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Dynamic monitoring of construction site activities based on BIM.

Supervisor:

Prof. Claudio Mirarchi

Author:

Han Sun



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I'm thankful to my family, their love is beyond everything, hope my family will always be happy. I carry a special wish for my beloved grandma, hoping that her next journey will be filled with joy.

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SOMMARIO

La quantificazione efficiente dell'avanzamento del progetto di costruzione è vitale per una gestione efficace del progetto, poiché richiede un equilibrio tra tempo di calcolo e accuratezza dei metodi di quantificazione. Le informazioni in tempo reale sulle quantità di lavoro completate sono essenziali per un processo decisionale tempestivo da parte dei project manager. Gli approcci esistenti basati sulla visione per la quantificazione automatizzata del progresso hanno dovuto affrontare sfide di implementazione quali complessità computazionale, personale specializzato e attrezzature costose. In risposta, questo studio introduce pipeline facilmente implementabili che quantificano in modo completo i progressi della costruzione, compreso il monitoraggio dei progressi degli elementi e l'analisi degli elementi. In questo articolo vengono presentati due metodi. Il primo metodo confronta il numero di punti nel modello as-built con quelli previsti dal modello as-design con le stesse intensità di punti. Integra perfettamente il modello BIM progettato con i dati di scansione utilizzando lo strumento di programmazione visiva intuitivo, Grasshopper3D, semplificando la quantificazione dei progressi con un input minimo da parte dell'utente per l'allineamento dei dati di base. Il secondo metodo trasferisce la nuvola di punti as-built sulla mesh e la confronta con il modello as-design, il modello as-design è stato popolato con punti e il progresso può essere ottenuto calcolando il numero di punti sulla mesh. Il secondo metodo riduce significativamente i requisiti di calcolo per l'intero processo e aumenta la velocità di analisi di oltre cento volte.

Inoltre, il potenziale del monitoraggio automatizzato dell'avanzamento della costruzione attraverso l'integrazione del BIM come pianificato e dei dati della nuvola di punti come costruito è sostanziale, offrendo opportunità per accelerare i lavori di costruzione e rilevare discrepanze. Nel Capitolo 2, questo documento introduce un approccio automatico agli elementi di analisi basato sulla nuvola di punti, e per generare automaticamente sezioni della nuvola di punti con la funzione di integrazione con altre fonti di dati.

Parole chiave: automazione nella gestione delle costruzioni; monitoraggio dello stato di avanzamento dei lavori; scansione laser; nuvola di punti; Scansione vs BIM

ABSTRACT

The efficient quantification of construction project progress is vital for effective project management, necessitating a balance between computation time and accuracy in quantification methods. Real-time information on completed work quantities is essential for timely decision-making by project managers. Existing vision-based approaches for automated progress quantification have faced implementation challenges such as computational complexity, specialized personnel, and expensive equipment. In response, this study introduces easily implementable pipelines that comprehensively quantify building progress, including element progress tracking and element analysis. Two methods are presented in this paper. The first method compares the number of points in the as-built model with those anticipated from the as-designed model of the same point intensities. It seamlessly integrates the as-designed BIM model with scan data using the user-friendly visual programming tool, Grasshopper3D, streamlining progress quantification with minimal user input for basic data alignment. The second method transfers the as-built point cloud to the mesh and compares it with the as-design model, the as-design model was populated with points, and progress can be obtained by calculating the number of points on the mesh. The second method significantly reduces computation requirements for the entire process and increases analysis speed by more than a hundred times.

Furthermore, the potential of automated construction progress monitoring through the integration of as-planned BIM and as-built point cloud data is substantial, offering opportunities for expediting construction work and detecting discrepancies. In Chapter 2, this paper introduces an automatic approach to the analysis elements based on the point cloud, and to generate point cloud sections automatically with the function of integration with other sources of data.

Keywords: automation in construction management; construction progress monitoring; laser scanning; point cloud; Scan-vs-BIM

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1. INTRODUCTION

Construction site monitoring is important for the successful execution of construction projects by capturing, analyzing, and managing data related to the project. However, traditional monitoring methods rely on manual data collection, which is time-consuming, labor-intensive, and inclined to errors. Additionally, the use of monitoring tools results in data fragmentation, making it challenging to obtain a comprehensive view of the construction site and hampering efficiency, accuracy, and timely decision-making. This paper aims to delve into these challenges and propose solutions centered around real-time data capture and integration. By leveraging advanced technologies and establishing collaborative practices, such as integrating information models and point clouds, the construction industry can enhance project outcomes and optimize resource allocation. The objective is to create an efficient and effective system that improves construction site monitoring, facilitates better decision-making, and validates these proposed solutions in real-world scenarios.

1.1. Challenges of Traditional Construction Site Monitoring

Traditional construction site monitoring methods suffer from several limitations. Manual data collection is often the primary method used, requiring significant time and effort from personnel. This approach is susceptible to human errors, leading to inaccuracies and delays in data availability. Furthermore, disparate monitoring systems and tools are employed, resulting in data fragmentation. Construction sites have many sources of information generated from various sources, such as sensors, equipment, and personnel. Without an integrated approach to data management, stakeholders struggle to obtain a holistic view of the project. A real-time data capture and integration method is needed to overcome these limitations.

1.2. The Importance of Real-time Data Capture and Integration

Real-time data capture and integration play a pivotal role in addressing the limitations of traditional construction site monitoring. By incorporating cutting-edge technologies like Internet of Things (IoT) devices, sensors, and drones, data collection can be automated, delivering precise and current data concerning construction advancement, material consumption, and adherence to safety protocols. Real-time monitoring systems, outfitted with a spectrum of sensors and cameras, furnish immediate insights into diverse facets of the project, empowering proactive decision-making and timely intervention whenever requisite. By seamlessly amalgamating data from an array of origins and disciplines, project stakeholders gain entry to an all-encompassing and coherent perspective of the construction site, nurturing collaborative efforts and facilitating well-informed decision-making.

Implementing real-time data capture and integration offers numerous benefits to construction site monitoring. Firstly, it enables enhanced project progress tracking by providing real-time updates on-site activities, allowing project managers to identify and address any delays or issues promptly. Safety monitoring can be significantly improved, as real-time data can help detect potential hazards or non-compliance with safety protocols. Additionally, real-time integration of data from different sources

enables accurate and dynamic resource allocation, optimizing project efficiency and reducing costs. Real-time data capture and integration provide stakeholders with access to timely and comprehensive information, allowing them to make informed choices and adapt strategies accordingly. By leveraging real-time insights, construction site monitoring becomes more proactive and responsive, ultimately leading to improved project outcomes.

1.3. Addressing Challenges and Promoting Collaboration

To effectively implement real-time data capture and integration in construction site monitoring, several challenges need to be addressed. Data interoperability is a key challenge, as different monitoring systems may utilize diverse data formats and protocols. Establishing industry-wide standards, protocols, and data exchange formats is crucial to ensure seamless integration and collaboration between different monitoring systems and stakeholders. Furthermore, ensuring data security and privacy is essential to protect sensitive information while allowing appropriate access to authorized personnel. Collaboration among industry stakeholders, including architects, contractors, technology providers, and regulatory bodies, is paramount for sharing knowledge, experiences, and best practices in implementing real-time monitoring solutions. Collaborative efforts can drive innovation, enhance interoperability, and accelerate the adoption of real-time data capture and integration. **Insights and Recommendations:** To drive the adoption of real-time data capture and integration in construction site monitoring, it is important to invest in advanced technologies. Building Information Modeling (BIM) and digital twins are examples of such technologies that provide virtual replicas of the construction site. Integrating BIM with on-site sensor data offers a comprehensive overview of the project's status, facilitating proactive decision-making and efficient resource allocation. Leveraging the power of BIM and digital twins allows stakeholders to simulate and visualize real-time changes, detect clashes, and optimize construction workflows. Additionally, ongoing research and development in areas such as IoT, Artificial Intelligence, and machine learning can further enhance real-time data capture and integration capabilities. Industry stakeholders should actively engage in research, collaborate with technology providers, and explore innovative solutions to overcome existing challenges.

1.4. Related work

The construction industry has made significant progress in recent years, integrating innovative technologies to enhance project management. Notably, advancements in construction progress monitoring and point cloud analysis have garnered attention. Researchers and practitioners have employed various techniques and tools, such as 4D BIM, automated progress monitoring, augmented reality (AR), deep learning approaches, and point cloud analysis for 3D reconstruction. These endeavors aim to improve project performance, mitigate risks, and achieve better construction outcomes. Armeni et al. (2016) present a method for 3D semantic parsing of large-scale indoor spaces, highlighting the potential of computer vision in comprehending intricate construction layouts. Building upon this, Ellinger et al. (2021) propose an innovative approach that combines point-cloud-to-model-comparison and image recognition for automated progress monitoring in road construction. This enables real-time monitoring and improved project management. Additionally, Che et al. (2019) provide a comprehensive review of object recognition, segmentation, and classification techniques for mobile laser scanning point clouds, elucidating their significance in capturing detailed information.

Utilization of 4D BIM for Risk Mitigation: Effective risk identification, analysis, and mitigation strategies are crucial for successful construction project management. Sloot et al. (2019) conducted a comprehensive study evaluating the usefulness of 4D BIM tools in risk mitigation strategies. Their findings underscored the potential of 4D BIM to improve risk management by enabling enhanced visualization, simulation, and communication of construction processes. Building on this research, Arif and Khan (2021) developed a smart progress monitoring framework that integrated videography, MATLAB, and BIM. Their framework facilitated real-time risk identification and mitigation by integrating multiple data sources and enabling data-driven decision-making.

Automated Progress Monitoring Techniques: The adoption of automated progress monitoring techniques has gained considerable attention in the construction industry due to their ability to enhance efficiency and accuracy. Wang et al. (2021) proposed a vision-based framework for automatic progress monitoring of precast walls using surveillance videos. Their framework enables real-time tracking and analysis, providing valuable insights for project managers to effectively monitor construction progress. Complementing this work, Mahami et al. (2019) developed an automated system that utilizes daily site images and BIM to control and monitor construction progress. This system offers an automated approach for progress monitoring, enabling real-time analysis and timely decision-making.

Point Cloud Analysis for 3D Reconstruction: Point cloud analysis techniques play a crucial role in generating accurate 3D models and recognizing construction elements. Maalek et al. (2019) focused on the automatic recognition of common structural elements from point clouds, enabling automated progress monitoring and dimensional quality control in reinforced concrete construction. Researchers have made significant strides in point cloud analysis, leveraging advanced algorithms and techniques for precise 3D reconstruction and accurate element recognition.

Augmented Reality and Mixed Reality for Construction Monitoring: Augmented reality and mixed reality (MR) technologies offer promising construction site monitoring and documentation solutions. Zollmann et al. (2014) explored the application of AR for construction site monitoring, enabling real-time visualization of design models on the construction site. Their research demonstrated the potential of AR to enhance communication, reduce errors, and improve construction quality. Khairadeen Ali et al. (2021) investigated the use of extended reality for remote indoor construction progress monitoring. Their study showcased the benefits of immersive experiences and interactive visualizations for remote stakeholders, facilitating enhanced collaboration and decision-making.

Deep Learning Approaches for Point Cloud Analysis: Deep learning techniques have shown great potential in point cloud scene understanding and automated scan-to-3D reconstruction. Chen et al. (2019) proposed a deep learning approach for point cloud scene understanding, facilitating automated scan-to-3D reconstruction with higher accuracy and efficiency. Zeng et al. (2020) developed a user-exemplar-based retrieval system for building element recognition from raw point clouds, demonstrating the effectiveness of deep point-level features in accurately identifying and retrieving building elements. These approaches further improve the automation and accuracy of point cloud analysis.

Considerations for Cost Estimation and Forecasting: Accurate cost estimation and forecasting are crucial for effective project evaluation. Salling and Leleur (2015) highlight the impact of inaccuracies in

demand forecasts and construction cost estimations on transport project evaluation, emphasizing the need for improved methodologies and tools in this context.

By highlighting the significance of computer vision techniques, 4D BIM integration, automated progress monitoring, point cloud analysis, and deep learning approaches, this synthesis contributes to the existing body of knowledge. The insights presented offer valuable guidance for researchers and practitioners in the construction industry. Future research should focus on further exploring and implementing these design and construction activities in a more automated way, to enhance project management practices and ensure successful project outcomes.

2. SYSTEM ARCHITECTURE

2.1. As-design, As-built model environment – Autodesk Revit

Revit offers a comprehensive platform that integrates 3D modeling, parametric design, and collaborative functionalities, enabling architects to create highly accurate and efficient building designs. It has been used in this research as a platform to gather and update all the information obtained from the construction and the analysis.

2.2. Point Cloud environment

2.2.1. Process – CloudCompare, Autodesk Recap

CloudCompare offers a comprehensive platform for processing and analyzing massive point cloud datasets with ease and efficiency. By harnessing the computing power and scalability of cloud-based infrastructure, architects can overcome the limitations of traditional desktop-based solutions and leverage advanced algorithms and techniques for point cloud registration, segmentation, visualization, and analysis.

Autodesk Recap is designed for the efficient processing and management of point cloud data, particularly in the fields of architecture, engineering, and construction (AEC). With Recap, users can seamlessly convert extensive laser scanning data into precise 3D models, providing a valuable foundation for various AEC projects. The software streamlines the cleanup of point cloud data, enabling users to remove unwanted elements and focus on essential components. Furthermore, Recap facilitates the alignment of point clouds with existing 3D models, allowing for accurate comparisons and analysis.

2.2.2. Analysis – Rhino, Grasshopper

Grasshopper offers a flexible and intuitive platform for processing, analyzing, and deriving valuable insights from these dense spatial datasets. By harnessing Grasshopper's extensive library of plugins, such as Point Cloud, Mesh, and Data Tree, architects can efficiently extract information from point clouds, including spatial relationships, surface geometry, and environmental characteristics.

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3. CHAPTER 1 - CONSTRUCTION PROGRESS MONITORING

3.1. Methodology

The basic concept underpinning this construction progress monitoring framework revolves around the development of a semi-automated methodology for the integration of data acquired from Laser Scanning and other reporting mechanisms into the BIM Model. This integration is important for maintaining an accurate and up-to-date representation of the project's status and progress. In this paper, two methods are elucidated to achieve this integration:

- Method 1: This method centers on conducting an in-depth analysis leveraging the As-built point cloud data. Here, the point cloud data is harnessed to directly assess and monitor the construction progress, providing valuable insights into the real-world state of the project.
- Method 2: In contrast, Method 2 introduces a nuanced approach. It involves the preliminary transformation of the As-built points into a mesh representation. This mesh serves as an intermediary data format that subsequently undergoes analysis. This method offers unique advantages, including the ability to leverage mesh-based analysis tools and techniques.

Both methods contribute to the goal of integrating Laser Scanning data and other reporting sources with the BIM Model. By offering two methods to achieve the goal, the framework serves diverse project requirements and preferences. This empowers project stakeholders to select the most suitable approach based on the specific project context, enhancing the efficiency and accuracy of construction progress monitoring.

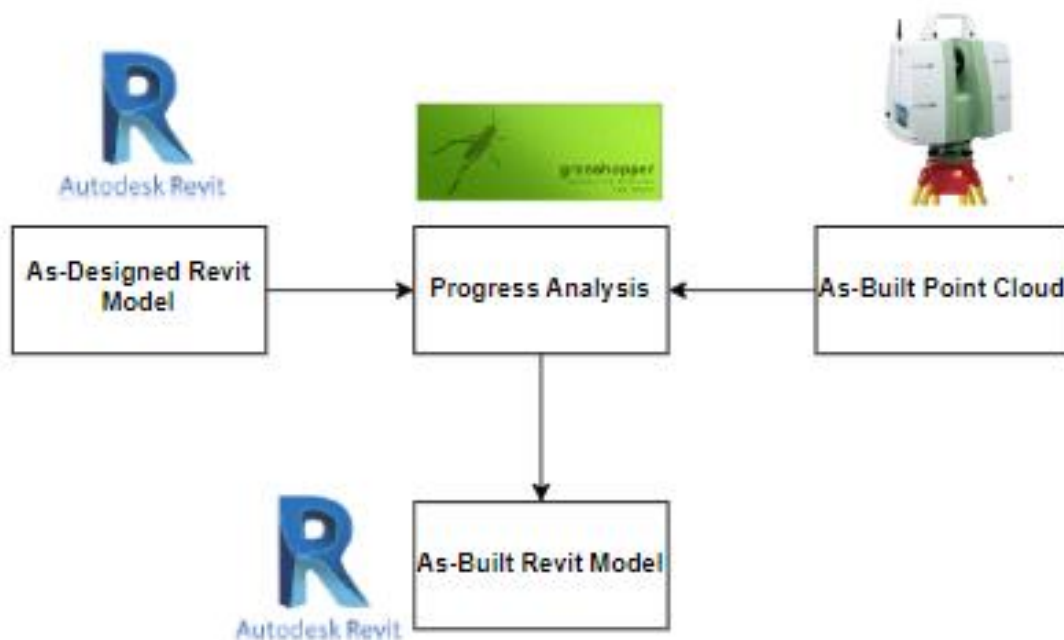


Figure 1 – General Pipeline of Construction Progress Analysis

3.1.1. Method 1- Points vs. model

Method 1 is to align between the As-designed model and the As-designed point cloud, with the primary objective of conducting a comparison with the As-Built Point Cloud. This method depends on achieving an equivalency in the point cloud density between the As-designed and As-Built datasets, thereby ensuring a meaningful basis for analysis. By equating the point densities in both the As-designed and As-Built point clouds, the resulting number of points associated with individual elements emerges as a potent indicator of the progress of these elements within the construction project.

This approach leverages the consistent point cloud densities as a metric for standardizing the construction progress of specific elements. As the project advances, alterations in point cloud densities, particularly on elements undergoing construction, provide clear visual cues that enable stakeholders to ascertain progress levels with precision. This method not only streamlines progress tracking but also enhances the accuracy of project reporting, ultimately contributing to the successful execution of the construction project.

A detailed pipeline of method 1 is described in the Figure 2

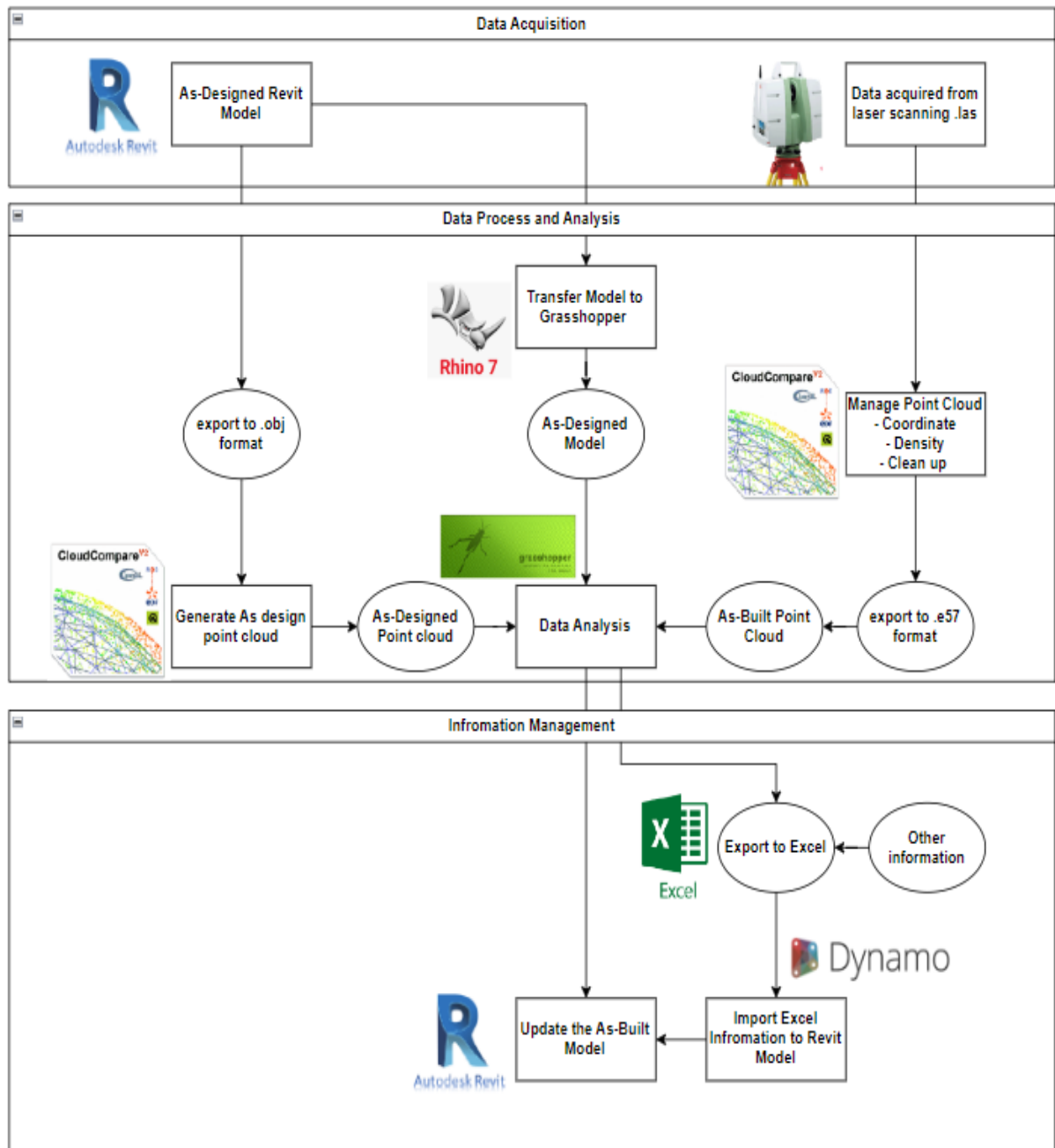


Figure 2 – Pipeline of Method 1

3.1.1.1. Data Acquisition

3.1.1.1.1. As-built Point Cloud

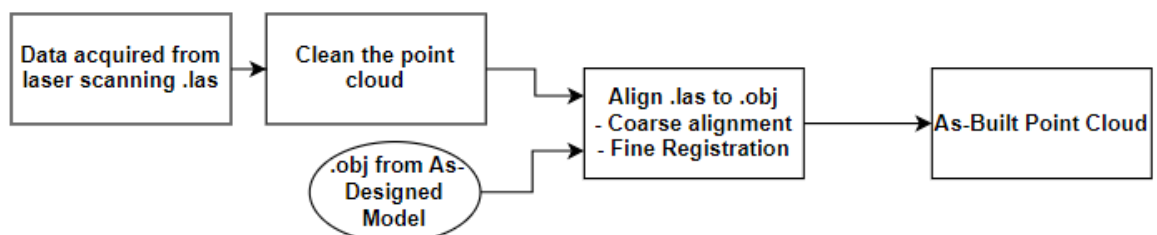
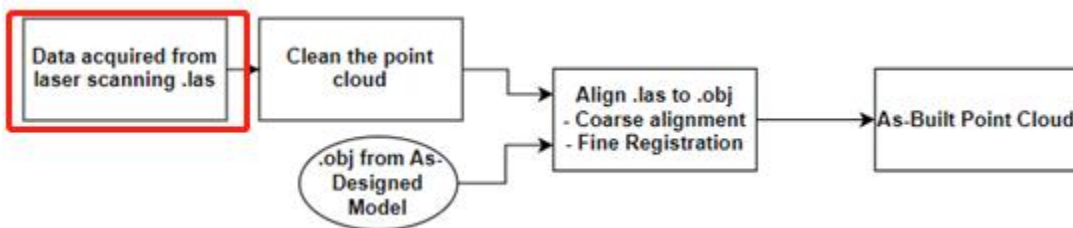


Figure 3 – Processing As-Built Point Cloud

An "as-built point cloud" refers to a three-dimensional (3D) digital representation of an existing physical environment or structure, typically created through a process known as 3D laser scanning or LiDAR (Light Detection and Ranging). This technology is commonly used in various industries, including architecture, engineering, construction, and facility management.

