Development of a prototype for optimising cut/fill underpinned by BIM in landscape site realisation process.

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ABSTRACT**:** *Landscape Architecture deals with the creation of spaces in the landscape that benefits society and ecology for which landform is an important part of the design and realisation. Landscape architects are posed for more involvements in the realisation processes, which can include, as well as ascetics and selection of materials design, scheduling, estimation, phasing, and optimisation of landscape architect projects. However, Current Landscape site processes are affected by numerous inefficiencies from the early specification of site surveys through the development of design to site operations. These are due to poorly integrated processes among clients, Landscape Architects, Engineers and site and the lack of processes and technologies for optimising information flow and cut/fill site operations. The prime objective of the research is to develop and adopt a prototype incorporating optimisation technologies to identify optimal relationship between project variables (cut/fill quantities, cost, aesthetics and schedules) underpinned by BIM technologies and processes. This is an on-going project and this paper only outlines the prototype to optimise cut/fill quantities in 3D CAD environment. The paper also discusses the results of case studies and tests the user-friendliness, accuracy/reliability/repeatability of results obtained with different prototype functionalities.*

KEYWORDS: *cut/fill optimisation, BIM, APIs development for Revit*

1. INTRODUCTION

Landscape Architecture deals with the creation of spaces in the landscape that benefits society and ecology for which landform is an important design element. Civil engineers meanwhile, ensure that the structural properties of the soil are investigated and appraise design. Landscape Architects and Civil Engineers both of these professionals are required to ensure that health and safety and the appropriate Construction and Design Management regulations are observed. The resulting landscape is one that is structurally sound, and meets all of the needs that people and wildlife have for the site. With the imposition of land-fill tax and the cost of shifting soil from and to site is very high, Landscape architects are required to seek balance between cut (soil removed) and fill (soil added) within their topographic design to reduce the need for transporting materials from or to site. This has the added advantage of reducing of not only reducing costs but also minimising construction carbon footprint.

Most of past earthwork research literature is associated with road constructions and are mainly on earthwork allocation to determine the most economic distribution of earthwork from cut sections to fill sections and disposing excess to disposal sites. The earthwork allocation techniques used includes mass haul diagram, linear programming, and optimization modelling. The mass haul diagram (Hickerson 1967, Oglesby and Russell 1982, stark and Mayer 1983, Anderson and Mikhail 1985 and Son et al 2005) is a graphical representation of the cumulative amount of earthwork moved along the centreline and distances over which the earth and materials are to be transported. However, this method proved inadequate as if the cut and fill are not balanced and it does not take into account the different types of soil and different degrees of compactions. Consequently, Stark and Nicholls firstly suggested mathematical modelling of earthwork allocation using linear programming in 1972. This was developed later, by Nandgaonkar (1981); Easa (1887, 1988); and Jayawardane and Harris (1990), to integrate not only the bulking factors to allow for swell and shrinkage but also includes the allocation of borrow/disposable sites, their set up cost and project duration.

Other research in road construction planning supported earthwork construction firms for the improvement of space allocation, equipment planning, and scheduling information from location aspects (Alkass, 1991; Castro, 2009; and Shah and Dawood, 2011).

In this research, we are concerned mainly about optimisation of cut/ fill earthwork within a confined site, as well as visually augmenting landscape site data and integrating this into Building Information Model (BIM) to aid landscape architects to design and optimise cut/fill construction activities . In addition, it is argued in this paper that Autodesk's Revit that has been effectively used by architects to design buildings, is incompatible with the workflow of landscape architects. The most prominent is the lack of site grading and hence Autodesk Civil 3D has been used to calculate the grading and is then exported to Revit (Flohr, 2011). Nevertheless, there are problems associated with interoperability between programs and lack of predefined site parametric objects. Indeed, Ahmad and Aliyu (2012) concluded that there is a need for a BIM software that is more specific for landscape architecture.

In this paper, we tackle the aforementioned issues by the development of an Application Program Interface (API) prototype to optimise cut/fill quantities in 3D CAD environment and incorporate landscaping workflow processes. The developed API is embedded into Revit. The remaining of the paper outlines the technical development of the work, prototyping of the requirements and case studies testing.

