering and management. The Excel spreadsheet model for implementing the least squares method is given in Table 1.

The least squares formulation for earthwork optimization can be conventionally solved by determinants and heuristic rules (such as Cramer's Rule.) These methods involve intensive manual calculation, which is time consuming and also difficult to program. The method presented in this paper uses an alternative way to solve the linear equations. First, based on the traditional grid cell method, the grid cells are created in certain intervals, e.g. every 20m. Then the average existing surface elevation in each cell is extracted from the 3D CAD model. The information is then transferred to an Excel file. Next, the standard linear programming model is automatically created in an Excel spreadsheet. Note each row corresponds with one particular cell in the site grid. Thus, the total number of rows is dependent on how many cells are defined in the site layout grid. By adjusting the highest elevation at a corner point on the site (H) and the two slopes (ix and iy) which are all bound on preset ranges, the "Solver" is used to drive the cell "*d*" at the right bottom corner of Table 1 to zero so as to satisfy all the optimum conditions given in Eq. 11-13. The end results from the "Solver" optimization are the optimum values for H, ix, and iy, along with the design elevations at each grid point (*h*) based on the derived design surface model. In this case, the optimum solution is shown Table 1: the highest elevation will be on the left-bottom corner of the site with elevation 5.99 m and the x axis's slope is 1.5% and y axis's slope is 1.7%. Lastly, the cut or fill volumes on each cell in the site grid can be calculated by elevation comparison between the existing surface and the designed surface.