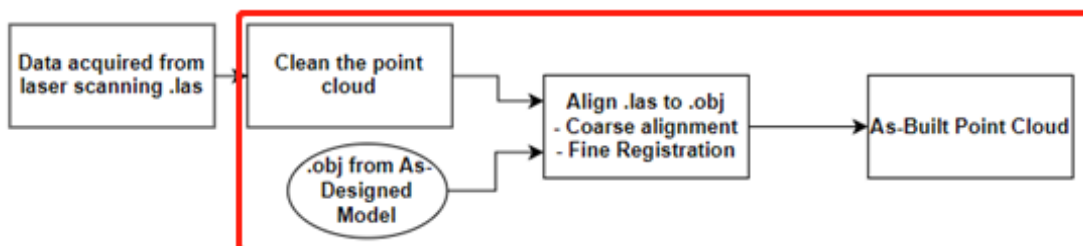
3.1.1.1.1. As-built Point Cloud Acquisition



The collected data is then processed to create a point cloud. A point cloud is a collection of millions or even billions of individual data points (or "points") in 3D space. Each point represents a specific location on a surface, object, or feature within the scanned area. These points are defined by their x, y, and z coordinates in 3D space, and they also often include additional information such as color or intensity values.

The point cloud was acquired from Total Station, Total Station combines electronic distance measurement (EDM) and angular measurement technologies, providing architects with a comprehensive tool for capturing accurate spatial data in the field. By integrating precise measurements of distances, angles, and elevations, Total Station facilitates the creation of detailed 3D models and accurate site plans, serving as a fundamental asset in architectural surveying and design processes.

3.1.1.1.2. Processing raw scan data



The point cloud is then processed by the CloudCompare to

- Clean off unnecessary parts. The process of cleaning up unnecessary parts in laser scanning data is a crucial step in preparing point cloud data for further analysis and visualization, particularly in the context of BIM. Removing extraneous elements such as buildings, machinery, or environmental clutter enhances the quality and clarity of the point cloud. This clean-up operation simplifies the identification and isolation of relevant BIM elements, streamlining subsequent data processing and analysis tasks.
- Define the density of the point cloud Adapting the density of point cloud data to match the specific requirements of the analysis is a key strategy in optimizing data acquisition and utilization. For

structural analysis, where precision is paramount, higher-density point clouds capture intricate details vital for assessing structural integrity. In contrast, when monitoring construction progress, the focus shifts to tracking changes and discrepancies, making excessively dense point clouds less practical. By tailoring density to the analysis type, resources are used efficiently, data remains manageable, and the collected information aligns effectively with the analysis objectives, whether they involve structural assessments or construction progress tracking, ensuring informed decision-making in diverse architectural and engineering contexts.

- Align with the As-design model for future analysis in Grasshopper. To compare the point cloud with the As-design model, it is necessary to align them. Coarse alignment and fine registration are involved in this step. Coarse alignment in CloudCompare is a pivotal step in the point cloud analysis workflow, involving the initial alignment of multiple datasets to establish a rough spatial relationship. This process utilizes manual techniques to estimate transformation parameters, ensuring that point clouds from different sources or viewpoints are aligned correctly. By accurately aligning the datasets, CloudCompare enables subsequent analysis and processing, ultimately leading to more accurate and reliable results in tasks such as fusion, registration, and further point cloud analysis. Fine registration is a crucial step in point cloud analysis, aiming to refine the alignment of datasets for achieving a higher level of accuracy and precision. In CloudCompare, this process involves employing advanced algorithms such as Iterative Closest Point (ICP) and feature-based registration to further optimize the spatial relationship between the point clouds. By iteratively matching corresponding points or features and iteratively refining the alignment, fine registration ensures that the point clouds are accurately aligned, minimizing any remaining misalignments or discrepancies. This precise alignment enables more reliable and accurate subsequent analyses, such as surface reconstruction, volumetric calculations, and feature extraction, facilitating better-informed decision-making in architectural design and other applications.

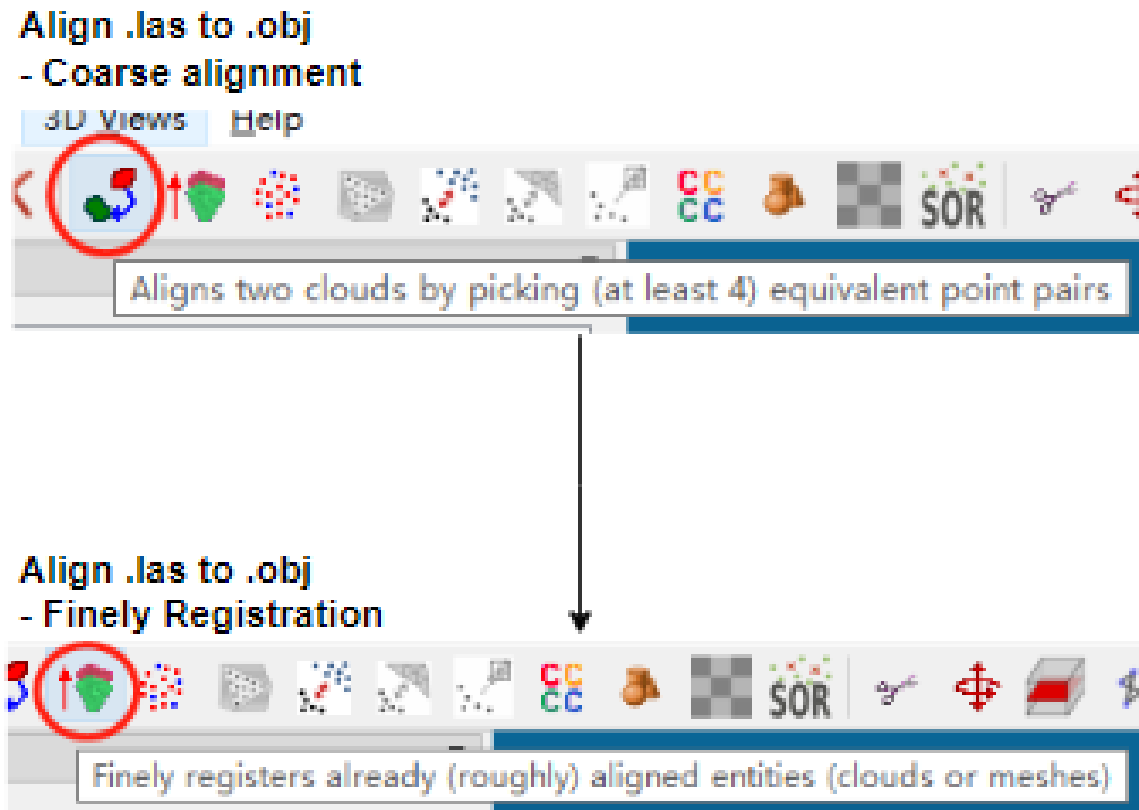


Figure 4 - Coarse and Fine Registration

3.1.1.1.2. Create As-design Point Cloud

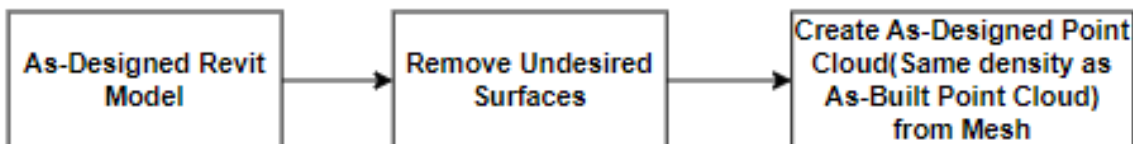


Figure 5 – Create As-Design Point Cloud

As-design Point Cloud refers to a conceptual point cloud that represents a 3D digital model of a structure or environment as it is designed or planned, rather than as it exists (as-built point cloud). It was transferred in a way from the 3D model.

An as-design point cloud would capture the digital representation of a structure or environment based on architectural or engineering plans and specifications. This means it reflects the design intent, showing how a building or project is expected to look and function once it's constructed or implemented. It can be used in comparative analysis with the as-built point cloud. This comparison allows for an assessment of how closely the constructed project aligns with the original design, highlighting any deviations or discrepancies that may need to be addressed.

The first step of creating an As-design point cloud is to export the model to .obj format to open it in Point Cloud processing software (CloudCompare). In CloudCompare, we can transfer this .obj mesh to

the point cloud with adjusted parameters such as point density, level of detail, and other parameters to control the quality and size of the generated point cloud.

However, since the laser scanner can only generate point clouds on the exposed surface of the scanned elements, we need a BIM Model that only has the exposed surface corresponding to it to achieve the same density of the two points on the element's Quantitative comparison. There are two ways to remove undesired surfaces.

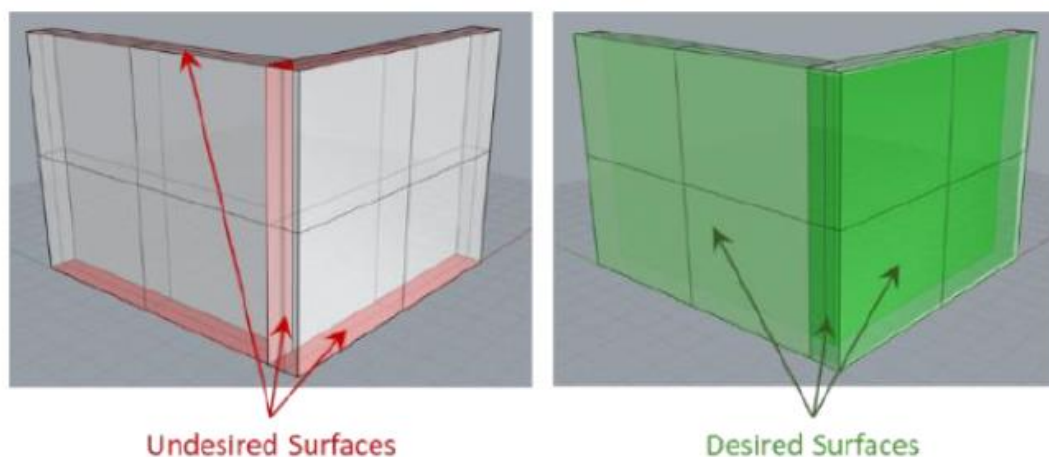


Figure 6 – Surfaces of Element

3.1.1.1.2.1 Undesired Surface Remove Method 1- Points from Mesh

The first method is to create a mesh from the as-designed model and transfer it to point cloud process software. In the point cloud process environment, the mesh is populated by points and creates a new mesh from those points using the " PoissonRecon " function in CloudCompare. It utilizes the Poisson surface reconstruction algorithm to convert point cloud data into a continuous surface representation. This function generates a mesh or surface model from the input point cloud dataset by analyzing local density and normal information. With adjustable parameters such as depth and scale, users can control the reconstructed surface's level of detail and size. Using the feature that the mesh is only generated on the outer boundary of the point cloud, a mesh that has value only on the exposed surfaces of elements can be obtained. Then use this mesh to make a point cloud that all the points are on the exposed surfaces of the elements.

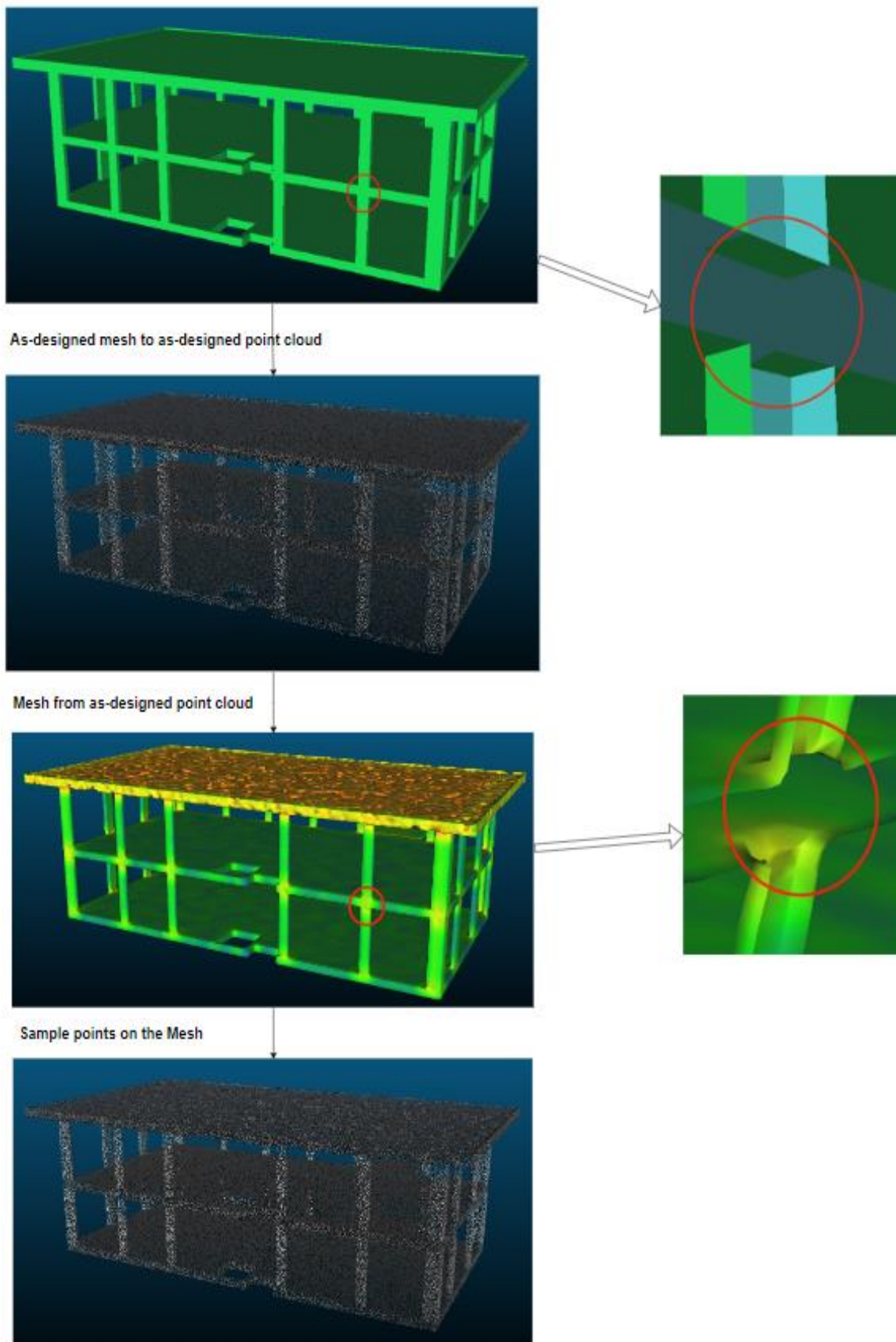
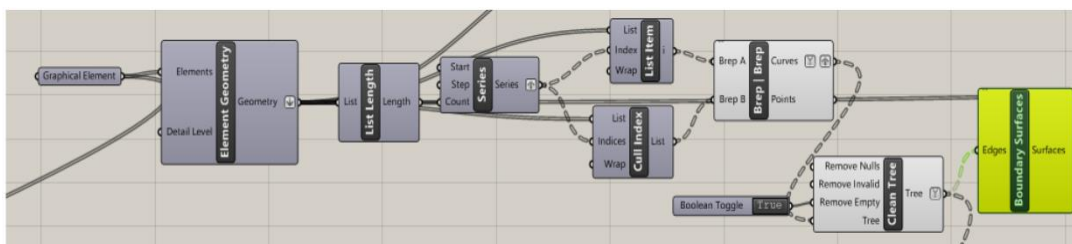


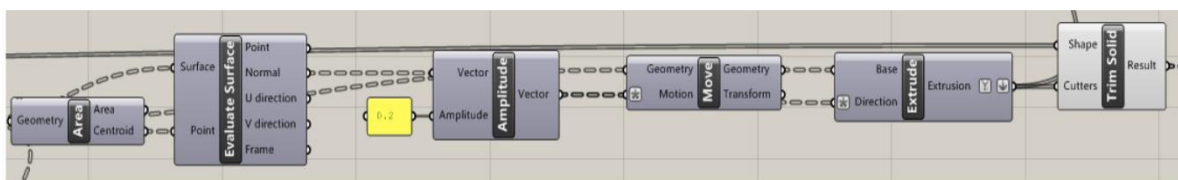
Figure 7 – Remove Undesired Surfaces, Method 1

3.1.1.1.2.2 Undesired Surface Remove Method 2- Visual Program

The second method is to use the visual programming language to eliminate Undesired parts of surfaces. The first is to identify which surfaces of Elements coincide with the surfaces of other Elements. In some cases, the entire surface does not necessarily repeat. For example, When the Column and Slab coincide, usually the upper and lower surfaces of the entire Column coincide with part of the surface of the Slab. Therefore, coincident entire surfaces cannot be deleted. The method I use here is to find the intersections between surfaces and create a very thin solid shape around the surface, then use this solid to trim the elements of the building, which removes all the surfaces within the trimmed area, leaving only exposed surfaces.



Find the Duplicate Surfaces

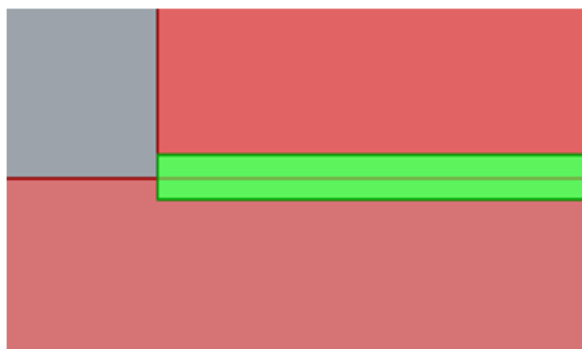


Remove the Duplicate Surfaces

Figure 8 – Find and Remove Overlapped Surfaces

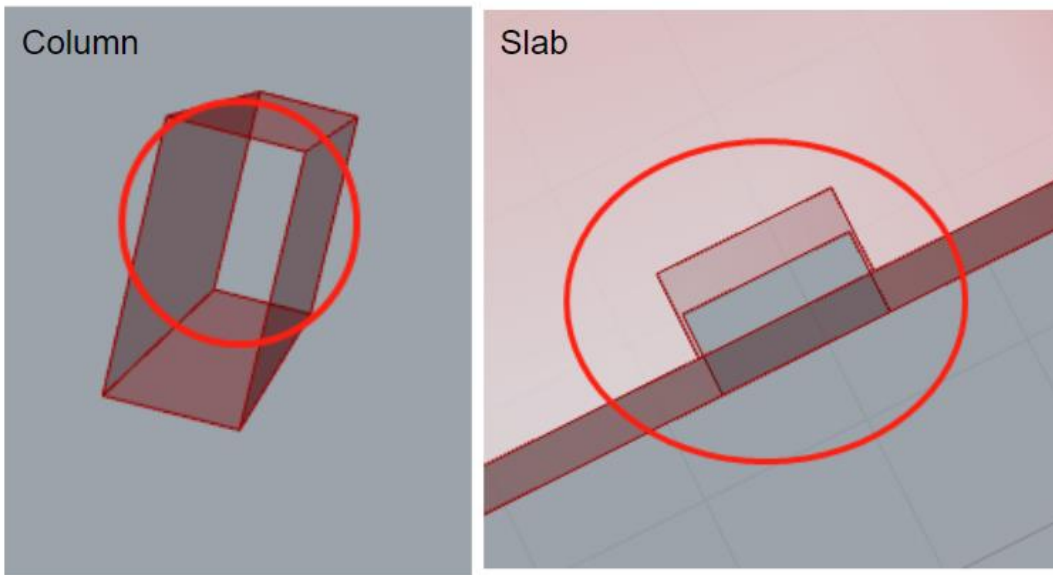


Intersections between surfaces



Trim Building elements←

Figure 9 – Trim Intersection Between Element



Duplicate Surface is removed

Figure 10 – Surface After Trimmed

Generating the As-Design Point using the "sample points on a mesh" function in CloudCompare after surface preparation is a systematic approach to maintaining consistency and density alignment between As-Design and As-Built point clouds. Defining the number of points based on the density of the As-Built point cloud, to ensure that both datasets are directly comparable and have equivalent levels of detail. Using a consistent density standardizes the data and streamlines subsequent analysis, enabling meaningful insights into engineering projects.