2. CUT/FILL OPERATIONS: TECHNICAL DEVELOPMENT

Grading is the prime design factor to site planners and landscape architects. The grading must display not only aesthetic and design principals but also ecological understanding and technical capability. Furthermore, these aspects are greatly influenced by cost and lower carbon footprint. Hence, optimisation of the cut and fill is paramount.

2.1 Grading operations

There are two basic ways to perform grading on site. Primarily is to balance the cut and fill required on site. This may be executed by cutting and filling in the same operation i.e. excavating and depositing the soil in one operation. Alternatively, is to stockpile the cut material and then place it in the fill areas as required. Secondly, import or export soil to satisfy cut and fill requirements. This method is costly and is only used when the cut and fill do not balance.

Since balancing the cut and fill on site is less costly and most energy efficient, this is the only method considered in this project.

2.1.1 Calculation of the cut and fill

Accurately calculating the cut and fill volume is necessary for ground levelling and hence form essential part of the planning process. There are three most common methods used for estimating the cut and fill volumes.

i. Cross-section method
ii. Grid method
iii. Prisms method

The cross-section method is also known as "The average end area method" and is most suitable for lineal construction such as roads, paths, and utility trenching. The formula states that the volume of the cut (or fill) between two adjacent cross-sections is the average of the two sections multiplied by the distance between them (Strom 2013).

$$V = \frac{(A_1 + A_2)L}{2} \tag{1}$$

Where

$A_1 \; and \; A_2 = \quad end \; sections, in \; ft^2 (m^2)$

$V = \quad volume, in \; ft^3, (m^3)$

$L = \quad distance \; between \; A_1 \; and \; A_2, in \; ft \; (m)$

To apply this method, cross sections must be taken at selected or predetermined intervals. The shorter the interval between sections, the more accurate the estimate will be.

The grid method, also known as "The borrow pit method", involves drawing a uniform grid onto a plan of the earthwork project, and taking off the existing and proposed levels at each node of the grid. The average depth of cut or fill required is calculated for each cell, and the volume for each cell is calculated by multiplying the depth by the cell area. The total cut and fill volumes can be estimated by summing up all the volumes for all cells.

The cut or fill depth for each cell is determined by subtracting the average existing level of the cell from the average proposed level. If the final depth is positive then this is a filled cell, otherwise, negative value indicates a cut cell. The volume for cut or fill is obtained by multiplying the cut or fill depth by the area of the grid cell.

Another approach is derived by simplifying the equation of the first approach by common factoring. This has the added advantage of reducing the number of calculation (Strom 2013).

$$V = \frac{A}{4} \times (1h_1 + 2h_2 + 3h_3 + 4h_4) \tag{2}$$

Where

$V = volume\ of\ cut\ (fill) in\ ft^3, (m^3)$

$A = area\ of\ one\ grid\ cell\ in\ ft^2, (m)^2$

$h_1 = sum\ of\ cuts\ (or\ fills) for\ all\ grid\ corners\ common\ to\ one\ grid\ cell$

$h_2 = sum\ of\ cuts\ (or\ fills) for\ all\ grid\ corners\ common\ to\ two\ grid\ cells$

$h_3 = sum\ of\ cuts\ (or\ fills) for\ all\ grid\ corners\ common\ to\ three\ grid\ cells$

$h_4 = sum\ of\ cuts\ (or\ fills) for\ all\ grid\ corners\ common\ to\ four\ grid\ cells$

The prisms method is also known as "Volume by triangulation" and is a volume method that compares two triangulation networks, one being the base surface and the other is the design surface. This method is different from the grid based and the cross section volume routines. This method is the preferred method for this project as it is the most accurate (Andrew Y.T Kudowor and George Taylor) because it uses TIN-to-TIN (Triangular Irregular Network) prismoidal volumes. Moreover, a bulking factor can be included into to the result of the volume calculation to accommodate for the quality of soil, which is either a cut "swell" factor and or a fill "shrink" factor.

Prisms method is usually based on splitting a site map into triangles, which are parameters, the projection points of the design landscape onto existing landscape are determined to form another triangle and a triangular prism is formed by setting up a depth. The total volume between the base surface and the design surface is calculated by summing the volume of all the prisms.

