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Faculty of Mechanical and Mechatronics Engineering

**Leveraging Point Clouds for Architecture, Engineering, and Construction**

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2A Mechanical Engineering

September 19, 2022

**Letter of Submittal**

**To** MME Department

**From** Kostubh Agarwal

**Date:** Sept 19, 2022

**Re:** Work Report: Leveraging Point Clouds for AEC

I have prepared the enclosed report, “Leveraging Point Clouds for Architecture, Engineering, and Construction”for my 2A work report and for Entuitive.

Entuitive is a company offering professional services in the field of structural engineering, building science, transportation, and various sustainability applications.

As a member of the Innovation department led by Mr. Blaine Jansen, my role is to help promote the culture of innovation by implementing new technologies and processes to improve the operation of the company.

This report was written entirely by me and has not received any previous academic credit at this or any other institution.

Sincerely,

Kostubh Agarwal

[20872383]

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**Executive Summary**

**The intent of this report is to examine the technology, research, and workflows which can help the AEC industry leverage point clouds.** Enabled by modern reality capture technologies such as LiDAR and Photogrammetry, point clouds are files whereby data is stored in a 3D space, defined by geospatial coordinates. With Point Clouds and reality capture technology being so nascent, the AEC industry is struggling to make sense of these files. Currently there is limited infrastructure to distribute, manipulate, and decipher point clouds. More specifically, raw point clouds are generally not in format conducive to BIM work, and are often clunky, noisy, and ridden with outliers. While academia has conducted a lot of research and development, these technicalities have yet to be abstracted away for the average engineer, architect of construction manager. There are technological obstacles which are in the way of mass adoption within the AEC industry. THis report attempts to offer a technical procedure to overcome these obstacles. This includes thorough analysis and reference of well-regarded academic papers related post-processing of 3D data, distribution platforms, file formats, and more. Overall, this report serves as introductory material for AEC to reference and begin leveraging point clouds.

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# 1 Introduction

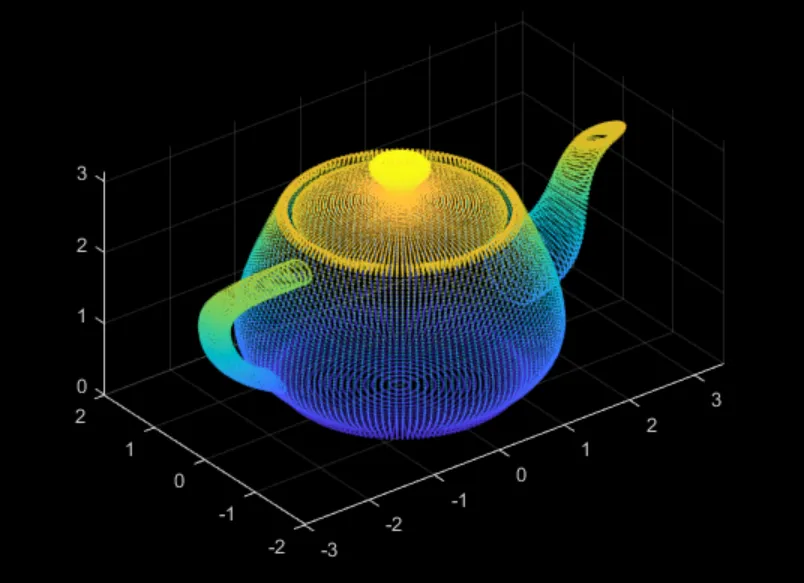
A point cloud is a set of data points plotted within a digital 3D space [<https://geoslam.com/point-clouds/>]. Point clouds are commonly used to represent physical objects, buildings, and or geography. LiDAR and photogrammetry equipment are the tools used to capture of such data - geo-spatial. These capabilities are especially relavaant for AEC[[1]](#footnote-0). Today, engineers, architects, and construction managers alike rely on manual measurement, video, and photographs to capture real-world conditions. In many cases, this information then has to be interpreted and translated by hummans to a higher-fidelity format: such as BIM models, or 2D drawings. Humans can be thought of as a translation layer, interfacing between the real-world and the digital world. Unfortunately, humans are prone to error, often missing or misinterpretting information. As such, the status quo for capturing and interpreting as-built conditions is costly. Many existing buildings have inaccurate, old, missing drawings; Taking manual measurements, photographs, and videos and then converting them to 2D drawings of BIM models is time-consuming; And most impportantly, inaccurate capture of as-built conditions lead to an ever-expanding set of problems downstream. Fortunately, the advent of LiDAR scanners and photogrammetry equipment enable the replacement of the human translation layer. Rather than relying on humans to piece together measurements, photos, videos, and old drawings there is a point clouds offer an opportunity to automate the reality capture process. Unfortunately, point clouds are diffficult to distribute, manipulate, and decipher - especially in the context of AEC. At best, the infrastructure to do so is limited. While there has been lots of academic research and development in the space, procedures, products, and services are not available or well-defined for non-technical consumers: File sizes are too large, riddled with uncertainties such as outliers, noise, and missing data, and there is simply lack of context and infrastructure to manipulate or translate this information. As such, engineers, construction managers and architects are hesitant to adopt point clouds and corresponding technology. LiDAR and reality capture technologies enable us to cut costs and deliver unparalleled accuracy and detail of as-built data for engineers and designers. Unfortunately, in their raw form, points clouds are hard to distribute, work-with, and or decipher. As such, the objective of this report is to provide a technical proposal to assist engineers, architects, and construction managers to easily leverage point clouds for use in AEC.