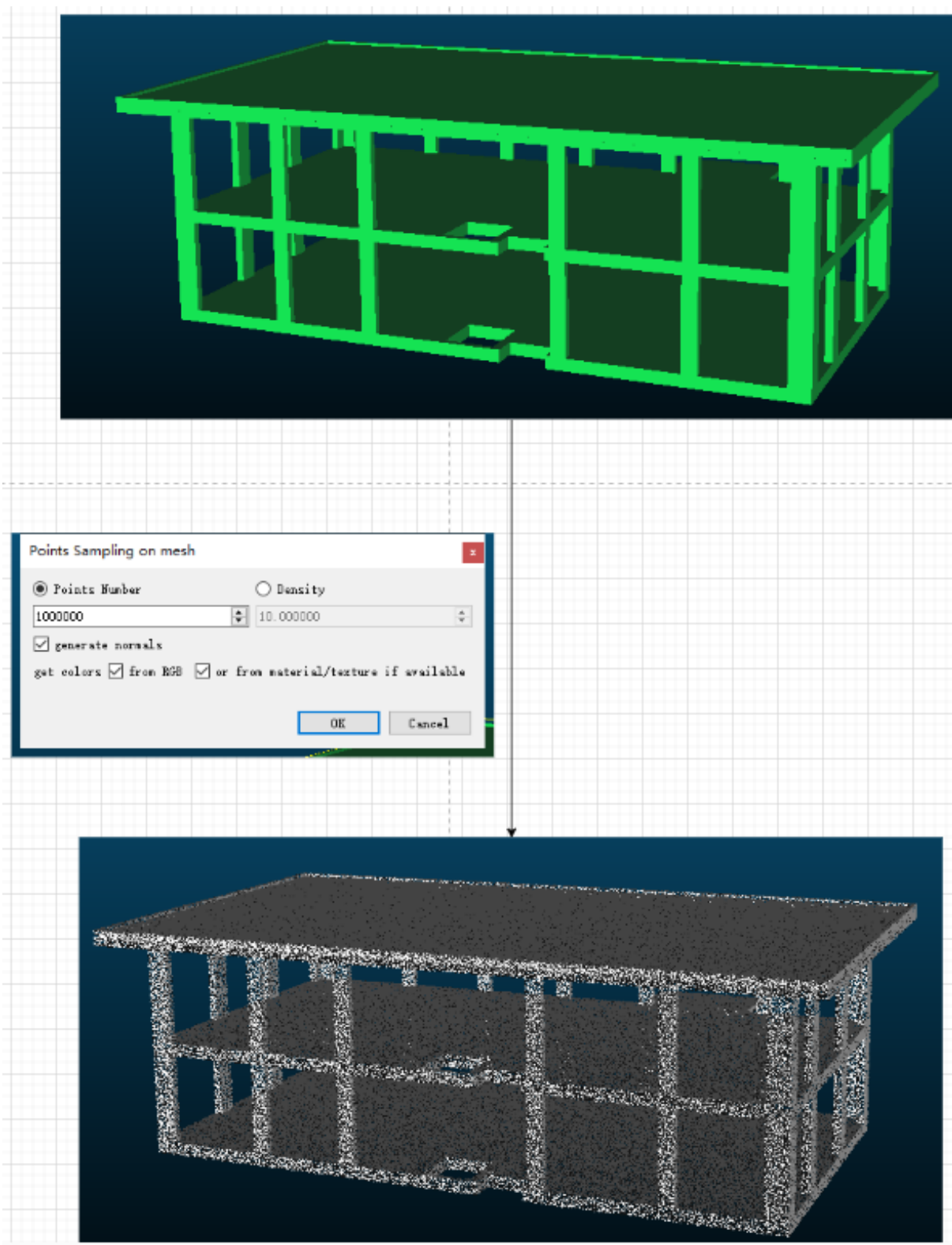


Figure 11 – Populate Points on As-Design Model

3.1.1.2. Data Analysis

The depicted flowchart provides a clear and structured overview of the data analysis process, emphasizing the integration of the As-Designed Model, As-Designed Point Cloud, and As-Built Point Cloud within a unified environment. This systematic approach ensures that essential information is

extracted from these three resources and subsequently used for analysis purposes. Bringing these data sources together, to create a comprehensive dataset that forms the foundation for various analytical tasks, such as construction progress tracking, quality control, or structural assessments.

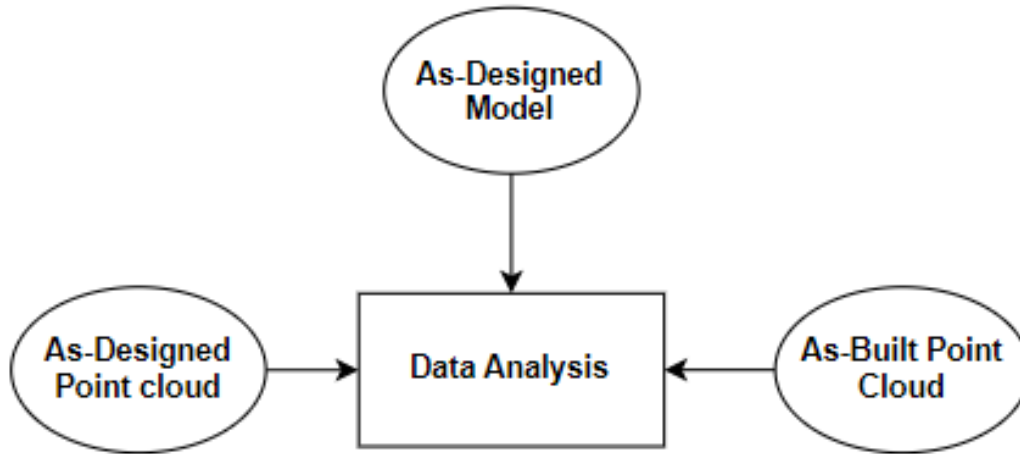


Figure 12 – General Pipeline of Data Analysis

3.1.1.2.1. Core Concept

The fundamental principle underlying the calculation of progress involves a direct comparison between the number of points associated with elements in the As-Designed Point Cloud and the As-Built Point Cloud. By utilizing the As-Designed models as a reference framework, this calculation begins by quantifying the count (A) of As-Designed Point Cloud points for each element. Subsequently, it computes the count (B) of As-Built Point Cloud points corresponding to the same elements. Given that both the As-Designed and As-Built Point Clouds share identical densities, progress is derived by comparing A and B for each element. This method ensures that progress assessments are grounded in precise, point-by-point comparisons, facilitating the monitoring of construction advancements, quality assurance, and alignment with design specifications with a high degree of accuracy and reliability.

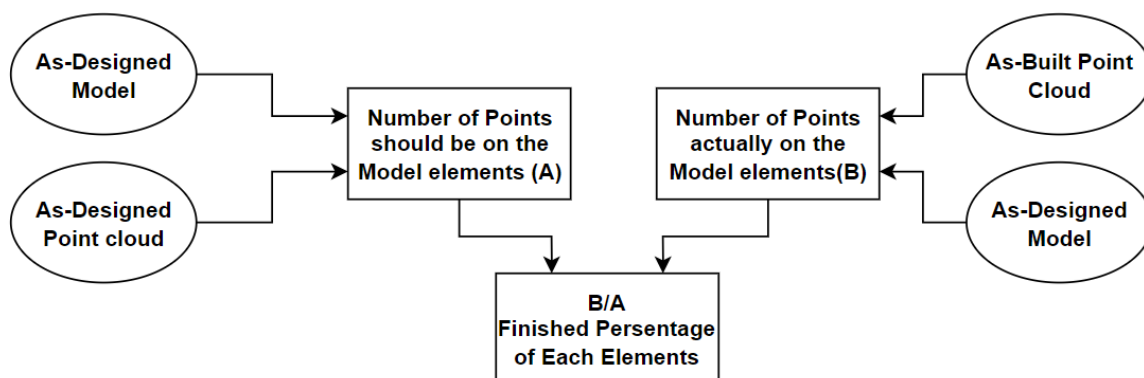
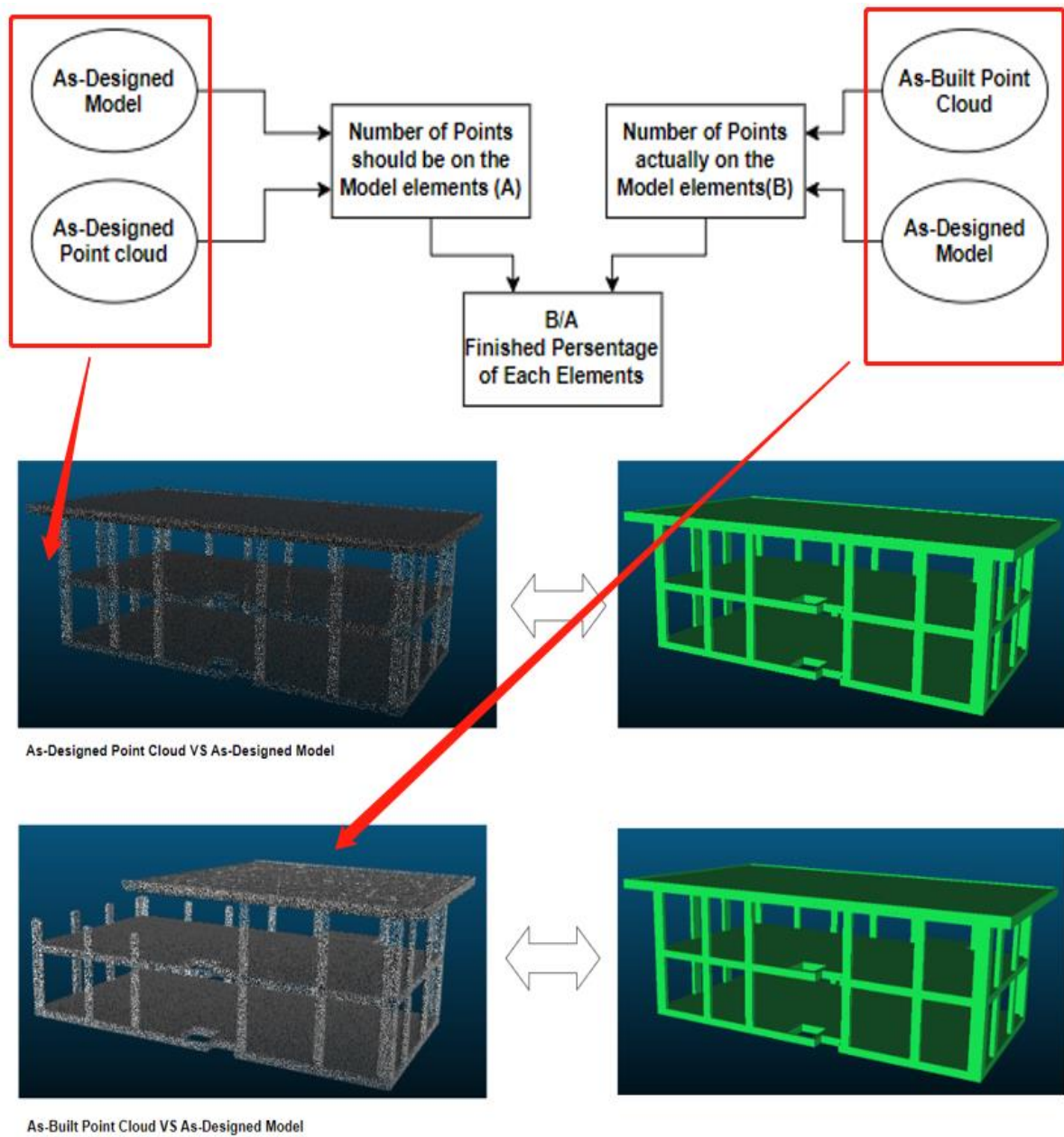


Figure 13 – Data Analysis



3.1.1.2.2. Grasshopper Script

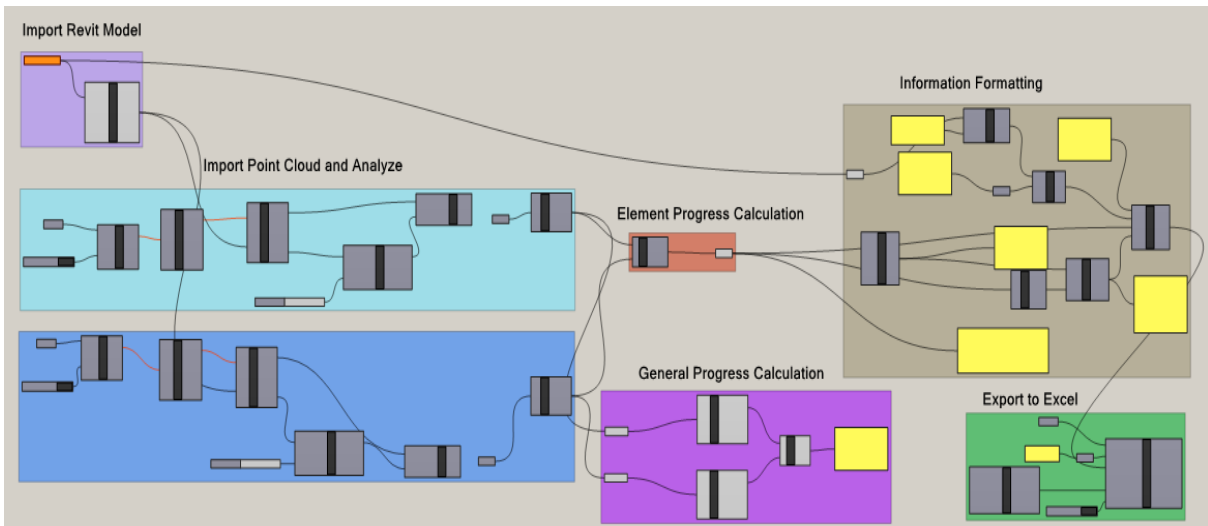


Figure 14 – Grasshopper Script

3.1.1.2.2.1 Point cloud analysis

The imported model could contain any information on the designed model according to the requirements. In this case, use the location and shape information of the As-designed model for matching and analysis with Point Cloud. All Points imported from the point cloud will calculate the distance with the Elements of the As-designed model, and stipulate that the points less than a certain distance belong to that Element. In this case, the tolerance is defined as 1 centimeter.

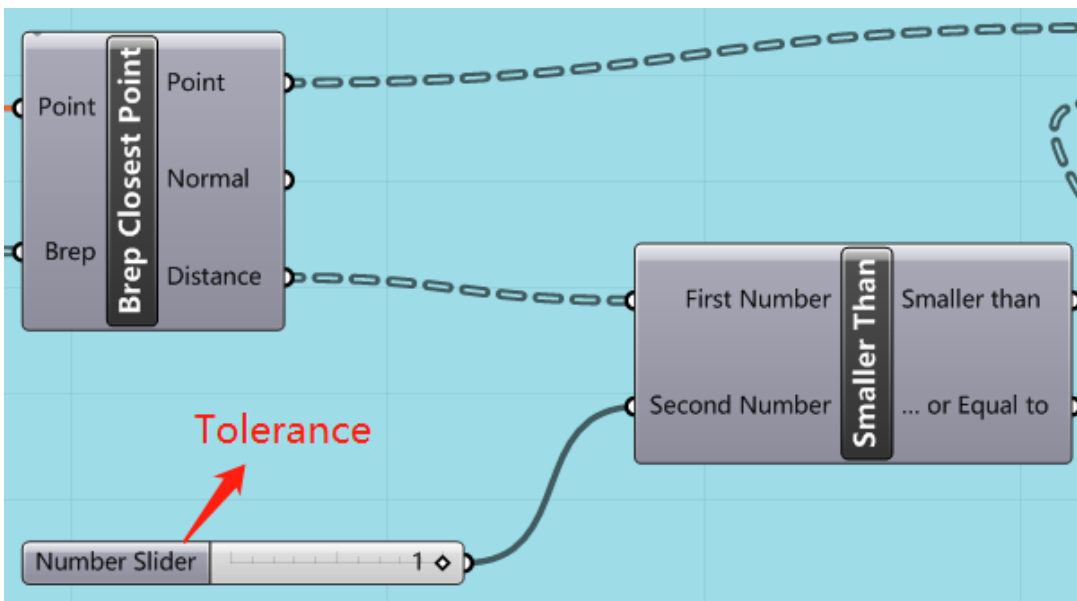


Figure 15 – Define Tolerance

Therefore, each Element will have a corresponding number of points (the number of Points should be on the Model element B, and the number of Points should be on the Model element A) by calculating the ratio of each B in A. The percentage of elements completed can be obtained.

3.1.1.2.2.2 General Progress and Element Progress

Calculating the general progress of the building by considering the total number of points in the As-Built point cloud that fall within the specified distance tolerance to the As-Design model, divided by the total number of points in the As-Design point cloud, offers a comprehensive view of the construction progress. This ratio provides a holistic measure of how closely the entire building construction aligns with the original design, taking into account all the elements and components. By evaluating the building, users can assess the overall quality and accuracy of the construction process.

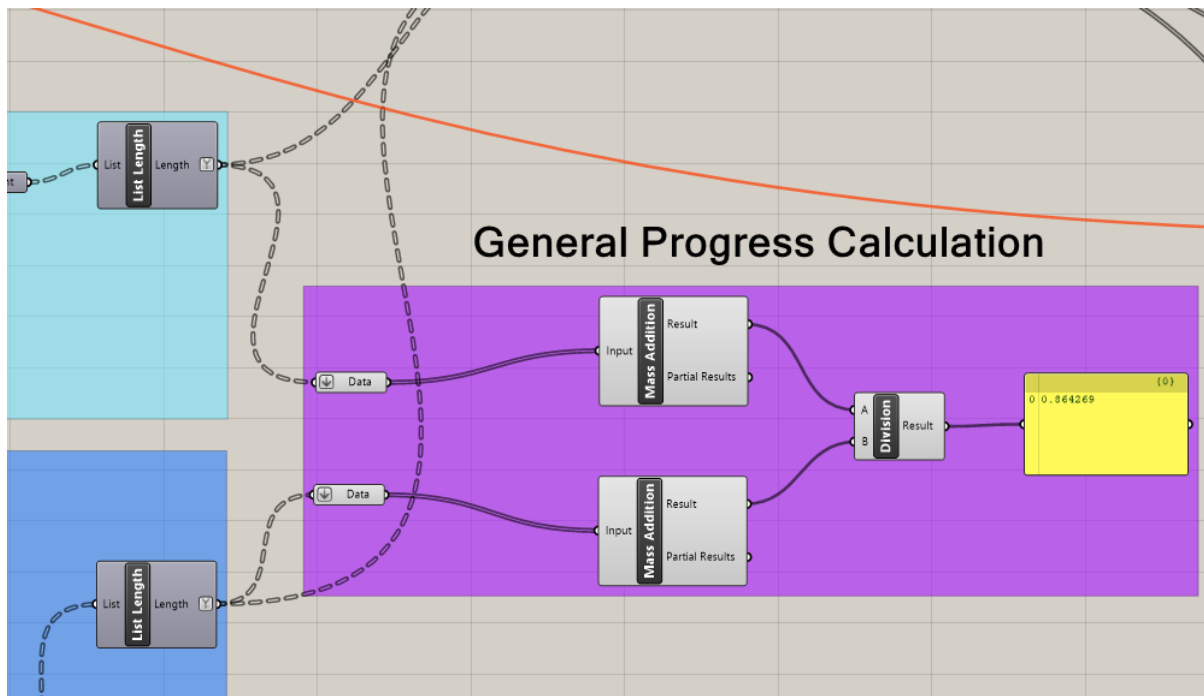


Figure 16 – General Progress

The calculation of the progress of each building element based on the number of points in the As-Built point cloud within the specified distance tolerance to the As-Design model, divided by the number of points in the As-Design point cloud for the same element, provides a data-driven measure of construction progress. This ratio effectively quantifies how closely the actual construction aligns with the intended design. By comparing these point cloud datasets, the script can assess the consistency of the built elements to the design, with a higher ratio indicating a closer match and better progress.