Cell	x	y	z	p	px	py	pz	pxx	pyy	pxy	pxz	pyz	h	ph
X_1Y_1	0	0	6.6	0.65	0	0	4.29	0	0	0	0	0	-0.006	-0.003902
X_1Y_2	0	100	5.7	0.80	0	80	4.56	0	8000	0	0	456	0.020821	0.0166568
X_1Y_3	0	200	4.7	0.85	0	170	3.995	0	34000	0	0	799	0.048644	0.0413477
X_1Y_4	0	300	4.0	1.20	0	360	4.8	0	108000	0	0	1440	0.073468	0.0881613
X_1Y_5	0	400	3.4	1.20	0	480	4.08	0	192000	0	0	1632	0.097291	0.1167494
X_1Y_6	0	500	2.7	0.80	0	400	2.16	0	200000	0	0	1080	0.122115	0.0976916
X_2Y_1	100	0	6.1	1.00	100	0	6.1	10000	0	0	610	0	-0.01604	-0.016037
X_2Y_2	100	100	5.4	1.00	100	100	5.4	10000	10000	10000	540	540	0.008787	0.0087865
X_2Y_3	100	200	4.4	1.00	100	200	4.4	10000	40000	20000	440	880	0.03661	0.0366099
X_2Y_4	100	300	3.8	1.00	100	300	3.8	10000	90000	30000	380	1140	0.060433	0.0604333
X_2Y_5	100	400	3.1	1.00	100	400	3.1	10000	160000	40000	310	1240	0.085257	0.0852567
X_2Y_6	100	500	2.2	1.00	100	500	2.2	10000	250000	50000	220	1100	0.11208	0.1120801
X_2Y_7	100	600	1.5	1.35	135	810	2.025	13500	486000	81000	202.5	1215	0.136903	0.1848197
X_2Y_8	100	700	0.7	0.80	80	560	0.56	8000	392000	56000	56	392	0.162727	0.1301815
X_3Y_1	200	0	6.7	1.00	200	0	6.7	40000	0	0	1340	0	-0.03707	-0.037071
X_3Y_2	200	100	5.9	1.00	200	100	5.9	40000	10000	20000	1180	590	-0.01125	-0.011248
X_3Y_3	200	200	5.0	1.00	200	200	5	40000	40000	40000	1000	1000	0.015575	0.0155755
X_3Y_4	200	300	4.2	1.00	200	300	4.2	40000	90000	60000	840	1260	0.041399	0.0413989
X_3Y_5	200	400	3.5	1.00	200	400	3.5	40000	160000	80000	700	1400	0.066222	0.0662223
X_3Y_6	200	500	3.2	1.00	200	500	3.2	40000	250000	100000	640	1600	0.087046	0.0870457
X_3Y_7	200	600	2.0	1.00	200	600	2	40000	360000	120000	400	1200	0.116869	0.1168691
X_3Y_8	200	700	1.2	1.20	240	840	1.44	48000	588000	168000	288	1008	0.142692	0.1712309
X_4Y_1	300	0	6.7	0.55	165	0	3.685	49500	0	0	1105.5	0	-0.05211	-0.028658
X_4Y_2	300	100	6.0	0.80	240	80	4.8	72000	8000	24000	1440	480	-0.02728	-0.021826
X_4Y_3	300	200	5.4	1.40	420	280	7.56	126000	56000	84000	2268	1512	-0.00346	-0.004843
X_4Y_4	300	300	4.4	1.00	300	300	4.4	90000	90000	90000	1320	1320	0.024364	0.0243644
X_4Y_5	300	400	3.4	1.00	300	400	3.4	90000	160000	120000	1020	1360	0.052188	0.0521878
X_4Y_6	300	500	2.6	1.00	300	500	2.6	90000	250000	150000	780	1300	0.078011	0.0780112
X_4Y_7	300	600	1.6	1.00	300	600	1.6	90000	360000	180000	480	960	0.105835	0.1058346
X_4Y_8	300	700	0.7	1.25	375	875	0.875	112500	612500	262500	262.5	612.5	0.132658	0.1658225
X_5Y_4	400	300	4.2	1.00	400	300	4.2	160000	90000	120000	1680	1260	0.01133	0.01133
X_5Y_5	400	400	3.6	1.00	400	400	3.6	160000	160000	160000	1440	1440	0.035153	0.0351534
X_5Y_6	400	500	2.4	1.00	400	500	2.4	160000	250000	200000	960	1200	0.064977	0.0649768
X_5Y_7	400	600	1.8	1.00	400	600	1.8	160000	360000	240000	720	1080	0.0888	0.0888002
X_5Y_8	400	700	1.0	1.25	500	875	1.25	200000	612500	350000	500	875	0.114624	0.1432795
X_6Y_4	500	300	3.9	1.30	650	390	5.07	325000	117000	195000	2535	1521	-0.0007	-0.000916
X_6Y_5	500	400	3.2	1.00	500	400	3.2	250000	160000	200000	1600	1280	0.024119	0.024119
X_6Y_6	500	500	2.3	1.00	500	500	2.3	250000	250000	250000	1150	1150	0.050942	0.0509424
X_6Y_7	500	600	1.7	1.00	500	600	1.7	250000	360000	300000	850	1020	0.074766	0.0747658
X_6Y_8	500	700	1.0	1.12	560	784	1.12	280000	548800	392000	560	784	0.099589	0.1115399
X_7Y_4	600	300	3.8	0.75	450	225	2.85	270000	67500	135000	1710	855	-0.01474	-0.011054
X_7Y_5	600	400	2.9	1.10	660	440	3.19	396000	176000	264000	1914	1276	0.012085	0.013293
X_7Y_6	600	500	2.2	1.30	780	650	2.86	468000	325000	390000	1716	1430	0.036908	0.0479803
X_7Y_7	600	600	1.5	1.00	600	600	1.5	360000	360000	360000	900	900	0.061731	0.0617313
X_7Y_8	600	700	0.9	0.55	330	385	0.495	198000	269500	231000	297	346.5	0.085555	0.0470551
			153.2	45.22	12485	17984	149.865	5016500	9110800	5572500	36354.5	43934	2.419926	2.54275
H														5.9997554
ix														0.0150344
iy														-0.017823
a	[p] H + [p x] i x + [p y] i y - [p z] =0													-11.38712
b	[p x] H + [p x x] i x + [p x y] i y - [p x z] =0													14651.803
c	[p y] H + [p y x] i x + [p y y] i y - [p y z] =0													-14640.42
d														-0.000001

Table 1: The Excel spreadsheet model for implementing the least squares method

The proposed application framework based on CAD-Excel integration provides practitioners with a more user-friendly, flexible and integrated earthwork design solution. For instance, there are almost an infinite number of feasible grades the designer can choose from, all of which satisfy the geometric specifications of the site. If the designer wants to move the coordinates of the desired highest point on the site or change the slope ranges, a different design surface model can be easily considered in the optimization analysis by simply changing the formulas behind the cells in column "*h*".