# 

# 2 Background Information

## 2.1 Point Cloud

As shown in figure 1, a point cloud is a collection of data points plotted in 3D space [<https://geoslam.com/point-clouds/>]. Each data point is infinistesmally small and consists of a set of coordinates to define its location within a 3D space.



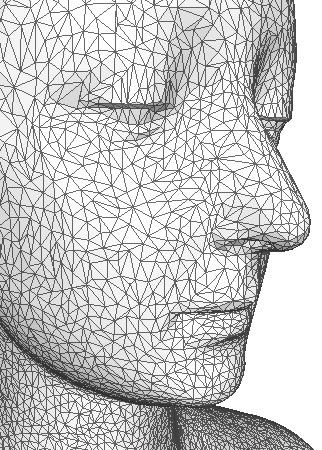
*Figure 1: a point cloud of a tea-kettle [*[*Point Cloud and 3D Image - Revopoint 3D Technologies Inc.*](https://www.revopoint3d.com/point-cloud-and-3d-image/)*]*

## 2.2 **LiDAR**

LiDAR stands for light detection and ranging[NOAA. Historical Maps and Charts audio podcast. National Ocean Service website, https://oceanservice.noaa.gov/podcast/july17/nop08-historical-maps-charts.html, accessed on 8/13/17.]. LiDAR scanners emit lasers to detect surfaces and their distance from the scanner[NOAA. Historical Maps and Charts audio podcast. National Ocean Service website, https://oceanservice.noaa.gov/podcast/july17/nop08-historical-maps-charts.html, accessed on 8/13/17.]. This data is encoded as a point cloud.

## 2.3 Mesh

As shown in figure 2, a mesh is a collection of vertices and polygons that define the shape of an object in 3D via a watertight surface [[Mesh, 3D | SpringerLink](https://link.springer.com/referenceworkentry/10.1007/0-387-30038-4_126)]. A mesh can can be generated from a point cloud.



*Figure 2: a mesh of a human-face [*[*Polygon Meshes (itcarlow.ie)*](https://glasnost.itcarlow.ie/~powerk/GeneralGraphicsNotes/meshes/polygon_meshes.html)*]*

## 2.4 BIM & Revit

The acronym BIM stands for building information modeling. BIM is technology for generating detailed digital models of buildings with information and data tied directly to geo-spatially within the model. Revit is a widely used BIM software.

## 2.5 Post-Processing

LiDAR scanners gather immense sums of data. As such, Point Clouds are often too large to distribute, too noisy to interpret, filled with outliers, or simply incompaitaible for BIM in its native form.

### 2.5.1 Sampling

LiDAR scanners capture large datasets. Correspondilgly, point clouds are oftentimes extremely large. In such cases, point cloud’s can become difficult to process, distribute, and view. To manipulate their size and fidelity, point clouds can be downsampled or upsampled.

#### 2.5.1.1 Decimation (Downsampling)

Decimation algorithms refer to algorithms which remove points on a numerical basis - independent of a points location within space. This may refer to the the removal of 3 points for every 4 points - which would reduce the file size by approximately 75% as ¾ data points are discarded.