In general, the volume V_n of a right prism with triangular base may be calculated starting from the projection surface A_n and the distance d_n between the centres of mass of the two triangles. See figure (1).

$$V_n = A_n d_n \tag{3}$$

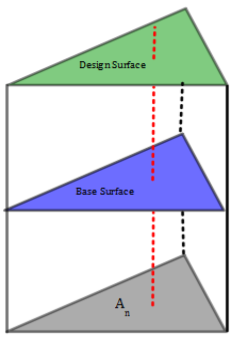


Fig. 1: Triangular Prism

2.1.2 Computation of the Cut and Fill Volumes using the API

It is desirable for most projects, or even required, that all grading be self-contained on site so that no soil can be imported or exported from it to keep both costs and carbon footprint down. Hence, the API was developed to carry out cut and fill calculation according to a desired specification set by the landscape designer.

The landscape designer starts by importing the existing landscape map into Revit. The map is split into triangles and the volume between the base surface and the design surface is calculated for each triangular column. In order to calculate each triangular column accurately and since both the base surface and the design surface is not parallel to the projection surface, the column is subdivided into three different parts: the top parallel prism, two triangular based pyramids and a general prism. The total volume is then calculated by summing up all triangular columns. Figure 2 shows the setting up of triangular column and figure 3 shows a triangular column with its coordinates.

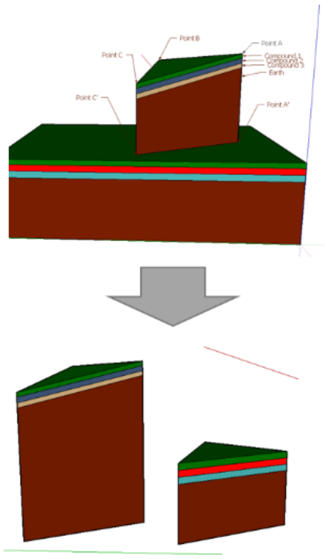


Fig. 2: Setting up Triangular column

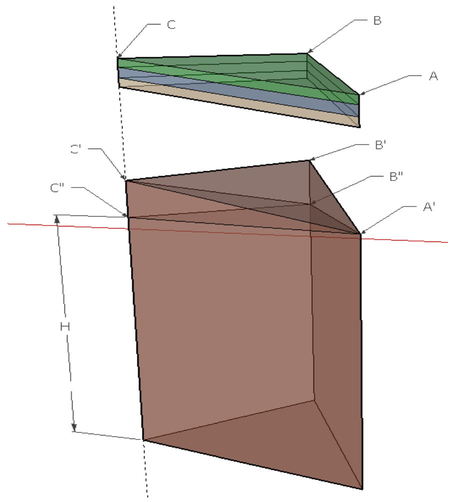


Fig. 3: Triangular column coordinates

The volume calculation for the triangular column depicted in figure 3, is described in equation 4. The balance volume of cut and fill operation equals the total difference volume of each prisms pairs of base surface and design surface. The projection prisms from design surface on to base surface could be determine vertically from points of design surface, shown as figure 3.

$$V = \sum \begin{aligned}[t] &(\text{Area of } \Delta ABC \times \text{Compound depth}_i \times \text{Bulking factor}_i) \\ &+ (area\ of\ \Delta A'B''C'' \times H \\ &+ volume\ of\ tetrahedron\ A'B''C'C'' \\ &+ volume\ of\ tetrahedron\ A'B'B''C') \times Bulking\_factor_{Earth} \end{aligned} \quad (4)$$

3. CUT/FILL OPERATIONS- TESTS

The developed API tool has been tested on the Cut and Fill volume calculations and the results are compared to the actual volume by performing the calculation manually. The tests are performed on different geometrical polygons such as triangle, rhombus, square, and a pentagon. The percentage error between the computerised and manual volumetric calculation is also calculated to determine the accuracy of the calculation. Additionally, the average percentage error and the standard deviations are calculated for each shape to determine any discrepancy between each shape. Test results are shown in tables 1-5 below.