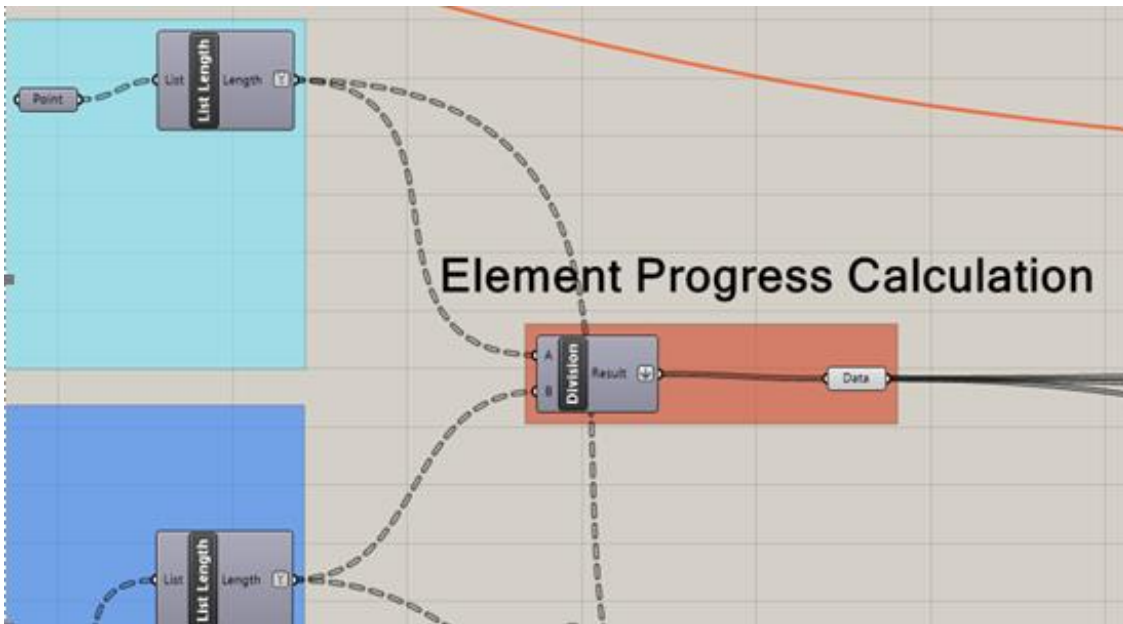


Figure 17 – Element Progress

3.1.1.2.2.3 Data Formatting

Data formatting, a crucial step in your script, involves structuring and organizing analysis results to align with the specific project requirements. Defined properties like "ID," "Progress," and "Updated at" play an important role in labeling and categorizing the data, ensuring its proper placement in Excel or matching with BIM model properties. This organized approach enhances the accessibility and readability of analysis results. Data formatting can be customized to adapt to project-specific needs to facilitate project tracking and management.

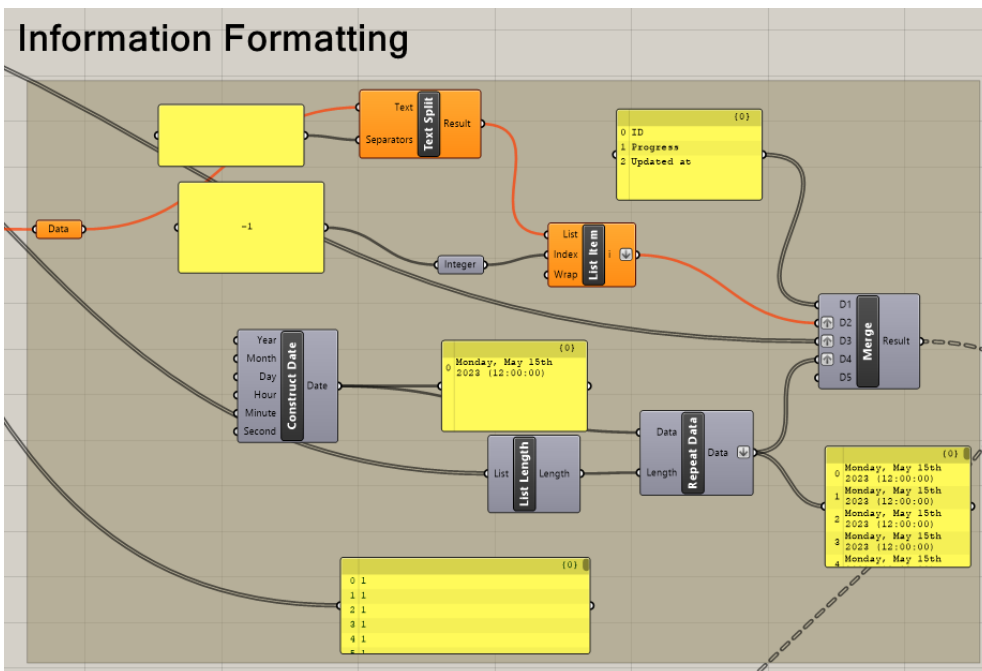


Figure 18 – Data Formatting

3.1.1.2.2.4 Export to Excel

Customizing the export of generated data to an Excel sheet within the script by defining parameters like the file path, sheet name, value settings, and more is a versatile and powerful capability. This customization allows users to tailor the data export process to match the specific needs and structure of the project or analysis. By specifying these parameters users can ensure that data aligns seamlessly with the intended format and layout.

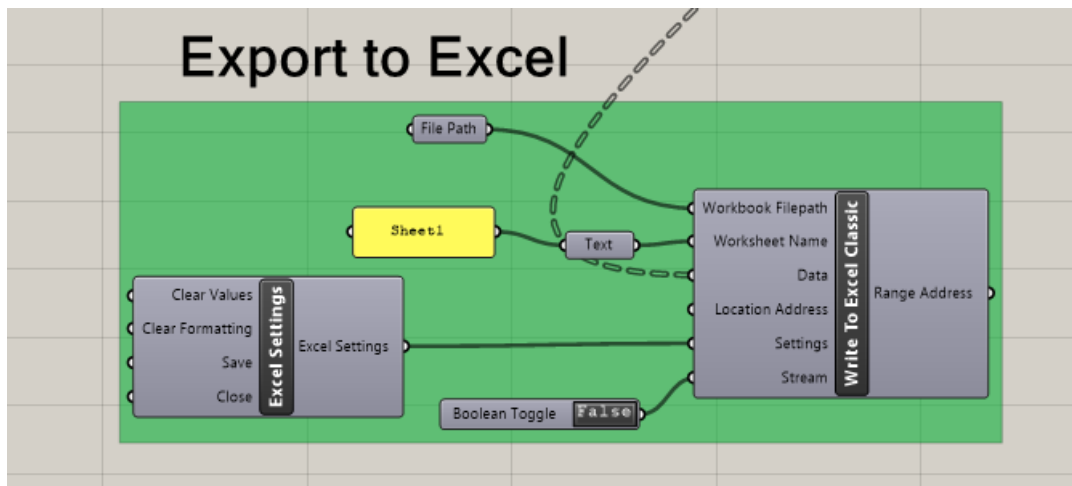


Figure 19 – Data Export

3.1.1.3 Analysis Result

As shown in the table below, each element (ID) has a “Progress” and an “Updated at”. For example, the Element “341585” was 22.18% done on Monday, May 15th. 2023.

ID	Progress	Updated at
339871	1	Monday, May 15th 2023 (12:00:00)
340301	1	Monday, May 15th 2023 (12:00:00)
340500	1	Monday, May 15th 2023 (12:00:00)
340532	1	Monday, May 15th 2023 (12:00:00)
340550	1	Monday, May 15th 2023 (12:00:00)
340578	1	Monday, May 15th 2023 (12:00:00)
340642	1	Monday, May 15th 2023 (12:00:00)
340689	1	Monday, May 15th 2023 (12:00:00)
340693	1	Monday, May 15th 2023 (12:00:00)
340778	1	Monday, May 15th 2023 (12:00:00)
340879	1	Monday, May 15th 2023 (12:00:00)
340882	1	Monday, May 15th 2023 (12:00:00)
340885	1	Monday, May 15th 2023 (12:00:00)
340888	1	Monday, May 15th 2023 (12:00:00)
340935	1	Monday, May 15th 2023 (12:00:00)
341202	1	Monday, May 15th 2023 (12:00:00)
341212	1	Monday, May 15th 2023 (12:00:00)
341585	0.221818	Monday, May 15th 2023 (12:00:00)
341586	0.218519	Monday, May 15th 2023 (12:00:00)
341587	0.189189	Monday, May 15th 2023 (12:00:00)
341588	0.25537	Monday, May 15th 2023 (12:00:00)
341589	0.25537	Monday, May 15th 2023 (12:00:00)

Figure 20 – Result in Excel

This approach extends its benefits beyond immediate construction-related documentation and BIM model updates. It serves as a pivotal bridge between the design phase and real-world implementation, enabling not only the seamless integration of design changes into Construction Reports but also fostering a dynamic feedback loop that drives the evolution of the entire project lifecycle.

By harnessing the data generated through Grasshopper, architects, engineers, and project managers gain a comprehensive understanding of how the design manifests in physical space. This wealth of information extends beyond mere geometry and includes aspects like material quantities, spatial relationships, and potential conflicts. Consequently, the data extracted from this innovative approach empowers stakeholders to optimize resource allocation, anticipate construction challenges, and make informed decisions that streamline the construction process.

Furthermore, it promotes an agile approach to project management, allowing for rapid prototyping and experimentation within the digital environment, reducing the likelihood of costly errors during the actual construction phase. Thus, the result becomes not merely a static update for documentation but a dynamic tool for design validation, clash detection, cost estimation, and overall project coordination, ultimately leading to more efficient, cost-effective, and sustainable construction practices.

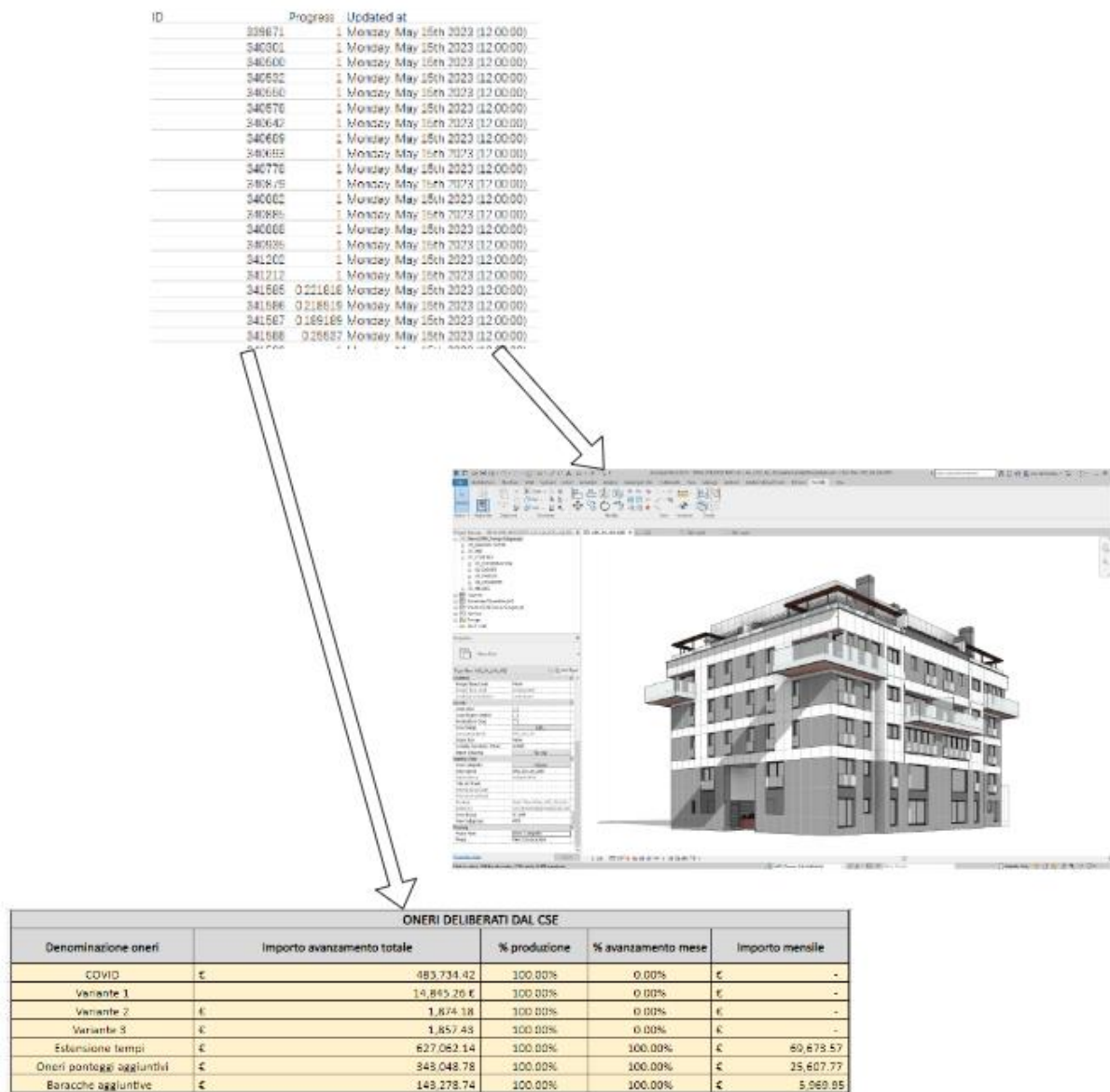


Figure 21 – Information Integration

3.1.2. Method 2- Mesh VS Model

The starting point in this method involves converting the point cloud data into a mesh representation. This transformation allows for a more structured and comprehensive approach to matching and updating the model. Instead of matching points directly, this method introduces the concept of "key points" on the elements of the as-designed model. These key points serve as reference markers for aligning the mesh data with the model. The script then compares the key points on the as-designed model with the mesh data generated from the point cloud. If a key point on the model is near the mesh, it is considered a successful match. This matching process ensures that elements of the model align with the real-world data represented by the mesh. Once key points are matched successfully, the script calculates the progress of each element. This calculation is typically based on the percentage of matched key points out of the total number of key points associated with an element. The more key points that are successfully matched, the higher the progress percentage for that element.

This method offers some advantages over the first method:

- **Structural Alignment:** By converting the point cloud to a mesh and using key points, this approach provides a more structured and systematic way to align the as-designed model with real-world data. It accounts for the overall shape and geometry of elements rather than individual points.
- **Progress Tracking:** The concept of progress calculation based on key points allows for a quantitative measure of how closely the as-designed model matches the real-world data. This can be valuable for quality control and tracking project milestones.
- **Flexibility:** This method is adaptable to various types of elements if they can be represented by key points. It's not limited to simple point-to-point matching.

However, it's important to note that this method may introduce complexities in defining key points, mesh generation, and matching algorithms. The choice between Method 1 and this alternative method should be made based on the specific requirements and constraints of the project, as well as the available software and expertise in the workflow.

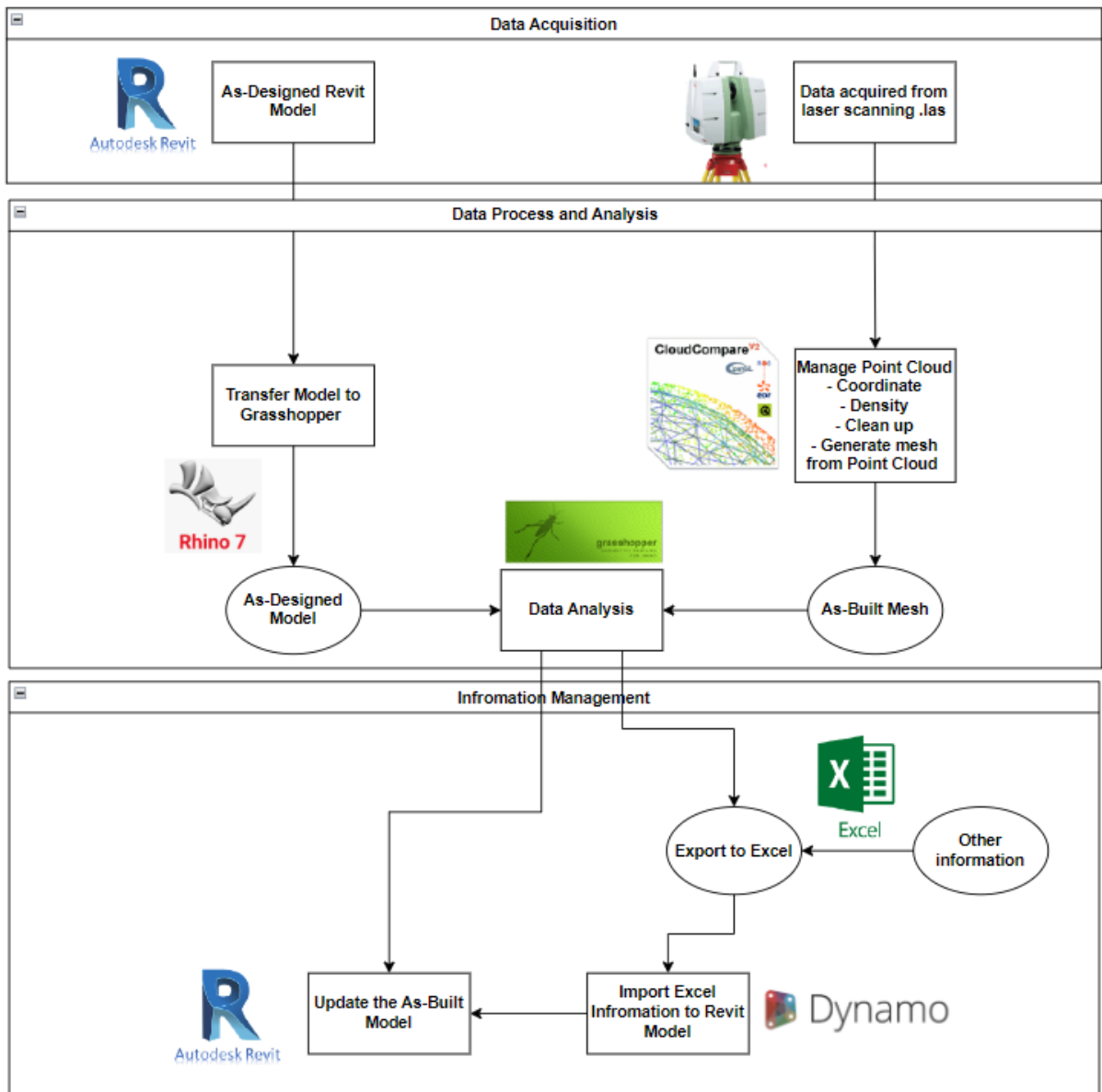


Figure 22 - Method 2, Mesh VS Model

3.1.2.1. Data Process

3.1.2.1.1. As-Built Mesh

Creating an as-built mesh from point cloud data in the CloudCompare environment involves several steps.

- Import Point Cloud Data: Open the point cloud data in CloudCompare. Ensure that the point cloud is properly registered and aligned if it consists of multiple scans.
- Clean and Remove Unnecessary Parts: Use CloudCompare's editing and filtering tools to clean up the point cloud data. Remove any unnecessary or outlier points that do not represent the desired area or object.
- Define Point Cloud Density: Adjust the density of the point cloud if necessary. Downsample or decimate the point cloud to reduce the number of points while retaining important features. This can

help improve processing speed and reduce file size.

- **Alignment with As-Design Model:** Align the point cloud data with the as-designed model. This step involves registering the point cloud to match the coordinates and orientation of the model. Various registration techniques may be used, such as manual alignment, feature-based registration, or cloud-to-cloud registration.
- **Creating a Mesh:** Once the point cloud is properly aligned, proceed to create a mesh from the scan data. CloudCompare provides tools for mesh generation, typically based on Delaunay triangulation or Poisson surface reconstruction algorithms. Adjust mesh generation parameters such as resolution, surface smoothing, and hole filling as needed to achieve the desired mesh quality.
- **Export the As-Built Mesh:** After creating the mesh, export it in a suitable file format (e.g., STL, OBJ) that can be imported into other 3D modeling or analysis software, such as Grasshopper.
- **Future Analysis in Grasshopper:** Import the as-built mesh into Grasshopper for further analysis, comparison, or integration with the as-designed model. Grasshopper's capabilities are used to perform various analyses and design-related tasks based on the as-built mesh data.

It's important to note that the specific steps and tools in CloudCompare may vary based on the version of the software and the complexity of your point cloud data. Additionally, the alignment with the as-designed model is a critical step to ensure accurate comparisons and analyses between the real-world scan data and the design model.