#### 2.5.1.2 Voxel Sampling (Downsampling)

Voxel sampling is also known as grid sampling. Voxel sampling divides the 3D space into a cubic grid. The user has control over the parameters and dimensions for grid itself. For example each cell can have a volume of 8mm. Once a grid has been established, one point is selected to represent the entire cell. This can be a point at the center of the grid or a point that represents the barycenter of all the other points in the cell.

### 2.5.2 Removing Outliers and Denoising

In uncontrolled environments, LiDAR scanners are prone to capturing datasets with innacuraries and outliers. As such, post-processing is often required to minimize these errors.

#### 2.5.2.1 Edge aware resample (EAR)

Edge aware resampling is an algorithm which generates a “clean, uniform, and feature-preserving set of oriented points” [[Edge-aware point set resampling | ACM Transactions on Graphics](https://dl.acm.org/doi/abs/10.1145/2421636.2421645?casa_token=A2QeSAvP7bMAAAAA:Mfrt3cUMQESgIMldbHghPPq56KY525JUYZhYWD7Cv2_csnvrn3e5u_5S0ZWyusRSgLpPE529B9X9dLc) ]from a noisy, outlier-ridden, undersampled data set. Edge aware resampling well approximates the underlying surface generate a new dataset to better represent the original dataset[]. This is done by resampling away from edges (identifieed by large differences in point orientations) and upsampling the gaps based on more reliable orientations. Repeating this process multiple times results in a sharp, data-rich pont cloud which is far more suitable for surface reconstruction procedures.

#### 2.5.2.2 Weighted Locally Optimal Projections (WLOP)

Weighted locally optimal projections generate a new dataset to robustly approximate the original point cloud data and be well distributed[[VCC](https://vcc.tech/research/2009/WLOP)]. To do so, L1 Spatial Medians are taken in well-defined local areas. L1 Spatial Medians are insensitive to outliers. Additionally, a repellant factor to ensure the projections are well distributed. Overall, WLOP can be described as a repeated local averaging algorithm [].

#### 2.5.2.3 Plane Fitting (MLS)

Moving Least Squares method relies on taking the surface of best fit, projecting all the points onto that surface, and repeating [[Point set surfaces | IEEE Conference Publication | IEEE Xplore](https://ieeexplore.ieee.org/document/964489)]. This is likely easier to visualize in a 2D space; Taking a line of best fit on a graph. This is a iterative process which if repeated enough times will render a flat surface. Overall, this is known as a smoothing procedure.

#### 2.5.2.4 L0 minimization (L0)

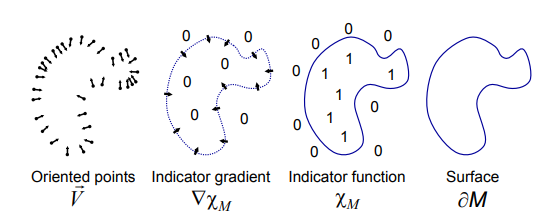
L0 minimization serve to preserve and recover sharp features while smoothing everything else. L0 minimization consists of three distinct stages. First using Prinicipal Componenet Analysis[[2]](#footnote-1) the point cloud is distingushed by smooth and sharp features. If a point is identified to exist within a smooth region, the point itself and its surrounding points should form a plane perpendicular to the point norm. Then points are upsampled along edges.

### 2.5.3 Meshing and Surface Reconstruction

Meshing refers to the generation of a watertight, intersection free, data-rich, and smooth surface from a set of points [[3D Surface Reconstruction Using a Generalized Distance Function - YouTube](https://www.youtube.com/watch?v=bMhR-UYlKqU)].

#### 2.5.3.1 Poisson Surface Reconstruction

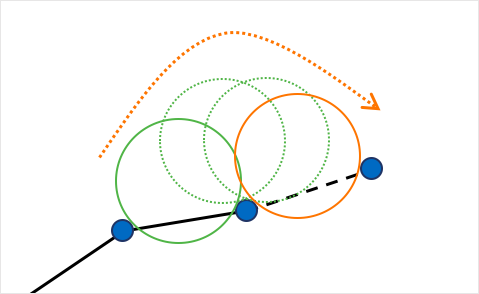
As shown in figure 3, Poisson Surface Reconstruction consists of a implicit function which generates an ‘implied’ point set from the original point set, with oriented normals. This is defined by a function which defines the inside of a surface as a value >0 and the surface itself as 0 and the value outside the surface as <0.