Table 1: Test results for equilateral triangular base columns

Shape	Regular Triangle	Point Height (cm)			Calculation (m^3)				
		Point 1	Point2	Point3	Cut	Fill	Balance	Manual Calculation	Percentage Error
Test	1	1000	1000	1000	0.00	433.02	433.02	433.01	0.00055
	2	-1000	-1000	-1000	433.02	0.00	-433.02	-433.01	0.00055
	3	0	0	1000	0.00	144.34	144.34	144.34	0.00054
	4	-500	-500	500	72.17	0.00	-72.17	-72.17	0.00055

Table 2: Test results for Rhombus based columns (two triangular bases)

Shape	Rhombus	Triangle 1 Height (cm)			Triangle 2 Height (cm)			Calculation (m^3)				
		Point 1	Point2	Point3	Point 1	Point2	Point3	Cut	Fill	Balance	Manual Calculation	Percentage Error
Test	1	0	0	0	1000	1000	1000	0	433.015	433.015	433.01	0.00055
	2	-1000	-1000	-1000	1000	1000	1000	433.02	433.015	0	0	0
	3	0	0	0	0	0	1000	0	144.338	144.338	144.34	0.00054
	4	0	0	1000	0	0	1000	0	288.677	288.677	288.68	0.00054

Table 3: Test results for Square based columns (two triangular bases)

Shape	Square	Point Height (cm)				Calculation (m^3)				
		Point 1	Point2	Point3	point 4	Cut	Fill	Balance	Manual Calculation	Percentage Error
Test	1	1000	1000	1000	1000	0.00	1000.01	1000.01	1000.00	0.00055
	2	-1000	-1000	-1000	-1000	1000.01	0.00	- 1000.01	-1000.00	0.00055
	3	0	0	0	1000	0.00	166.67	166.67	166.67	0.00055
	4	0	0	1000	1000	0.00	500.00	500.00	500.00	0.00055
	5	-500	-500	500	500	88.33	88.33	0.00	0.00	0.00000
	6	-500	-500	-500	500	333.34	0.00	-333.34	-333.33	0.00063

Table 4: Test results for Pentagon based columns (Three triangles)

Shape	Pentagon	Point Height (cm)					Calculation (m^3)				
		Point 1	Point2	Point3	Point 4	Point 5	Cut	Fill	Balance	Manual Calculation	Percentage Error
Test	1	1000	1000	1000	1000	1000	0.00	1720.49	1720.49	1720.48	0.00054
	2	-1000	-1000	-1000	-1000	-1000	1720.49	0.00	-1720.49	-1720.48	0.00054
	3	0	0	0	0	1000	0.00	573.50	573.50	573.49	0.00054
	4	0	0	0	1000	1000	0.00	732.01	732.01	732.00	0.00054
	5	0	0	1000	1000	1000	0.00	1146.99	1146.99	1146.98	0.00054
	6	0	1000	1000	1000	1000	0.00	1561.98	1561.98	1561.97	0.00054

Table 5: Average percentage error and standard deviation for different shaped prismoidal volumes.

Shape	Average percentage error	Standard Deviation
Equilateral triangle	0.000546173	5.81188E-06
Rhombus	0.000405589	0.000270413
Square	0.0004705	0.000233022
Pentagon	0.000542694	6.99822E-07

3. CUT AND FILL OPTIMISATION: A TEST CASE

The functionality of the API is tested using a test design project that focuses on the optimisation of the cut and fill balances at the design phase.

Figures 4 and 5 depict respectively, a cross sectional representation of the test site and the model test site. Cut operations (removal of earth) are required for this test site to accommodate sustainable drainage systems. Bunds (requires addition of earth) are created to screen site from local area both visually and acoustically. Hybrid cut and fill processes (movement of earth across site) are required according to road specification in terms of appropriate grade or slopes within health and safety limits.