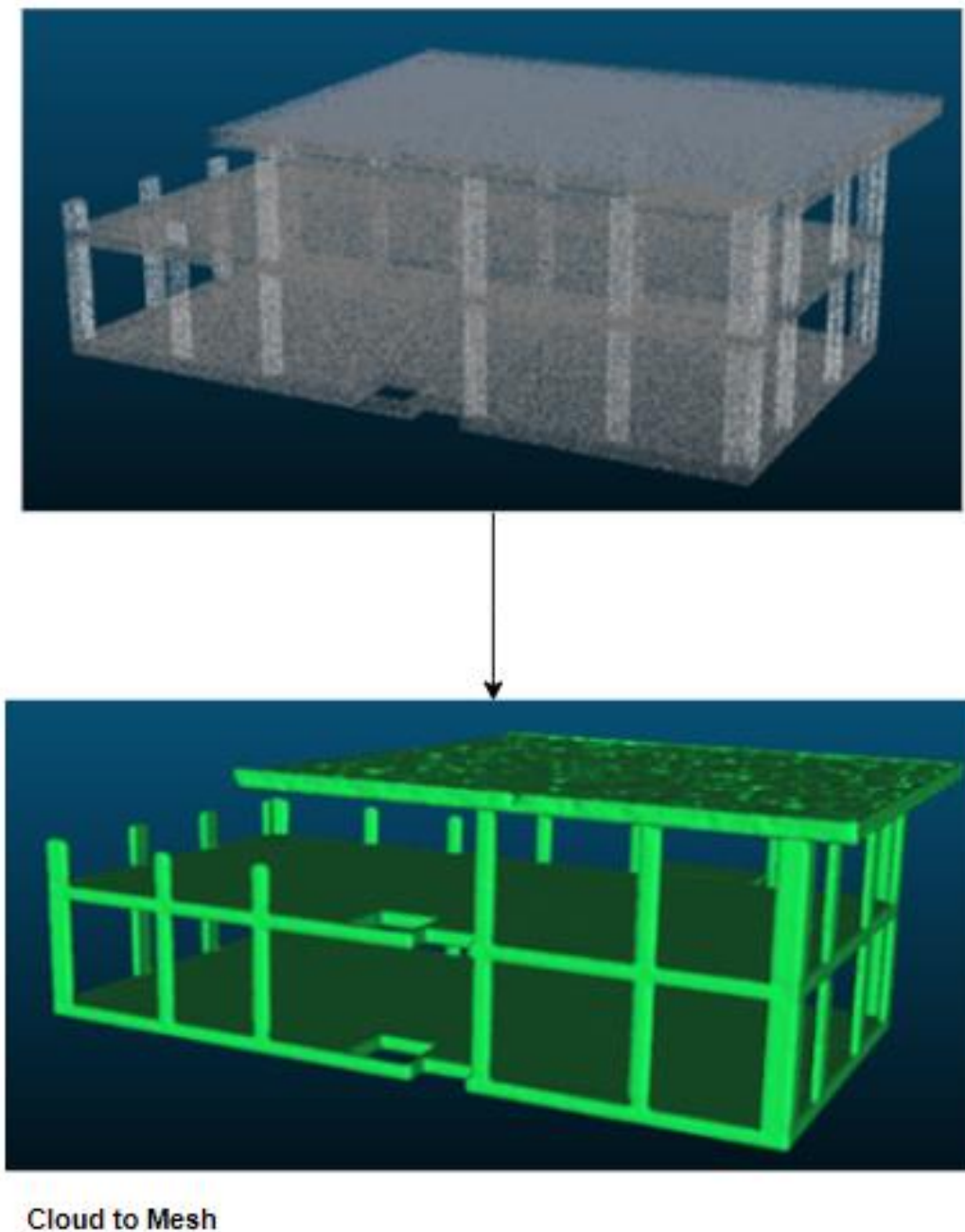
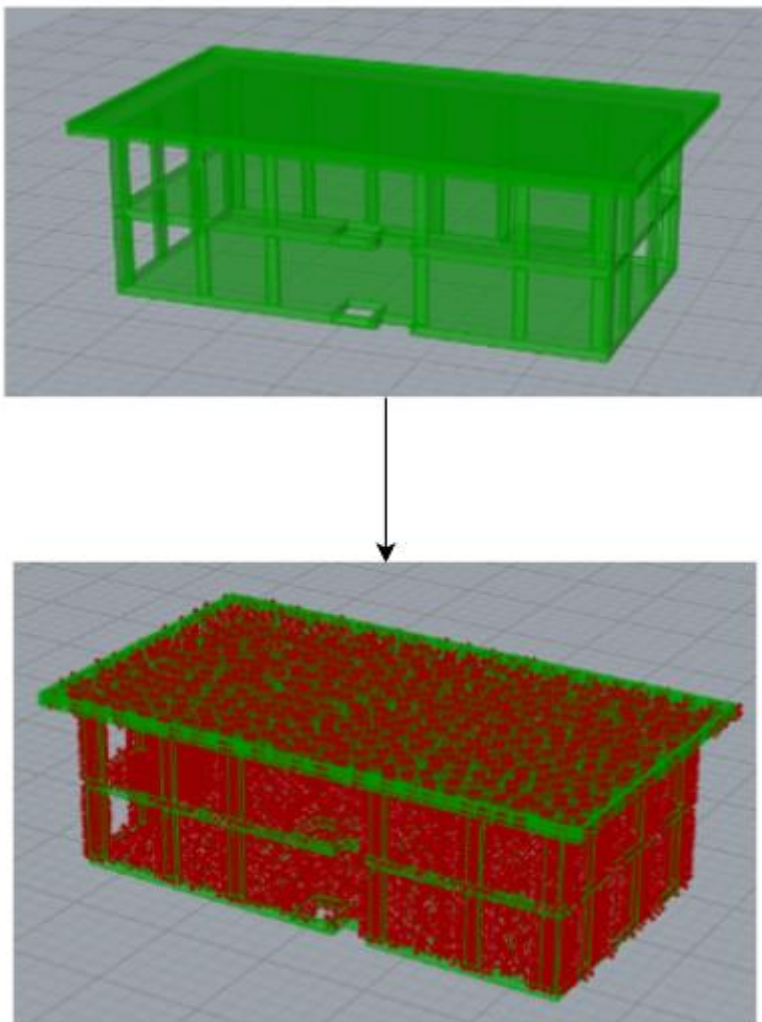


Figure 23 - Point Cloud to Mesh

3.1.2.1.2. As-Designed model

The As-design model utilizes a specific approach by placing key points (B) on its surface to align with the mesh created from the as-built point cloud. The number of these points is determined based on the volume of the model's components. To illustrate, the system categorizes volumes into three distinct groups: "Volumes less than 0.1CBM," "Volumes greater than 0.1CBM but less than 1CBM," and "Volumes exceeding 1CBM."

It's important to note that even the smallest elements are provided with 100 key points for synchronization with the scan data. In simpler terms, this means the system is highly adept at detecting the tiniest elements within the model. This methodology contributes to a comprehensive analysis of the data, ensuring that even the most minute elements are accounted for and thoroughly assessed.



Populate Model

Figure 24 - Populate Points on As-design Model

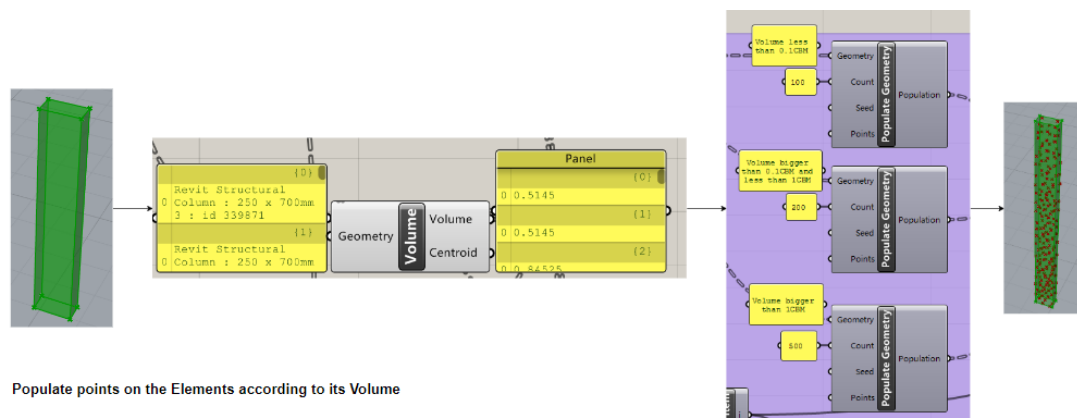


Figure 25 – Define the Number of Points

3.1.2.1.3. Comparison of As-Built Data and As-Designed Data

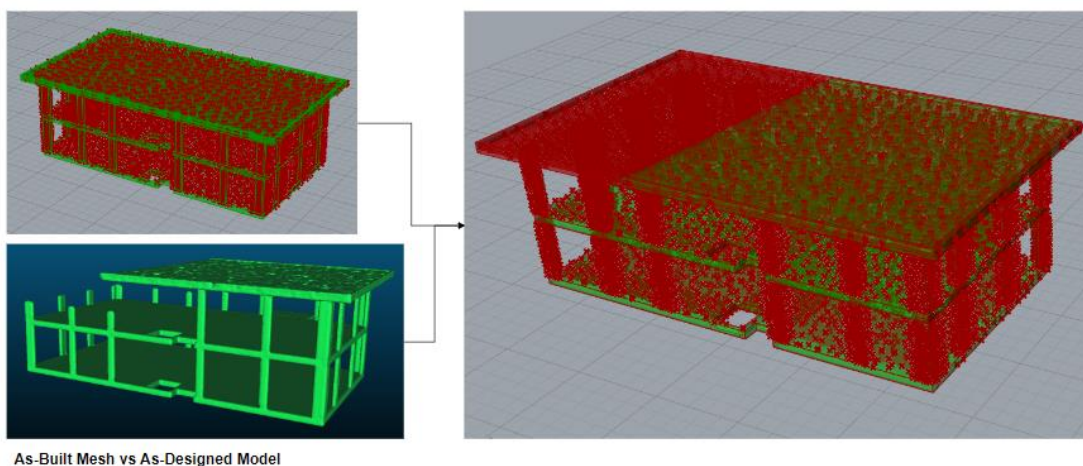


Figure 26 – Mesh vs. Model

To calculate the distance between points and the as-built mesh and define a tolerance for this distance, as well as to count the number of points (A) on the elements under the tolerance and determine the progress of elements (A/B), the following steps were taken:

- Calculate Distance: For each point in your dataset, calculate the distance to the nearest point on the as-built mesh. This can be done using the Euclidean distance formula in a computational environment (Grasshopper).
- Define Tolerance: Define a tolerance value that represents the maximum allowable distance between a point and the as-built mesh for it to be considered a match. This tolerance value is typically specified based on the accuracy requirements of your analysis.
- Count Points within Tolerance (A): Iterate through the calculated distances and count the number of points where the distance is less than or equal to the defined tolerance. These points fall within the acceptable range of the mesh and are considered matches.
- Determine Total Points (B): The total number of points on the elements, representing all points regardless of whether they are within the tolerance, was defined by its volume in the grasshopper script.
- Calculate Progress (A/B): To determine the progress of elements, divide the count of points within

the tolerance (A) by the total count of points (B). This ratio, expressed as a percentage, provides an understanding of how many points conform to the specified tolerance.

The formula for calculating the progress:

$$\text{Progress (A/B)} = (A/B) \times 100\%$$

Analyze Results: Interpret the progress value to assess the alignment between the model and the as-built mesh. This process allows us information to quantify how well the points align with the as-built mesh within the defined tolerance, providing a valuable metric for evaluating the quality and accuracy of building progress.

ID	Progress	Updated at
19482054	0	Thursday, May 25th 2023 (12:00:00)
19482055	0	Thursday, May 25th 2023 (12:00:00)
19482076	0	Thursday, May 25th 2023 (12:00:00)
19482081	0.140374	Thursday, May 25th 2023 (12:00:00)
19482143	0.123159	Thursday, May 25th 2023 (12:00:00)
19482177	0	Thursday, May 25th 2023 (12:00:00)
19482182	0.14248	Thursday, May 25th 2023 (12:00:00)
21345252	0.184211	Thursday, May 25th 2023 (12:00:00)
21347978	0	Thursday, May 25th 2023 (12:00:00)
22177746	0.741007	Thursday, May 25th 2023 (12:00:00)
22177747	0.163987	Thursday, May 25th 2023 (12:00:00)
22177748	0.909091	Thursday, May 25th 2023 (12:00:00)
22177749	0.215278	Thursday, May 25th 2023 (12:00:00)
22177750	1.07124	Thursday, May 25th 2023 (12:00:00)
22177751	0.91198	Thursday, May 25th 2023 (12:00:00)
22193988	0.1875	Thursday, May 25th 2023 (12:00:00)
22193989	0.018182	Thursday, May 25th 2023 (12:00:00)
22193990	0.05618	Thursday, May 25th 2023 (12:00:00)
22193991	0.152174	Thursday, May 25th 2023 (12:00:00)
22193992	0.380952	Thursday, May 25th 2023 (12:00:00)
22193993	0.323529	Thursday, May 25th 2023 (12:00:00)
22193994	0.0625	Thursday, May 25th 2023 (12:00:00)
22193995	0.128302	Thursday, May 25th 2023 (12:00:00)
22204066	0.00035	Thursday, May 25th 2023 (12:00:00)
22205211	0	Thursday, May 25th 2023 (12:00:00)
22205215	0	Thursday, May 25th 2023 (12:00:00)
22205219	0.007494	Thursday, May 25th 2023 (12:00:00)
22205227	0.272106	Thursday, May 25th 2023 (12:00:00)

Figure 27 – Result on Excel Sheet

3.1.2.1.4. Grasshopper Script

There are three main parts in this script. Import model, Populate Points, and Analysis.

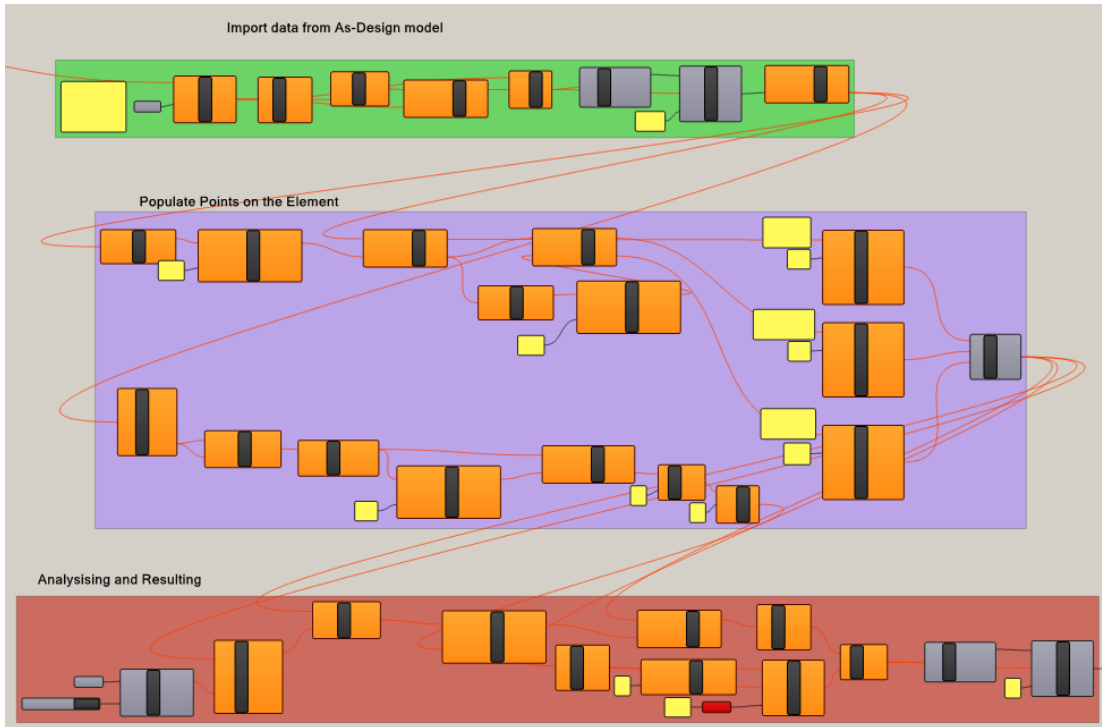


Figure 28 – Grasshopper Script, Method 2

3.1.2.2.4.1 Data Import

The data can be designated when imported from the model by defining a filter from the input. For example, here I input “Column” “floor” “Beam”, and “Structure wall”, so the script will select those families and import them from the BIM model to the script.

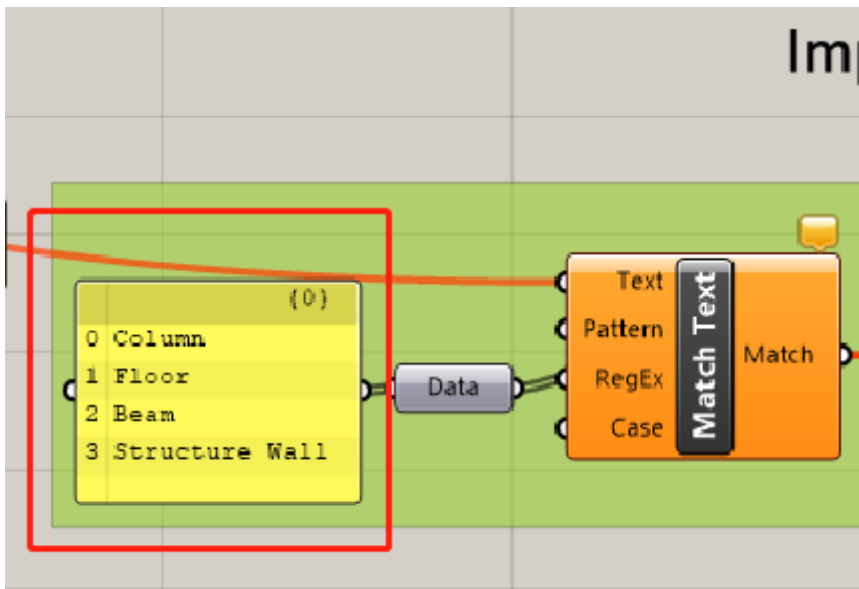


Figure 29 – Data Filter

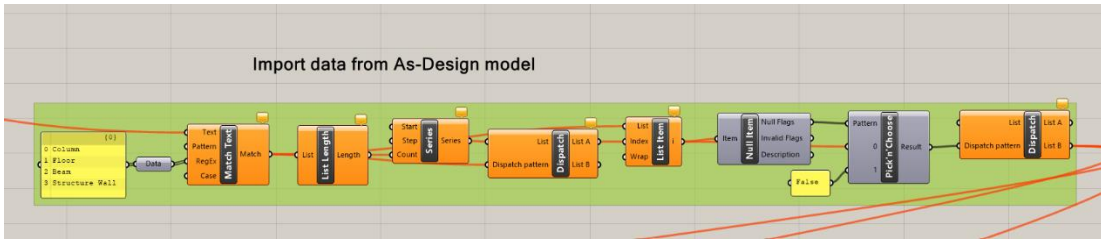


Figure 30 - Import Data

3.1.2.2.4.2 Populate Points on the Elements

The elements are filtered by their volume, I divided them into three groups, volume less than 0.1CBM, between 0.1CBM and 1CBM, and bigger than 1CBM. And to populate different number of points based on their volume to ensure the accuracy of analysis.

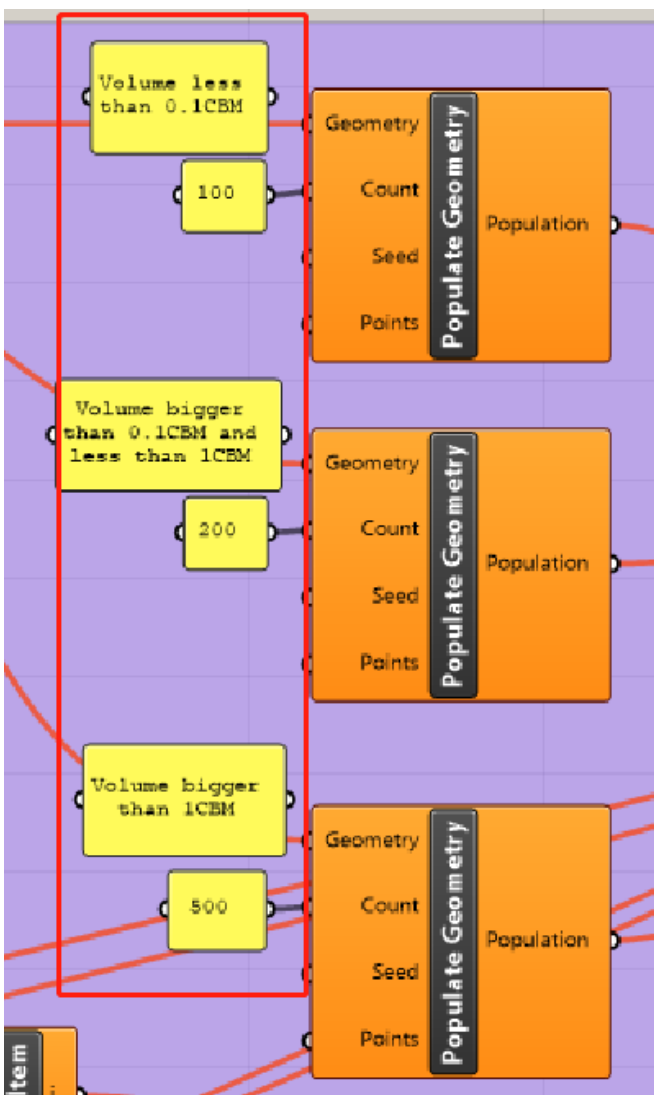


Figure 31 – Define Number of Points on the Elements

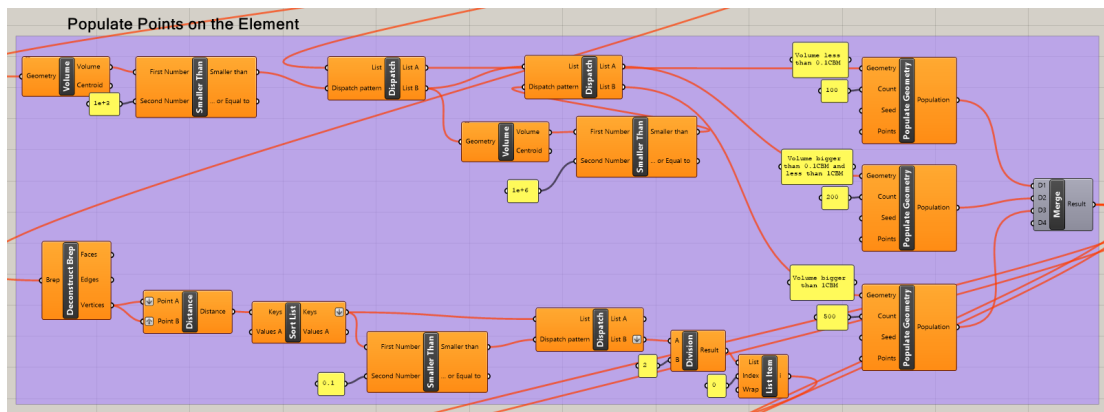


Figure 32 – Populate Points on the Elements, Grasshopper Script

3.1.2.2.4.3 Resulting

The script's ability to calculate the distance between the As-Built mesh and the points on the As-Design model and subsequently provide data indicating the percentage of points on the element within the tolerance range is a valuable feature. This data represents the finished percentage of each element, offering a precise and objective measure of how closely the constructed elements adhere to the design specifications. This metric is instrumental in progress tracking and quality control, allowing users to assess the completeness and accuracy of construction work in real time.