*Figure 3 : An intuitive illustration of poissson reconstruction in 2D [*[*Poisson surface reconstruction (hhoppe.com)*](https://hhoppe.com/poissonrecon.pdf)*]*

#### 2.5.3.2 Ball Pivoting Algorithm

As shown in figure 4, the ball pivoting algorithm is a fairly intuitive algorithm to visualize. It models a ball which rolls over the points in a point cloud, filling in the spaces where the ball does not fit. The radius of the ball is dynamic.



*Figure 4: Anintuitive illustration of ball-pivoting algorithm[*[*Point Cloud to Mesh: BPA (cs184team.github.io)*](https://cs184team.github.io/cs184-final/writeup.html)*]*

### 2.5.4 Optimizing for BIM

While a high fidelity mesh is suitable visually, and for 3D graphics purposes,

it fails in the BIM setting. For example, if an engineer wants the dimensions

of what he perceives at a wall, rather than getting the distance from once

corner of the wall to the other, his measurement will be hindered by the

tens of hundreds of vertices that exist in between - Even if the wall is flat. As

such, the mesh needs to be defeatured. Or in simpler terms, the vertices of

the mesh need to be removed on perceived single plane surfaces.

## 2.6 Distribution

Point Clouds provide accurate as-built conditions. As such, many parties and departments, would collectively benefit from using a Point Cloud as a single source of truth.

**2.6.1** **File Type**

#### 2.6.1.1 3D File Formats

3D digital files are built to store polygons and their vertices. As such, they are also capable of storing points - point clouds.

*eg. ply, obj, stl*

#### 2.6.1.2 LiDAR Format

LiDAR scanner manufactures have developed their own private file format to record LiDAR data to. LiDAR scanners collect geospatial data along with RGB data, and Thermal Data in unique cases.

*eg. faro, las, laz*

#### 2.6.1.3 Point Cloud Formats

ASCII is a digital file format where points are simply stored in a text file as coordinates in most cases.

*eg. ASCII, pcl, pcd*

### 2.6.2 Visualization, Storage, and Distribution

#### 2.6.2.1 Speckle.xyz

Speckle.xyz is a platform to host, visualize, and distribute 3D information on the cloud, especially in the context of the aec industry. It has added benefit of offering verision control, interoperability, and automation.

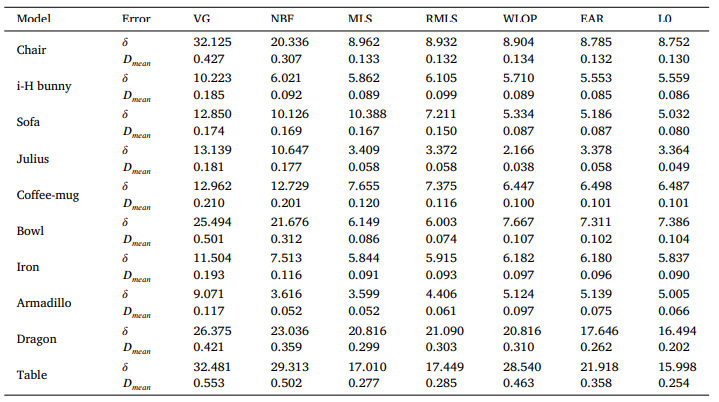
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# 3 Analysis

To optimize a point cloud for distribution, visualization and information extraction, especially in the context of AEC, technical post-processing is required and distribution/storage/visualization platforms have to be edfined.. Post processing ensures enough fidelity to automate and replace the human translation layer between the physical and digital world. LiDAR scanners and photogrammetry equipment of all types are susceptible to noise, outliers, and missing information. Ideally, a raw point cloud should be converted to cloud hosted, BIM optimized, interoperable file type.