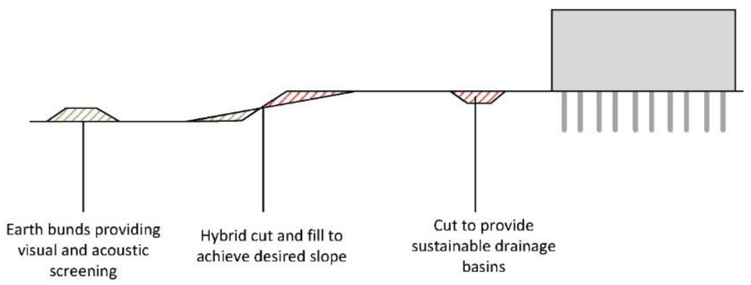


Fig. 4 cross sectional representation of test site

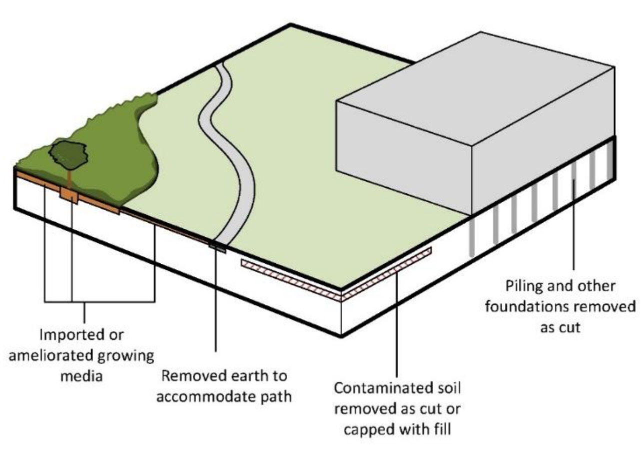


Fig.5: Model test site

The earthwork design workflow begins with an up to date and coherent ground survey that effectively describes the site topography. Site Surveyors generate a 3D contours using GPS equipment. The GPS equipment generate x, y, z coordinate in CVS (comma separated value) file. The generated coordinates from the site survey include spot elevation, contour elevations, and building outline. Revit imports these points from the CSV file and generate an accurate 3D site model.

Before using the API functions, Revit functions are used first to generate existing landscape site creating phases. This is followed by landscape initialization where the landscape is separated into separate floors so that the user can move from one phase to another see figure 6. The API allows the user to select a phase and then move from one phase to the next calculating the cut or fill and modify floor shape and elevation according to requirement or specification. To ensure accurate calculation of the cut and fill, bulking factors of the different soil compounds are included to rectify swells and shrinkage. The API cut and fill optimisation start by comparing the floors of the existing phase and the current design phase extracting triangles then finding projection points from the current phase to the existing phase forming triangular columns and calculating the volume difference between the current phase and the projected triangle columns. See Figure 6.

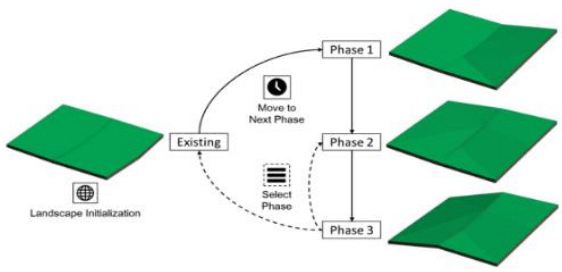
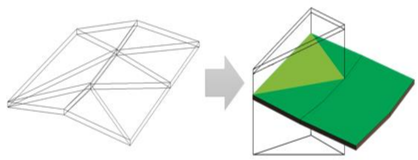


Fig. 6: Landscape initialization



Fig, 7: Finding projection point from "Phase 3" to "Existing" phase

Figures 8 and 9 show the process maps for the designed workflow and the API cut and fill calculations.