The function of extracting data from CAD to Excel is not available in AutoCAD itself. The present research uses a third party plug-in called *Cad2File* created by Psanders (2008) for illustrating the proposed application framework. This plug-in function can export a selected feature (e.g. arc, line, circle, ellipse, point, solid, text, etc.) to a file, either in text format or Excel .csv format. The *Cad2File* interface is shown in Figure 6. The optimization results obtained in Excel can be exported back to CAD in order to update the design surface with the optimum model, which can be based on the similar techniques applied in Hotchkiss (2007).

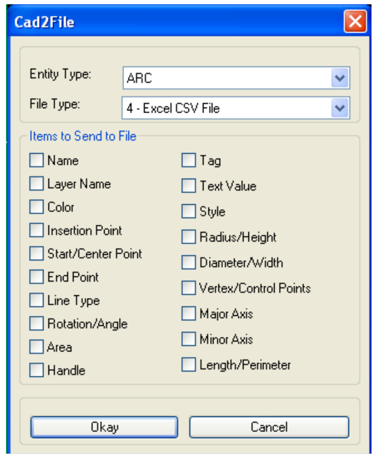

Figure 6: Cad2File interface for extracting data from CAD to Excel

3. CASE STUDY

A case study was conducted to demonstrate the effectiveness of the proposed application framework for earthwork optimization based on site formation on an industrial project in Alberta. The site features a triangular shape with an area of about 244,000 sq.m. By using the CAD-Excel integrated system, the total earthwork for rough grading was designed as: cut bank volume 200,000 cu.m and fill compacted volume is 150,000 cu.m. Because the shrinkage factor for the soil is about 0.75, the cut and fill are balanced on this site. Figure 7 presents an overview of the processing steps and the resulting cut / fill areas on the site. Though the optimization model described above, the final highest elevation, H, is at 683.9 m, the slope along x axis, ix, is 2.1 percent and the slope along y axis is 1.5 percent.

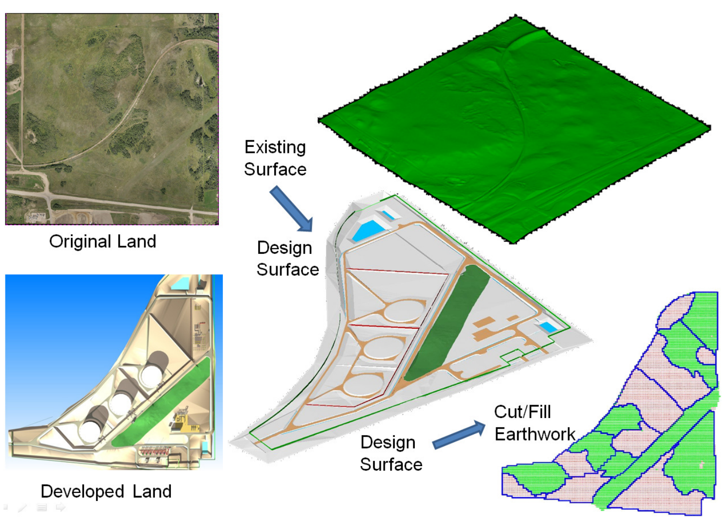

Figure 7: Case Study on an Industrial Site; Optimized Site Cut (in red) and Fill (in green)

4. CONCLUSION

Land formation for an industrial construction site needs to consider many engineering constraints such as ensuring proper drainage, prevention of flood, driving safety, optimizing earthwork by balancing cut and fill, minimizing truck travel distances in earthmoving, proper equipment matching and achieving high equipment utilization rates. Traditionally, experienced civil engineers manually perform site formation design by the cell grid method, the end section method or other methods. Usually several solutions will be created from the manual process, and the best one will be chosen. Because the intensive earthwork design and calculation relies heavily on human expertise, the site formation design can be time-consuming, tedious and expensive. We first reviewed the basic theory of the "least squares" method is reviewed in order to find a new way to model and solve the problem by taking full advantage of computer power. We then developed a computer-based application framework by seamlessly integrating earthwork design in CAD and earthwork optimization in Excel, in order to facilitate the practical application of the proposed framework on site formation for industrial construction. As a result, the AutoCAD-Excel integration augments CAD design functions with the optimization analysis enabled by Excel.

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