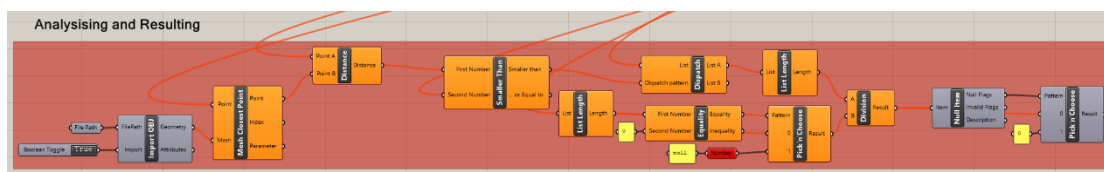


Figure 33 - Resulting

3.1.3. Information Management

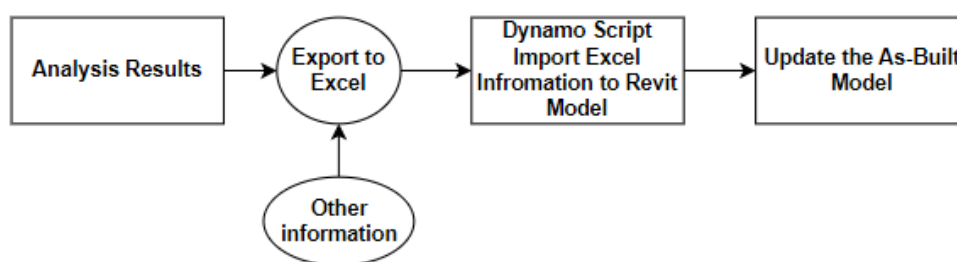


Figure 34 – Pipeline of Informing Management

Integrating data from various disciplines and project phases is a fundamental strategy that not only promotes streamlined workflows but also catalyzes improved coordination and elevated project outcomes. This holistic approach empowers users to deftly manage changes, meticulously track revisions, and derive invaluable insights, thereby culminating in the optimization of project efficiency, precision, and overall success. The significance of this step cannot be overstated, primarily due to the inherent complexity of the information being sourced from diverse platforms. Managing this eclectic

amalgamation of data in a coherent and cohesive manner is pivotal to realizing the full potential of integrated project management.

One notably effective method for updating the As-built model involves the direct importation of analysis results into the model, facilitated by utilizing dedicated nodes within the analysis script. This seamless integration not only expedites the incorporation of critical data but also ensures that the As-built model remains continuously aligned with the most up-to-date information, bolstering accuracy, and facilitating data-driven decision-making processes. This dynamic approach not only simplifies the workflow but also enhances the As-built model's comprehensiveness, offering a comprehensive view of the project's evolving landscape and aiding in the proactive resolution of potential discrepancies or challenges.



Figure 35 – Update Model using Grasshopper

However, real-world scenarios often entail the incorporation of a myriad of additional information that necessitates seamless integration with the analysis results. In such cases, a pragmatic approach involves exporting the analysis outcomes to a versatile platform like Excel, where they can be harmoniously combined with other pertinent data sources, such as engineering monthly reports, in a structured format. This amalgamation of data can then be efficiently processed through tools like Grasshopper or Dynamo Scripts to facilitate their smooth assimilation into the overarching model. Furthermore, opting for Dynamo over Grasshopper in this phase offers certain advantages, particularly in terms of accessibility. Dynamo's compatibility with a Revit license grants accessibility to a broader user base, making it more convenient for individuals who might not possess a Rhino license. This inclusivity ensures that a wider spectrum of project stakeholders can actively participate in the data integration and modeling process, fostering collaboration and knowledge sharing across the project team. Consequently, Dynamo serves as an invaluable tool for democratizing the integration of diverse data sources into the model, thereby promoting an inclusive and efficient project management ecosystem.

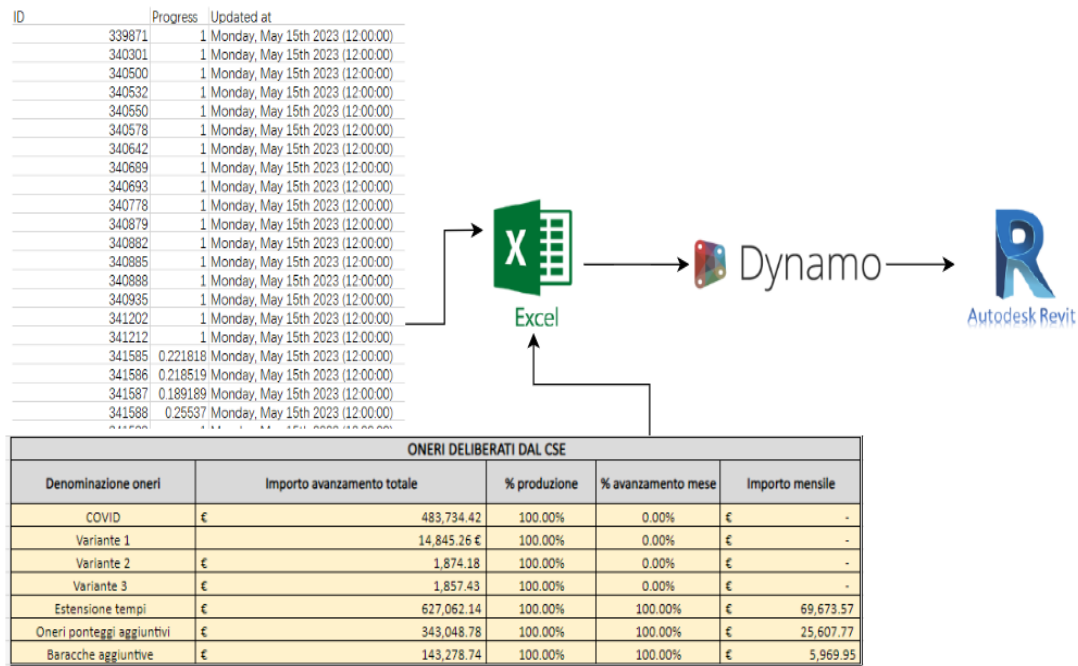


Figure 36 - Integration of Data

3.1.3.1. Dynamo Script

The fundamental concept of the script is to facilitate the systematic updating of information within the model, orchestrating a seamless synchronization between the data stored in Excel and the model itself. This synchronization relies on the establishment of a common identifier shared between these two data sources, which can encompass a variety of attributes such as Element ID, GUID, WBS code, or even user-defined parameters. This identifier acts as the linchpin that binds the information from Excel to the corresponding elements within the model.

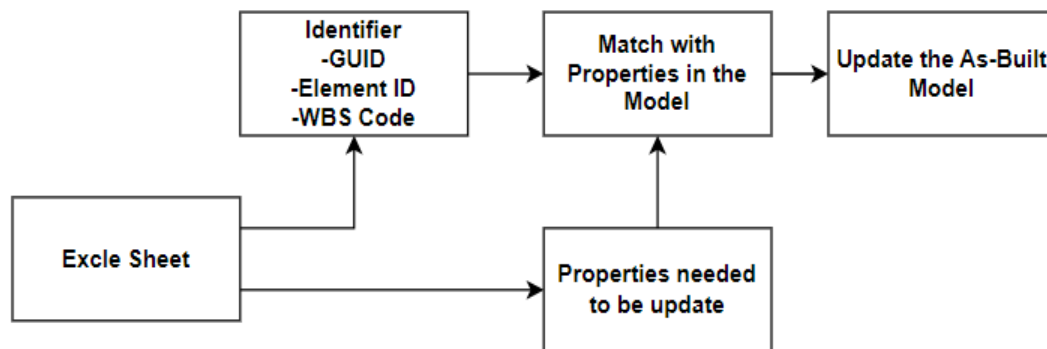


Figure 37 – Pipeline of Dynamo Script

The workflow can be summarized as follows:

- Identification and Matching: The script begins by extracting data from both Excel and the model. It relies on the common identifier to match entries from Excel with their respective counterparts in the model. This could entail comparing Element IDs, GUIDs, WBS codes, or custom parameters, ensuring a robust alignment between the two datasets.

- Index Sequence Matching: Once the data entries are matched based on the common identifier, the script utilizes index sequences or positional information to ensure precise alignment. This step helps guarantee that the updates are applied to the correct elements within the model.
- Data Update: With a secure match established, the script proceeds to update the information model, incorporating the changes and revisions sourced from Excel. This update process ensures that the model accurately reflects the most current data, thus enhancing its accuracy and relevance. By following this systematic approach, the script effectively bridges the gap between external data sources and the model, enabling dynamic data synchronization and ensuring that the model remains a reliable and up-to-date representation of the project's evolving state. This methodology promotes efficient data management and contributes to the overall success of the project.

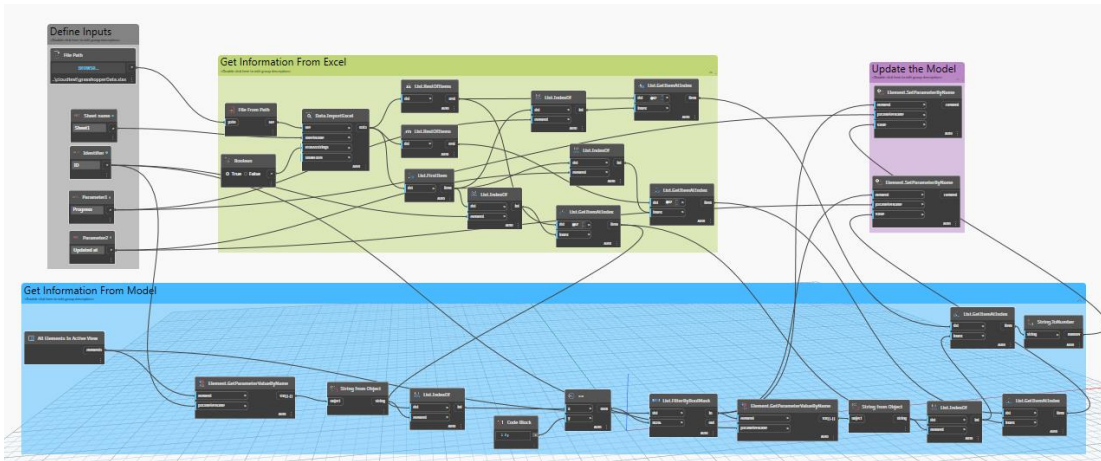
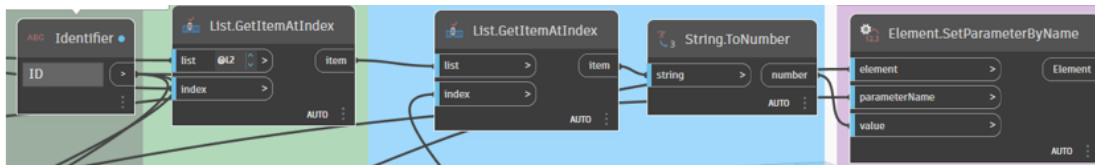


Figure 38 – Dynamo Script



Match information using the identifier

Figure 39 – Matching Dat

3.2. Case Study

3.2.1. Introduction of Case Study

In the scope of this thesis work, our primary focus is directed toward an architectural structure ensconced within the CityLife complex, a multifaceted urban development that holds substantial prominence in the Milan, Italy urban landscape. The Hadid Residences, a noteworthy subset within this complex, comprise a constellation of seven distinct edifices. Each of these architectural possesses its unique design language. In proximity to the Hadid Residences, the Libeskind Residences form another integral facet of the urban tableau.

A specific architecture located in the center of the Hadid Residence with 9 floors is of particular interest in this thesis endeavor. This case study will focus on the progress track of the construction of the architectural model of this building.



Figure 40 - Residence Building, Citylife

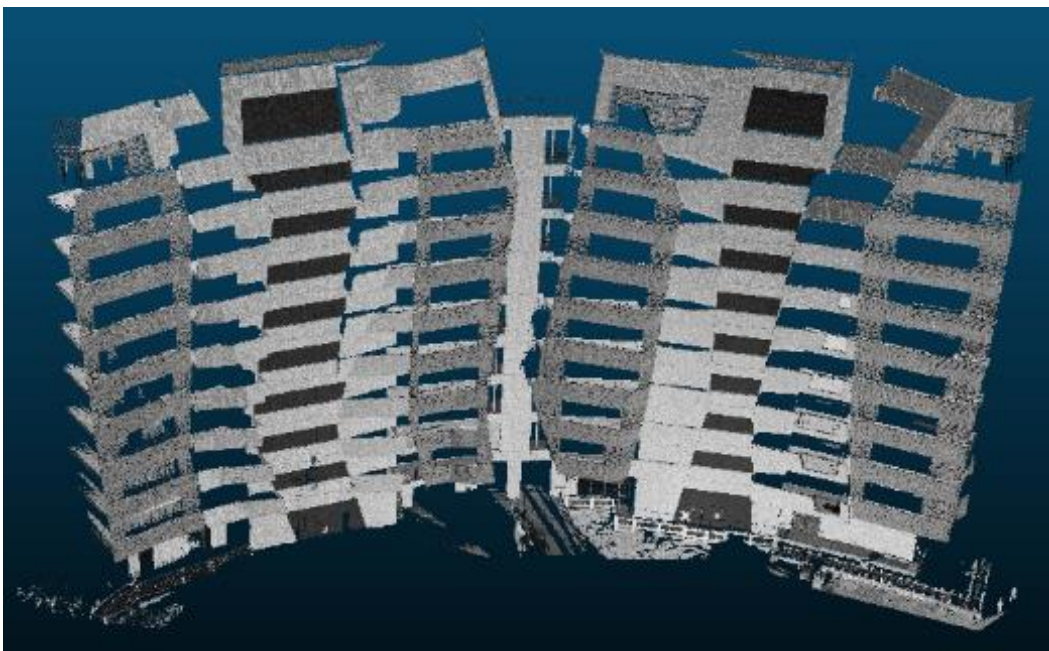


Figure 41 - Point Cloud, Citylife

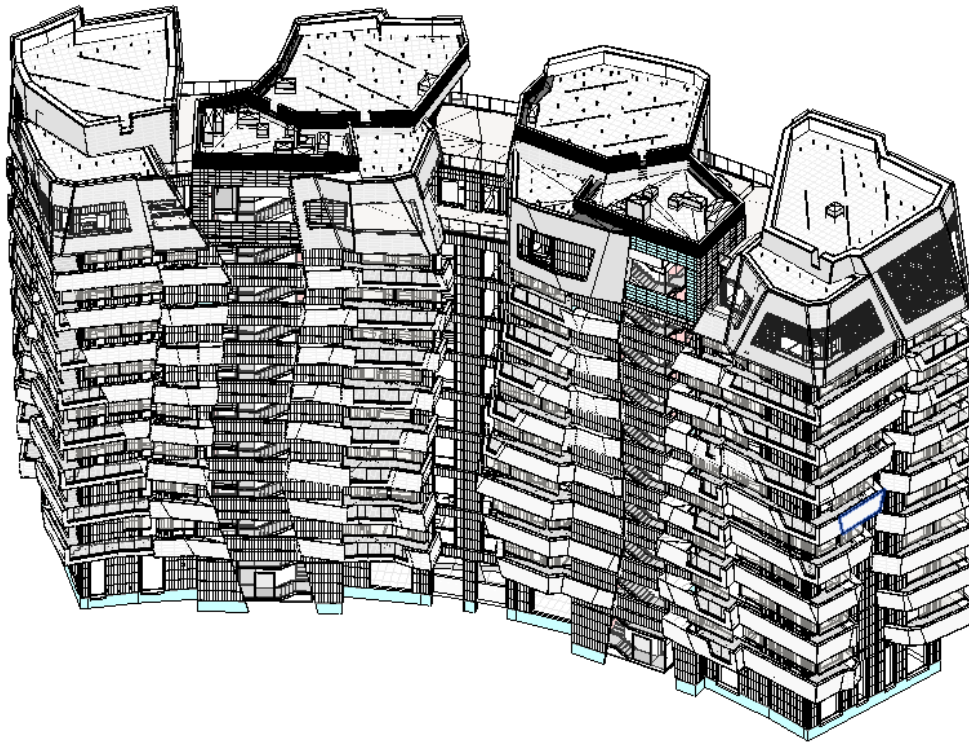


Figure 42 – Revit Model, Citylife

The Point Cloud of this building generates Laser scan data from the Total Station and is processed and managed in Autodesk Recap and CloudCompare. The As-design model of the building is from Autodesk Revit.

The point cloud data for this building is derived from laser scanning, facilitated by a Total Station. This data is then processed and managed through the utilization of Autodesk Recap and CloudCompare, two software platforms tailored for these purposes. On the other hand, the As-designed model of the building is crafted within Autodesk Revit. This dynamic interplay between laser scan data and Revit modeling forms the cornerstone of this architectural project's data management and integration.

3.2.2. Case Study Resulting

Within the scope of laser scan data, it's noticeable that certain points don't correspond to the building structure; instead, they represent extraneous data points inadvertently captured during scanning. To maintain data precision in architectural modeling, it is necessary to conduct a curation process, removing these non-building-related points. This process enhances dataset clarity and reduces distractions for more efficient analyses. Then integrating the mesh derived from the As-design model into the point cloud environment, using software like CloudCompare. This integration aligns the digital model with the cleaned point cloud data, establishing a relationship between As-built and As-design data for architectural analyses.

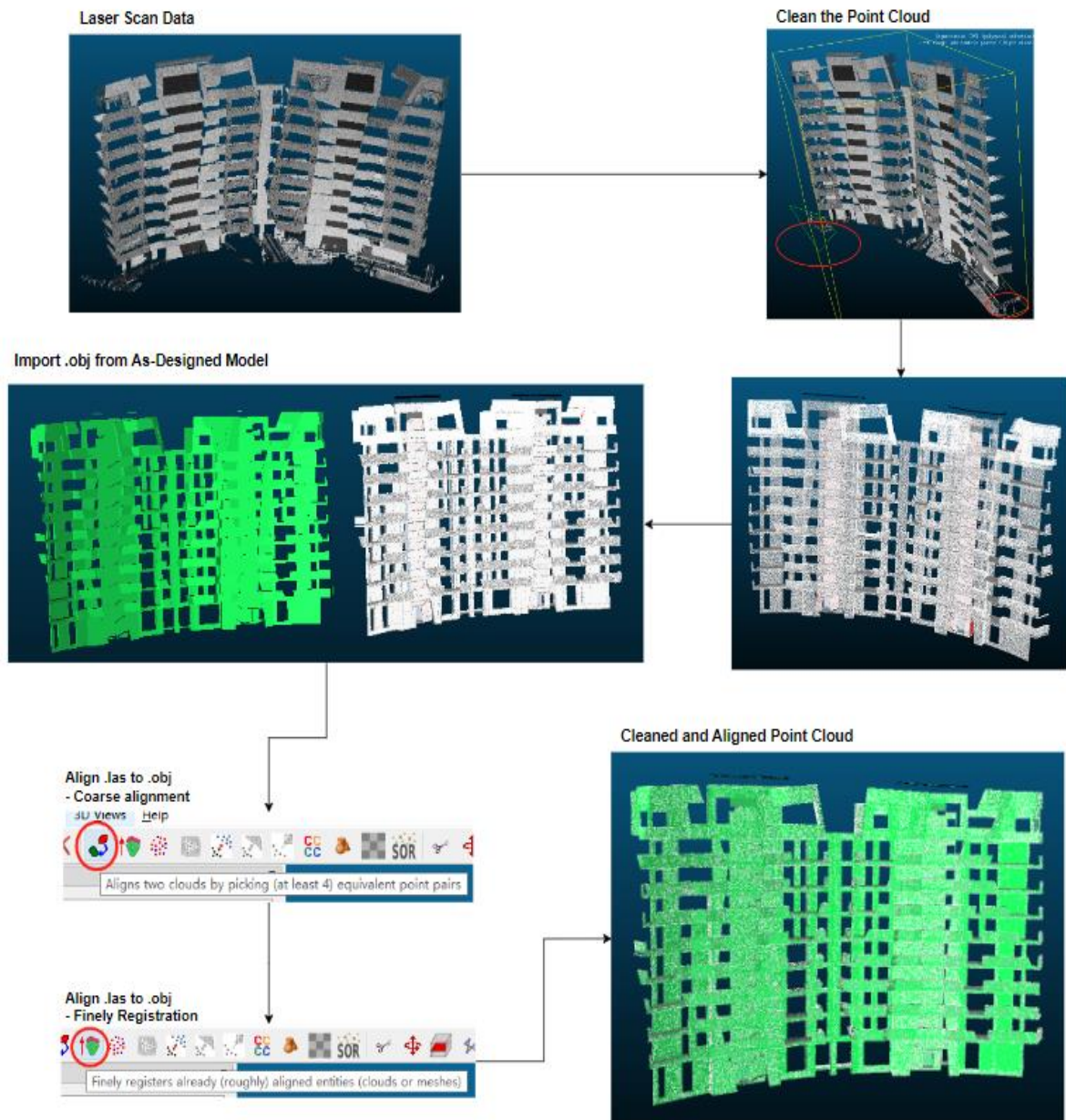


Figure 43 - Clean and alignment of the Model and Point Cloud

Data transfer from the point cloud to the model involved the meticulous incorporation of values into specific attributes within Autodesk Revit, namely, the "ID," "Progress," and "Updated at" properties, guided by the data provided in the corresponding Excel sheet. This integration of data serves as a critical step in the alignment of the digital architectural model with real-world spatial information. Notably, the visual representation of elements within the Revit model was augmented to provide at-a-glance insights into the construction status of individual components. This was achieved by assigning distinct colors to Revit elements, each color serving as a visual indicator of the element's construction status. Specifically, the color scheme implemented consists of Green - "Finished," Yellow - "Under Construction," and Red - "Not Constructed." This color-coded approach offers a swift and intuitive means of assessing the progress and status of architectural elements within the digital model, thereby facilitating efficient decision-making and project management.