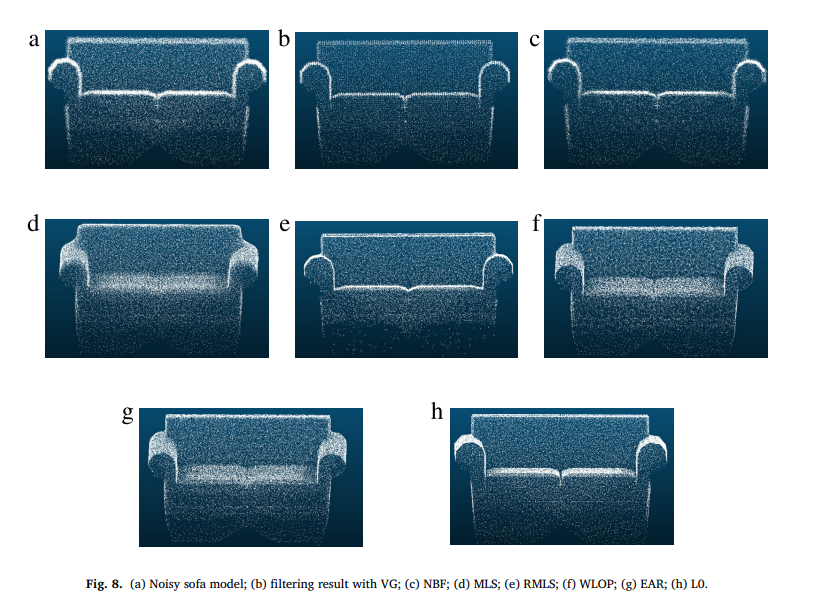
## 3.1 Denoising and Outlier Removal

With the end goal in mind, creeating a tight mesh which can be converted into a BIM model, de-noising and outlier removal is critical. Four such filtration algorithms exist: L0 Minimization, Plane Fitting with Moving Least Squares, Weighted Locally Optimal Projections, and Edge Aware Resampling. A paper Xian-Feng Han et al.[[Sci-Hub | A review of algorithms for filtering the 3D point cloud. Signal Processing: Image Communication, 57, 103–112 | 10.1016/j.image.2017.05.009](https://sci-hub.st/https://doi.org/10.1016/j.image.2017.05.009)] includes detailed tests comparing the filtering algorithms listed above. The four filtration algorithms are tested against a benchmark: a ground truth point cloud with artificial gaussian noise. As shown in figure \_\_, the quality of the output is defined by two error metrics: standard deviation and cohen’s mean. The standard deviation measures averaged angle over all angles between the ground truth point normals and the resulting point normals []. Cohen’s mean is a measurement of the average distance between the output points and their corresponding ground truths [].



*figure 5 - point cloud filtering algorithm benchmark testing (numerical) []*

Visually WLOP, EAR, and MLS seem to perform well, as seen in figure 6 . Conversely, EAR, WLOP, and L0 Minizmization preserve shape.



*figure 6- point cloud filtering algorithm benchmark testing (visuals) []*

Overall L0 minimization and EAR was able to retain shape, while producing the best visual results.

## 3.2 Sampling

Sampling is often important, simply for the ska eof reducing the computational and storage loads downstream in the post-processing workflow. Downsampling a point cloud before filtration or before surface reconstruction makes it more difficult retain shape and produce quality results. As such, it is a matter of finding a ‘sweet spot’. Preferably a point cloud is not downsampled before filtration, as this leads to the greatest error. In terms of choosing a downsampling algorithm, voxel sampling is the preferred method, as it downsample’s point clouds in a predictable and uniform manner. Additionally, it is customizable, with the parameters for defining the grid and the orientation of corresponding points being configurable. Whereas, rank decimation is fairly unpredictable and results in a non-uniform removal of points. Overall, the degree of downsampling and when it is applied, should be context dependant, and is a matter of trading-off between performance and quality.

## 3.3 Surface Reconstruction

Surface reconstruction is arguably one of the most critical aspects of post-processing, but also the most complex. While sampling, the lack therof, and filtration are all precursors to the quality of mesh created, the choice of surface reconstruction algorithm is even more important. Whilst there are many credible papers on surface reconstruction from the likes of Boissonnat, Hoppe et al, Tight Cocone, Ball-pivorting, Poissoin Surface REconctctionetc, very few are robust [[Performance analysis of different surface reconstruction algorithms for 3D reconstruction of outdoor objects from their digital images - PMC (nih.gov)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4929111/)]. For instance, Boissonat, Tight Cocone, and the reconstruction algorithm by Hoppe et al. are limited by the quality of the input, ie suscptlbel to noise and sparsity []. The Ball Pivoting Algorithm, especially with advent of a dynamic ball radius (based on sparsity of pointcloud) is more robust and has quote on quote ‘seperated itself from the pack’ []. The BPA is extremely sensitive to changes in radius[]. THe radius is inversely related to the susceptibility to noise []. However, the best performing algorithm in the context, of robustness and quality of output. Poisson Surface Reconstruction is fairly insensitive to noise and outliers. Octree depth (level of detail) is the greatest determinant for quality of output.