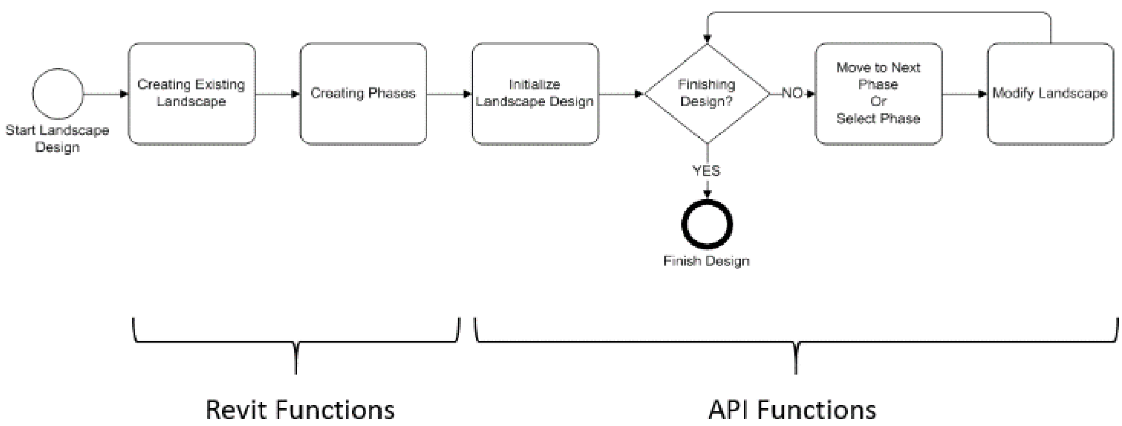


Fig. 8: Process map of the designed workflow

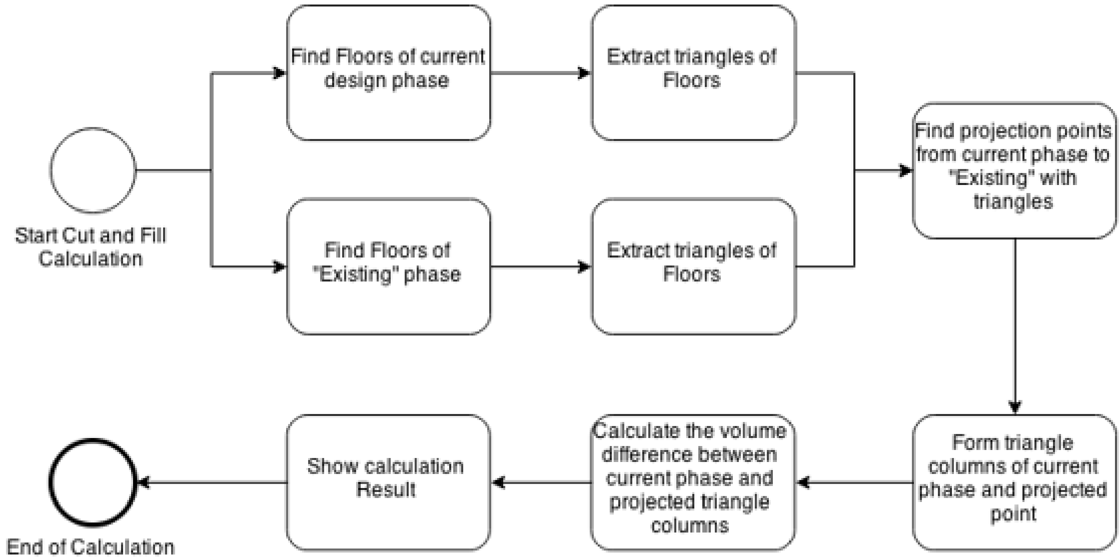


Fig. 9: Process map of the API cut and fill calculations

6. CONCLUSION

In this research, a methodology and APIs has been developed for optimising cut/fill for construction projects in Landscape Architecture underpinned by 3D data-rich BIM environment. APIs was implemented in Revit software for keeping all data in one software environment, and to resolve the lack of interoperability between different software currently being used by Landscape architects. Furthermore, the integration of the API within Revit enabled the development of BIM-specific functions for Landscape Architecture practices and augmenting Landscape site realisation processes with visualisation and cut/fill optimisation.

Test results of cut/fill volume calculations, performed on different geometrical shapes, proved to be very reliable as the average percentage error was very similar for all shapes, and ranged between approximately 0.00041% and 0.00055% and the standard deviations are minimal, ranging between 0.0000007 and 0.0003. Moreover, the implementation of the API and testing its functionality to perform cut and fill optimisation, using a test design project, proved to be successful. However, the robustness of the API needs to be tested on real architectural landscape site designs. Thus, future work will include case studies using an existing landscape designs.

It is envisaged that the integration of the API within Revit will not only provide a 3D data-rich visualisation of construction site operations; planning and scheduling of cut/fill operations in construction projects, and BIM protocols and processes applied to landscape design projects but also be developed further, to include time and cost. Hence, supporting 5D processes (that is integration of 3D, time, and cost) as well.

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