3.2.2.1. Result from Method 1

The result was consistent with the data from the point cloud. Generating the progress of elements for a portion of the building, consisting of 40 to 50 elements, in approximately 15 minutes. This processing result indicates that the script is capable of handling substantial data loads while providing valuable insights into the progress of individual elements as a percentage.

Inputs: Revit Model, As-Design Point Cloud, As-Built Point Cloud

Excel Output:

	Progress	Updated at
339871	1	Monday, May 15th 2023 (12:00:00)
340301	1	Monday, May 15th 2023 (12:00:00)
340500	1	Monday, May 15th 2023 (12:00:00)
340532	1	Monday, May 15th 2023 (12:00:00)
340550	1	Monday, May 15th 2023 (12:00:00)
340578	1	Monday, May 15th 2023 (12:00:00)
340642	1	Monday, May 15th 2023 (12:00:00)
340689	1	Monday, May 15th 2023 (12:00:00)
340693	1	Monday, May 15th 2023 (12:00:00)
340778	1	Monday, May 15th 2023 (12:00:00)
340879	1	Monday, May 15th 2023 (12:00:00)
340882	1	Monday, May 15th 2023 (12:00:00)
340885	1	Monday, May 15th 2023 (12:00:00)
340888	1	Monday, May 15th 2023 (12:00:00)
340935	1	Monday, May 15th 2023 (12:00:00)
341202	1	Monday, May 15th 2023 (12:00:00)
341212	1	Monday, May 15th 2023 (12:00:00)
341585	0.221818	Monday, May 15th 2023 (12:00:00)
341586	0.218519	Monday, May 15th 2023 (12:00:00)
341587	0.189189	Monday, May 15th 2023 (12:00:00)
341588	0.25527	Monday, May 15th 2023 (12:00:00)

Figure 44 – Excel Output

Updated Model:

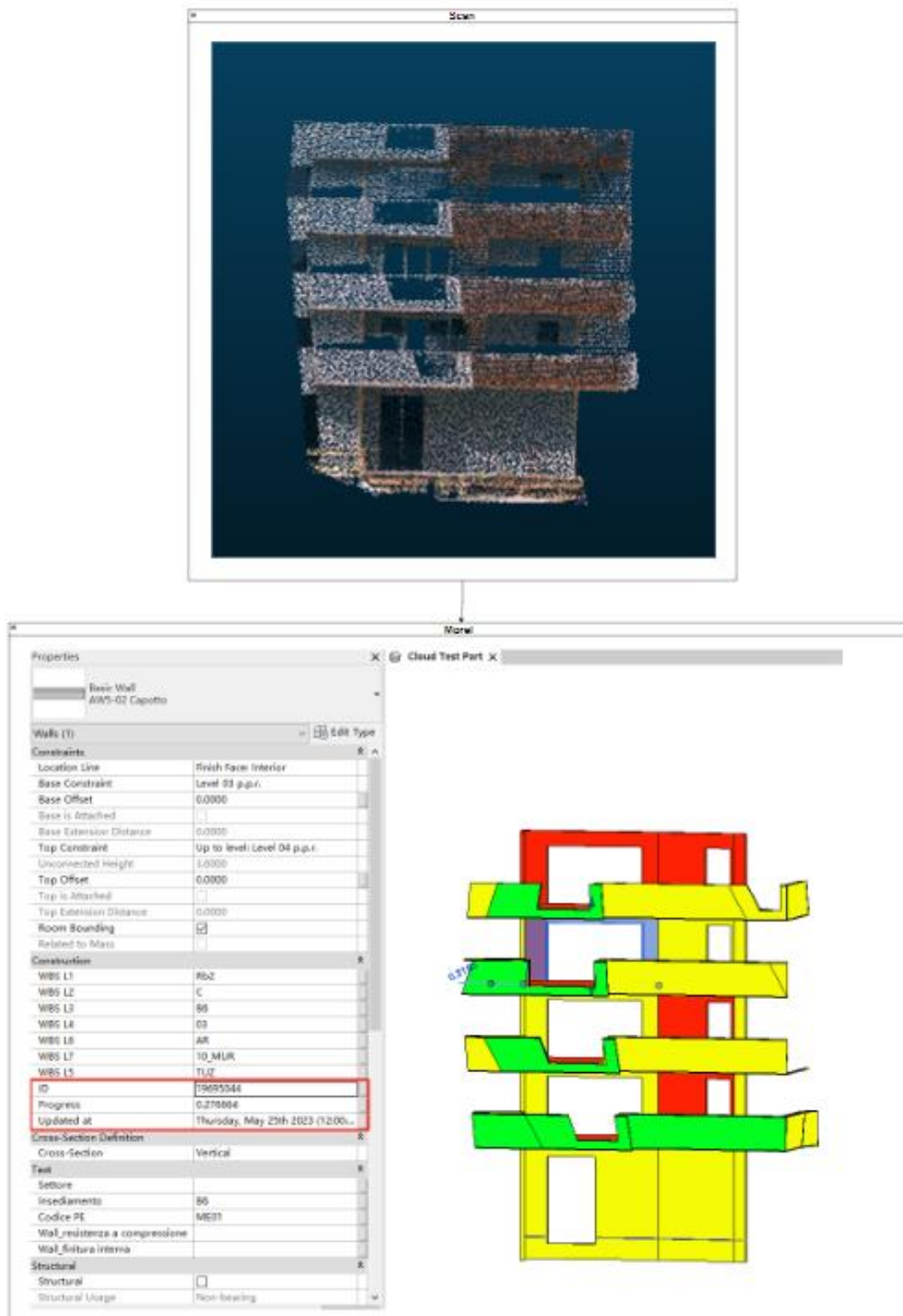


Figure 45 – Updated Model

Time consumed from inputs to updated model: 10-15 minutes.

Intel(R) Core(TM) i7-4810MQ CPU @ 2.80GHz 2.80 GHz

3.2.2.2. Result from Method 2

Method 2 able to compute progress results for more than 1000 elements in approximately 30 seconds demonstrates the efficiency of the solution. This rapid processing time allows users to analyze and monitor a large number of elements efficiently, which is particularly valuable for complex projects with extensive datasets. The ability to provide accurate progress tracking across a wide range of elements contributes significantly to project management.

Inputs: Revit Model, As-Built Mesh

Excel output:

19482081	0.140374	Thursday, May 25th 2023 (12:00:00)
19482143	0.123159	Thursday, May 25th 2023 (12:00:00)
19482177	0	Thursday, May 25th 2023 (12:00:00)
19482182	0.14248	Thursday, May 25th 2023 (12:00:00)
21345252	0.184211	Thursday, May 25th 2023 (12:00:00)
21347978	0	Thursday, May 25th 2023 (12:00:00)
22177746	0.741007	Thursday, May 25th 2023 (12:00:00)
22177747	0.163987	Thursday, May 25th 2023 (12:00:00)
22177748	0.909091	Thursday, May 25th 2023 (12:00:00)
22177749	0.215278	Thursday, May 25th 2023 (12:00:00)
22177750	1.07124	Thursday, May 25th 2023 (12:00:00)
22177751	0.91198	Thursday, May 25th 2023 (12:00:00)
22193988	0.1875	Thursday, May 25th 2023 (12:00:00)
22193989	0.018182	Thursday, May 25th 2023 (12:00:00)
22193990	0.05618	Thursday, May 25th 2023 (12:00:00)
22193991	0.152174	Thursday, May 25th 2023 (12:00:00)
22193992	0.380952	Thursday, May 25th 2023 (12:00:00)
22193993	0.323529	Thursday, May 25th 2023 (12:00:00)
22193994	0.0625	Thursday, May 25th 2023 (12:00:00)
22193995	0.128302	Thursday, May 25th 2023 (12:00:00)
22204066	0.00035	Thursday, May 25th 2023 (12:00:00)
22205211	0	Thursday, May 25th 2023 (12:00:00)
22205215	0	Thursday, May 25th 2023 (12:00:00)
22205219	0.007494	Thursday, May 25th 2023 (12:00:00)
22205237	0.273196	Thursday, May 25th 2023 (12:00:00)
22205241	0.1875	Thursday, May 25th 2023 (12:00:00)
22205309	0.003831	Thursday, May 25th 2023 (12:00:00)

Figure 46 – Excel Output

Updated Model:

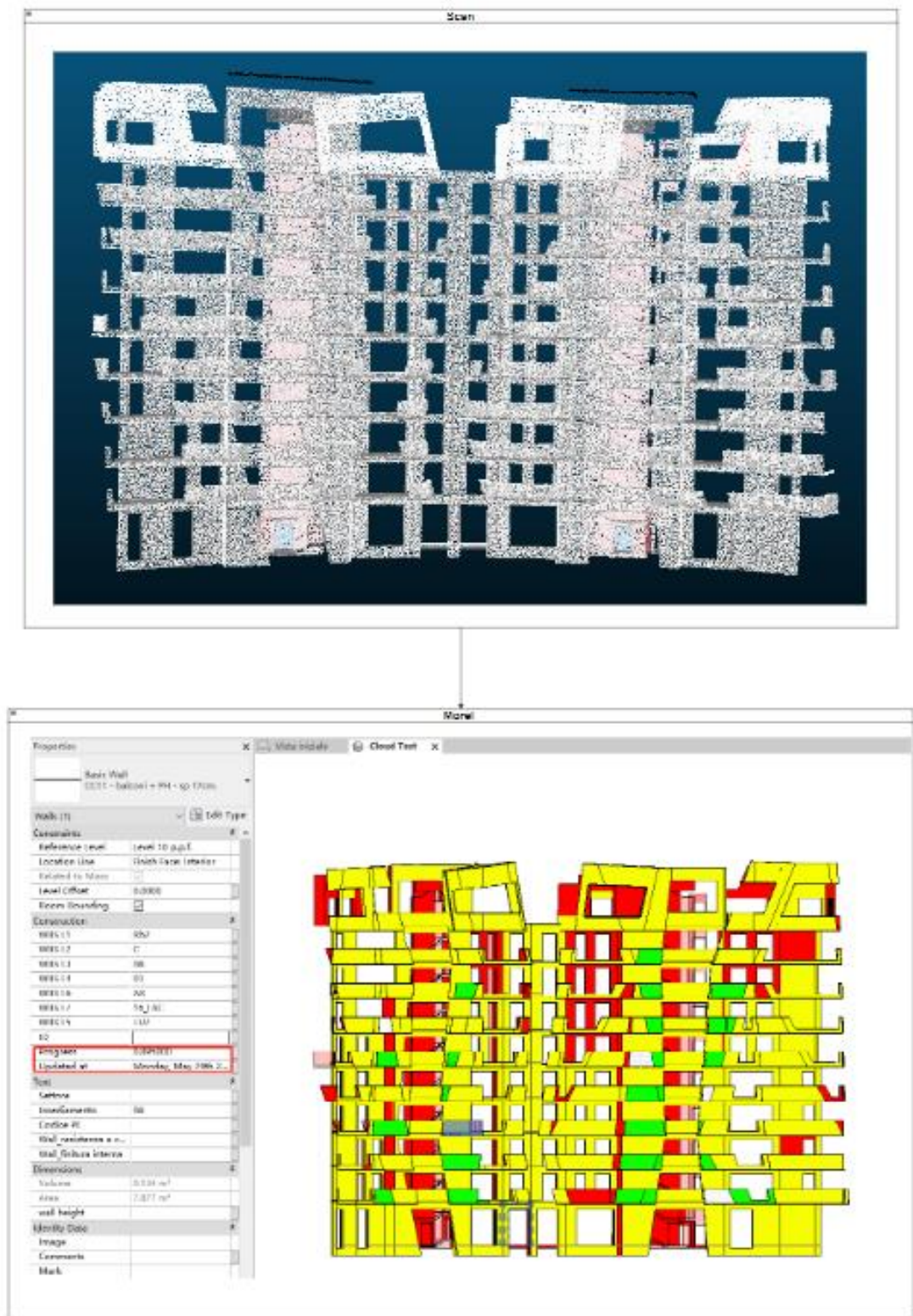


Figure 47 - -Updated Model

Time consumed from inputs to updated model: 20-30 seconds.

Intel(R) Core(TM) i7-4810MQ CPU @ 2.80GHz 2.80 GHz

3.3. Result and Discussion-method 1 vs. Method 2

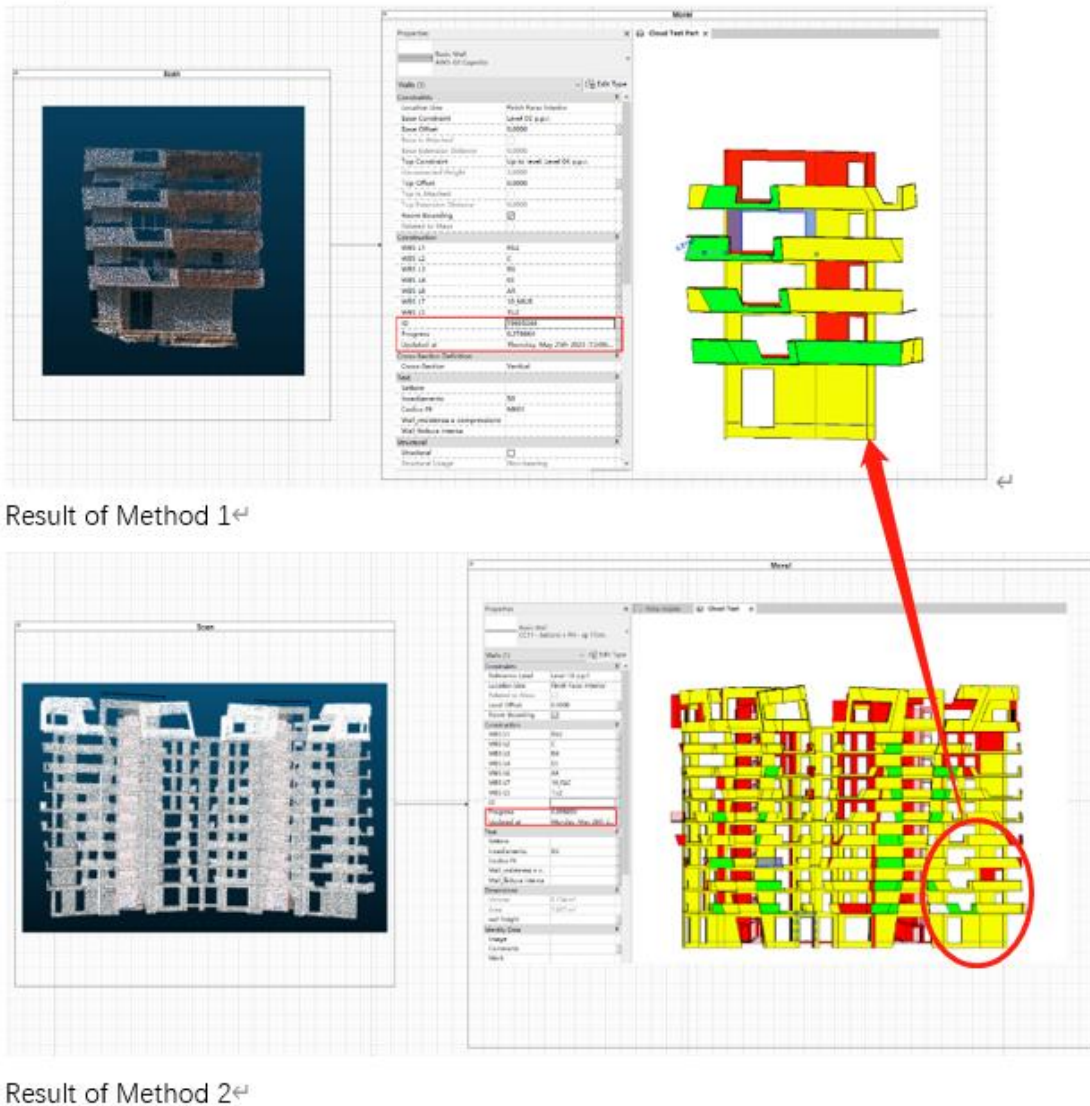


Figure 48 - Comparison of Results

	Model Size	Resulting Time	Small Elements detection
Method 1	A	10 to 15 mins	Inaccurate on the small elements
Method 2	More than 6 times A	20 to 30 seconds	Accurate on the small elements

Table 1 - Table of Comparison Result

by Intel(R) Core (TM) i7-4810MQ CPU @ 2.80GHz 2.80 GHz

Advantages and disadvantages of method 1 and method 2

From the graph and table above, we can see that the Advantages of Method 2 are:

- i. **Speedier:** The pipeline significantly enhances processing speed by reducing the number of calculations, resulting in shorter analysis times.
- ii. **Enhanced Accuracy:** With a greater number of points allocated to smaller elements, the pipeline ensures a higher level of accuracy in progress monitoring.
- iii. **Increased Capability:** The pipeline empowers users to conduct analyses on a larger and more comprehensive scale, facilitating broader insights and more effective decision-making in construction monitoring.

But, there are disadvantages to Method 2 as well:

- i. **Mesh Complexity:** The conversion of point clouds to meshes, while powerful, can lead to increased complexity in handling the data. Managing and analyzing mesh data may require more computational resources and software capabilities.
- ii. **Potential Data Loss:** The process of mesh generation may lead to some loss of fine details or precision compared to the original point cloud data. This can affect the accuracy of certain analyses, especially in situations where fine-grained data is crucial.
- iii. **Limited Applicability:** Method 2, which relies on the as-built mesh, may not be suitable for all types of construction projects or elements. Its effectiveness can vary depending on the specific project and the quality of the mesh generated.
- iv. **Skill and Software Dependency:** Like Method 1, Method 2 also requires expertise in working with mesh data and specialized software tools, which can be a limitation for some users or projects.

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4. CHAPTER 2 – ELEMENTS ANALYSIS

4.1. Introduction

The point cloud is very useful for construction analysis, with applications spanning various domains. Point clouds, characterized by their unique feature of encapsulating information through numerous individual points, present distinct advantages, and differences in comparison to conventional model-based analytics. Point cloud-based analysis offers a multifaceted approach to addressing construction challenges:

- i. **Deformation Analysis:** Point clouds are exceptionally well-suited for monitoring and analyzing deformations in engineering elements. By tracking the positions of individual points over time, deviations and structural shifts can be detected with precision, enabling timely interventions, and ensuring structural integrity.
- ii. **Engineering Nodes:** Point clouds provide a resource for the evaluation and optimization of engineering nodes within a construction project. The dense data capture allows for detailed assessments of node connections, stress points, and load distribution, contributing to robust structural design.
- iii. **Geological Information Analysis:** In geological and geotechnical studies related to construction, point clouds are instrumental in capturing intricate surface details, subsurface structures, and topographic variations. This data aids in geological mapping, site characterization, and risk assessment.
- iv. **As-Built Verification:** Point clouds are invaluable for as-built verification, where the actual construction is compared to the design plans. This ensures that the constructed elements align with the intended specifications, enhancing quality control.
- v. **Environmental Impact Assessment:** Point cloud data is leveraged for assessing environmental impacts, such as terrain changes, vegetation analysis, and hydrological modeling. In conclusion, the use of point cloud-based analysis in construction offers a rich array of applications, allowing for a thorough understanding of complex projects and facilitating data-driven decision-making. The choice between point cloud-based and model-based analytics depends on the specific requirements and objectives of the analysis, with each approach offering unique advantages in the construction industry.

4.2. Methodology

4.2.1. Section

In the context of working with point cloud data in construction analysis, there's a significant consideration when it comes to obtaining valuable information from the cloud. Cutting through the middle of a construction element, for instance, may not yield useful insights since points won't naturally

align with an infinitely thin plane. Therefore, a method is necessary to define node planes to extract node information from the point cloud.

The approach described in this article involves the extension of node planes by projecting them outward from a specific construction element. The scale of this extension is adjusted based on the density of the point cloud. Subsequently, all the points falling within this extended area are associated with the respective node plane. This method allows for the extraction of node information from the point cloud, contributing to a more comprehensive understanding of the spatial layout and structural elements.

Moreover, this technique facilitates the connection of boundary points within the point cloud by creating line segments, ultimately resulting in the generation of closed line segment nodes. This step is crucial for constructing a coherent representation of the spatial features and boundaries within the point cloud data, which can be useful for various construction analyses and assessments.

4.2.2. Volume

The calculation of volume for three-dimensional objects hinges on integral calculus principles, wherein the cross-sectional area across the entire object is integrated. Each line segment node, strategically positioned along the object, provides area information relevant to specific points. The cumulative volume of the object is then determined by integrating the areas associated with all line segment nodes. This method, rooted in mathematical rigor, is a fundamental tool across various disciplines, enabling precise volumetric analysis and design refinement.