## 3.4 BIM Optimization

While high-fidelity meshes are extremely performant in the context of 3D graphics, they cause problems in the BIM setting. Not only are they computationally intensive and cumbersome to manipulate, but they are difficult to extract information from. For instance, an engineer wants to collect the dimensions of a wall. With a high-fidelity 3D mesh, this will not be possible, as there will be hundreds of vertices between the corners of a wall. In other words, the BIM software will have trouble differentianing a single-plane wall from hundreds of small triangular plans which are adjacent to each other and make up a wall. Because of this inherent constraint with a default mesh, the status quo for converting a point cloud to BIM model, simple requires engineers to create a BIM model from scratch with the point cloud acting as points of reference: essentially enabling the engineer to ‘colour within the lines’. However, the intention of this report is to replace and automate engineers. As such algorithms must be applied to the mesh to automatically render it into a BIM friendly format. This consists of a light-weight mesh, without any vertices intercepting a single flat plane. To do this, one must “defeature” the mesh without defeaturing any true features or edges. In a manual context, a mesh can be thrown into blender where the edges can manually be locked, and the rest of the mesh can be defeautred. Overall, this is the single biggest barrier to the automated conversion of point clouds to BIM models.

## 3.5 Distribution / Storage / Visualization

Due to the general scale of AEC projects, collaboration is critical: between companies, progression, departments, and people. As such working from a single point of truth has extreme benefit. As projects become more and more abstract and specific, having a common starting point will minizme the downstream errors that are prone. ]

Filetype.

As such a cloud based service such as speckle.xyz would serve best. It enable widespread collaboration, visualization on many mediums, and stores information in a cloud based format. Additionally, the ability to convert between file-types, softwares, and keep maversion control is critical in an environment like this. Overall, the interoperability, friendliness to 3D file formats, and collaborative features make speckle.xyz the best platform fro storage, distribution and visualization purposes.

[Speckle - The Platform For 3D Data](https://speckle.systems/)

# 4 Proposal

To take full advantage of Point Clouds and resolve the issues related to distribution, information extracation, and interoperability a user-friendly post-processing workflow must be developed to render point clouds to a more user-friendly format. The following post-processing procedure is defined based on academic research and analysis conducted in this report[[3]](#footnote-2).

Using CGAL, PDAL, and PCL develop a script to process a raw point cloud.

1. EAR
2. L0
3. Meshing

Using Blender, Unreal Engine, or Unity

1. De-polygon / Defeautre

Distribute on a speckle.xyz server.

1. Best Distribution / Storage / Visualization

# 

# 5 Conclusion and Reccomendations

Point clouds have the capacity to revolutionize the AEC industry. However, it will be decades before Point Clouds become the native 3D file format. The current barrier to adoption is technical. As such, tO ease teh transition from BIM models to point clouds, a workflow is required to limit and eliminate these technical barriers. TO make point cloud technology to the general population - the AEC industry, all of the technological challenges must be abstracted away, and the benefits must be provided in a format that the AEC industry is used to and comfortable with: BIM models. Although arguably we are not even at that stage yet. Further research and development is required, and more importantly consumer-level products have to be be developed. Point clouds are a wasted technology if limited to academia. This report proposes a workflow to automate the and best leverage point clouds in an AEC context. However, more research and testing has to be done in the context of compute resources. Especially the infrastructure defined for many of the post-processing algorithms is fairly critical in determining its feasibility.

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1. Acronym for Architecture, Engineering, and Constrcution [↑](#footnote-ref-0)
2. [Principal Components Analysis (okstate.edu)](http://ordination.okstate.edu/PCA.htm) [↑](#footnote-ref-1)
3. Note: There are many post-processing techniques which have not been considered for this report, some of which may improve or detract from the current procedure. [↑](#footnote-ref-2)