4.2.3. Information Integration

In the realm of engineering projects, many information sources often converge to analysis. In this landscape, it is necessary to unify an identifier—an element that can connect and correlate data from various sources with the point cloud. Among the most practical and convenient identifiers available within the point cloud system, the location information takes center stage.

Location information, inherently embedded within the point cloud data, serves as an intuitive identifier. It provides a spatial reference that ties together datasets and allows for precise geospatial alignment. This alignment facilitates the integration of information originating from different sources, whether it be architectural plans, engineering schematics, or geospatial surveys.

The utilization of location information as an identifier within the point cloud system represents a pivotal step in the effective amalgamation of diverse data sources, fostering a holistic and informed approach to engineering projects. It underscores the importance of spatial accuracy and precision in achieving project objectives and ensuring the seamless interaction of digital and physical domains.

4.2.4. Grasshopper Script

The purpose of the Script is to 1. Find the Abnormal part of the elements 2. Connect point cloud information with other sources of information 3. Generate point cloud sections 4. Integrate other sources of information and point cloud together in a unified format.

4.2.4.1. Identify Anomalous Segments within the Elements

The first part of the script is to find the abnormal part of the element and to provide a clear view to the users, color all the points that go beyond the tolerance.

In the first part of the script, the objective is to identify and visually highlight abnormal or out-of-tolerance elements within the point cloud data. This serves as a valuable quality control and visualization step for users. Here's a breakdown of this process:

- i. **Abnormality Detection:** Utilize Grasshopper components or custom scripts to analyze the point cloud data and determine which points or elements fall outside the specified tolerance limits. The criteria for abnormality could relate to factors such as distance, and deviation from a reference.
- ii. **Color Coding:** Assign distinct colors to the points or elements that are identified as abnormal. This color coding helps users quickly identify and differentiate elements that require attention due to their deviation from expected parameters.
- iii. **Tolerance Adjustment:** Consider providing users with the ability to adjust the tolerance limits interactively within the Grasshopper definition. This allows for real-time exploration of different tolerance settings and their impact on the color-coded visualization.

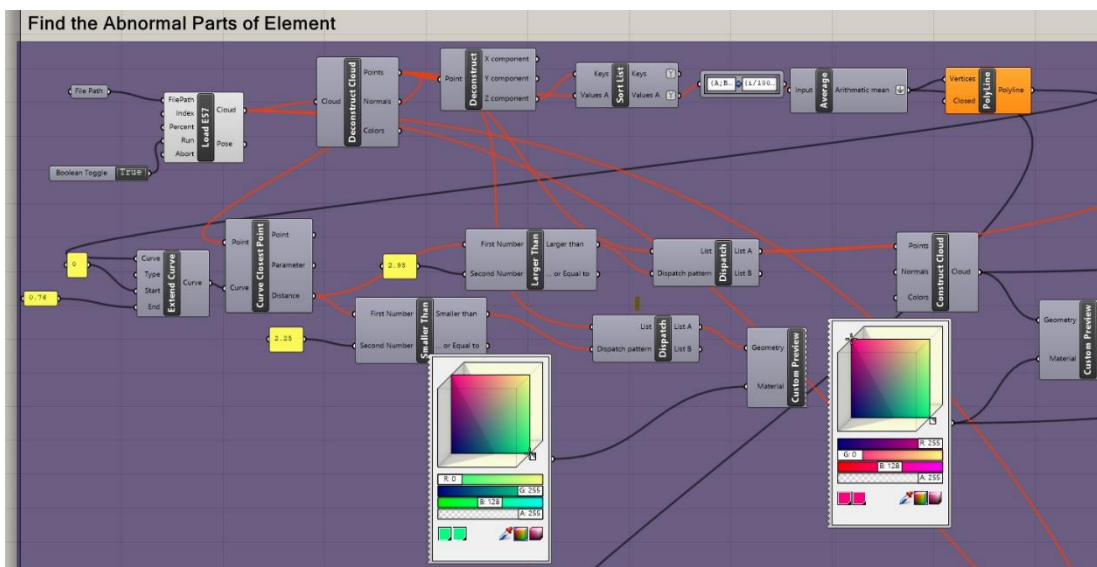


Figure 49 - Find the Abnormal Parts of the Elements

In Grasshopper, the "Dispatch" component is a tool used for filtering and sorting data based on specified conditions. It enables the script to separate or dispatch data into different branches depending on whether certain criteria are met. For example, in the script, the normal distance between points and the middle of the element is 2.25cm, with a tolerance of 0.7cm, all the points over 2.95cm are dispatched and colored.

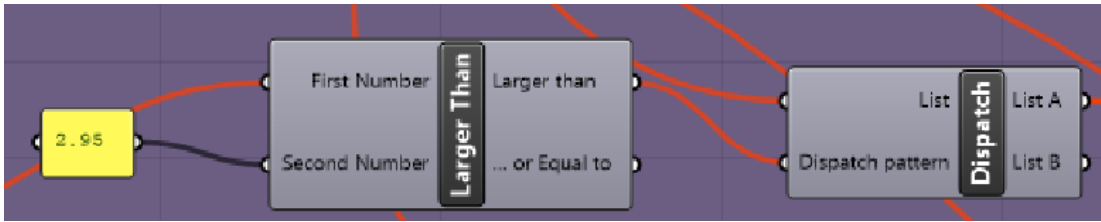


Figure 50 - Define the Tolerance

4.2.4.2. Import information from Excel

To import Excel to Grasshopper, a plugin is used in the script called TT Toolbox.

It simplifies the process of importing Excel data into Grasshopper. This plugin enables users to effortlessly locate Excel files, define specific sheet names and data locations, and seamlessly transfer essential information into their Grasshopper scripts. By bridging the gap between Excel and Grasshopper, TT Toolbox enhances the efficiency and accuracy of data integration. This dynamic link ensures that any changes in the Excel data are instantly reflected within Grasshopper, facilitating real-time design adjustments.

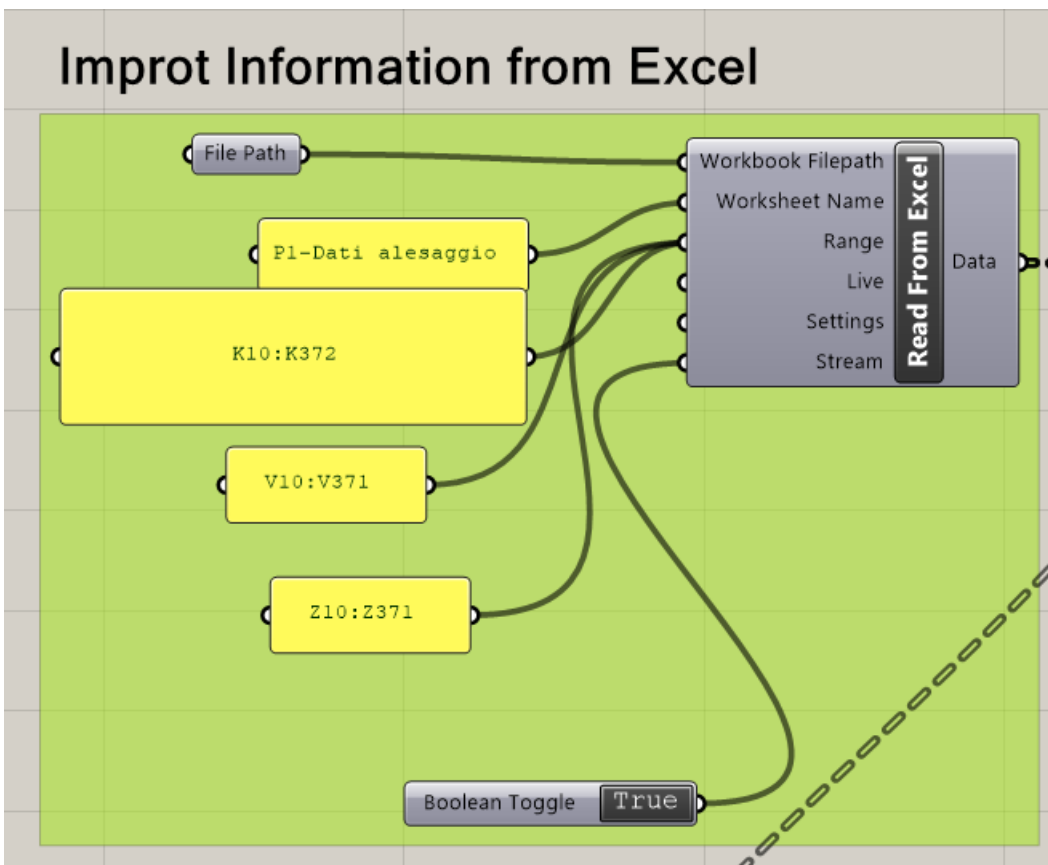


Figure 51 – Data Import

4.2.4.3. Set Plane for sections

The plane can be set according to the Excel information to have a better correction with other sources.

By using the Excel data to define the plane's orientation and position, the script can ensure that the analysis within Grasshopper is closely coordinated with external data. This alignment facilitates geometric adjustments, measurements, and interactions between different datasets, ultimately enhancing the overall integrity. Leveraging Excel information to set the plane helps establish a solid foundation for harmonizing diverse data sources.

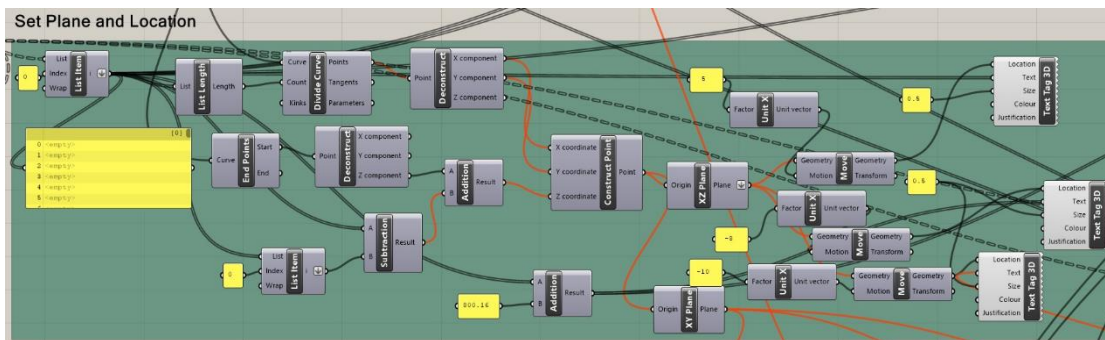


Figure 52 – Set the Plane and Define the Location

The "Plane" component is a fundamental tool used to create and define planes in three-dimensional space. Planes are essential for various operations in parametric and generative design, as they serve as reference surfaces for geometry and transformations. The plane can be in the XY, XZ, or YZ direction or follow the direction of a curve.

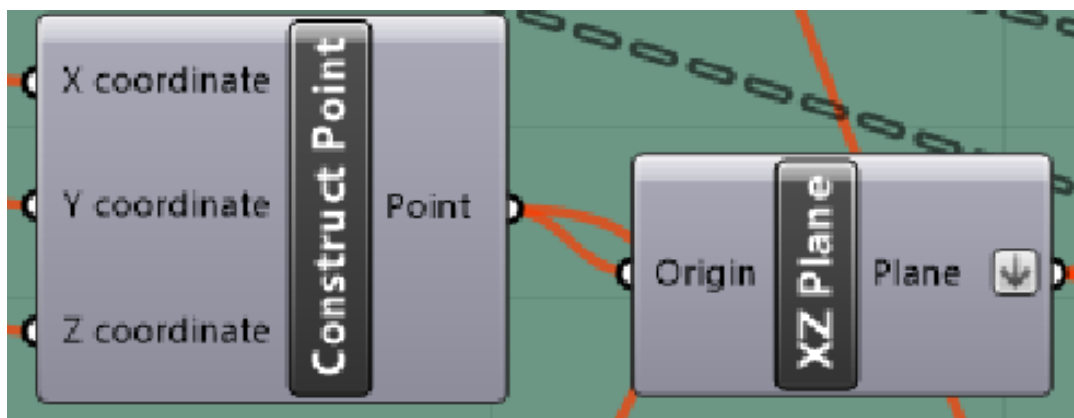


Figure 53 – Coordinate of Plane

Adding marks or identifiers to each plane within the Grasshopper model is very important, particularly when dealing with multiple planes that serve different purposes or contain specific information. These identifiers can take the form of location information, labels, or other contextual details that help users quickly identify and locate the relevant plane when needed. Such marks not only enhance the accessibility of plane-related data but also contribute to the organization and clarity of your design or analysis workflow.

4.2.4.4. Point Cloud Sections

Creating sections or slices from a point cloud in Grasshopper can be useful for various purposes, such as visualizing data, analyzing specific parts of the point cloud, or preparing it for further processing.

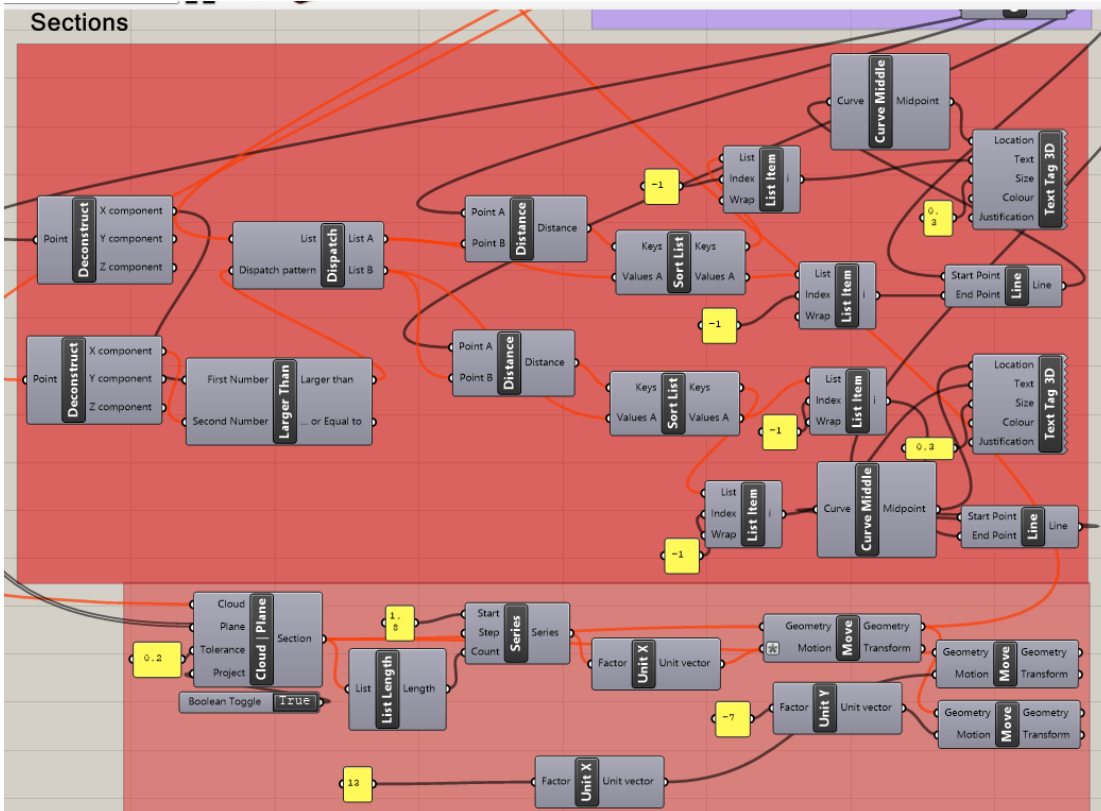


Figure 54 – Define the Sections

Utilizing the "Cloud Plane" node from the Volvox plugin is a solution to address the challenge of sectioning a point cloud by a plane in Grasshopper. This node allowing the script to extract and group points that fall within the specified tolerance range relative to the defined plane. By pulling together these points, you can create organized datasets that facilitate subsequent analysis, visualization, or manipulation within the Grasshopper script. This capability enhances the ability to work with point cloud data in a controlled and efficient manner.

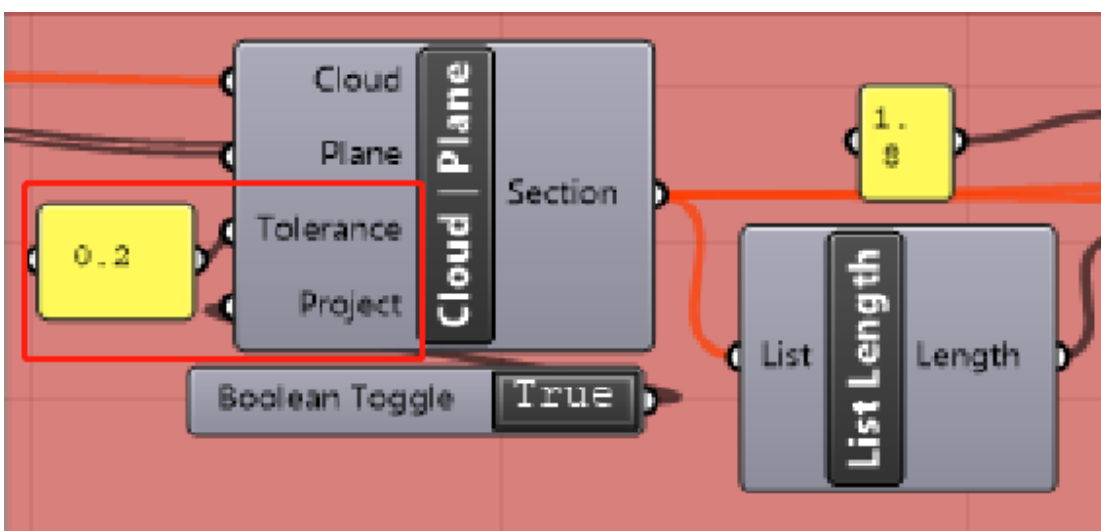


Figure 55 – Define the Tolerance Range

4.2.4.5. Volume of Elements

Calculating the volume of an element by averaging the area of its cross-sections and multiplying it by the height is a common method in geometry and calculus. This calculation can also be expressed as the integral of the area over the entire span or range of the element. In mathematical terms, it can be represented as follows:

$$\text{Volume} = \int_a^b A(x) dx$$

Where:

- Volume is the total volume of the element.
- A(x) represents the area of the cross-section at position x along the element's height.
- a and b are the limits of integration, defining the range of the element's height over which the integral is evaluated.

This mathematical approach allows you to compute the volume of complex shapes by breaking them down into smaller cross-sectional components and summing up their contributions over the entire height of the element.

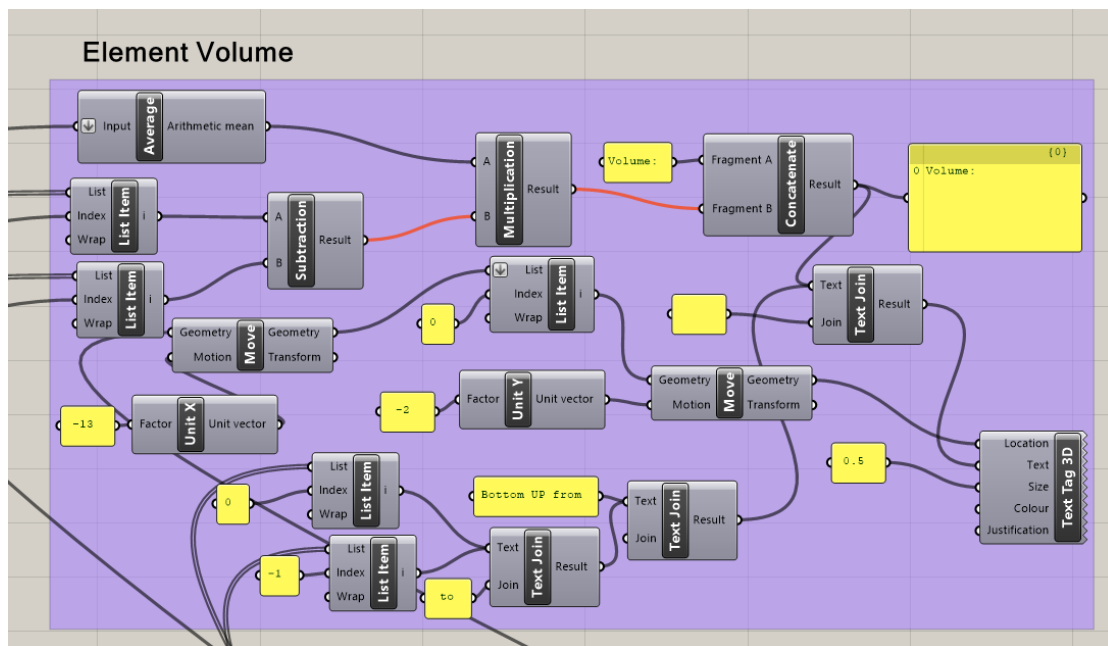


Figure 56 – Volume of Point Cloud

4.2.4.6. Information Integration

Integrating information from Excel into Grasshopper is valuable in the context of parametric design, generative design, and data-driven workflows. Some key benefits are as follows:

- i. Data-Driven Design: Excel often serves as a central repository for project data, including parameters, specifications, and design constraints. By importing this data into Grasshopper, you

can create design models that respond directly to changes in the Excel data, enabling data-driven design processes.

- ii. Parameterization: Excel can store a wide range of parameters, such as dimensions, material properties, or cost data. By bringing this information into Grasshopper, you can create parametric models that adapt to changes in these parameters, streamlining design optimization.
- iii. Custom Reporting: Grasshopper allows you to generate custom visual reports and diagrams based on Excel data. This can be particularly useful for creating client presentations or project documentation.
- iv. Data Validation: Grasshopper can be used to validate data from Excel against design constraints, ensuring that the design remains compliant with predefined criteria.

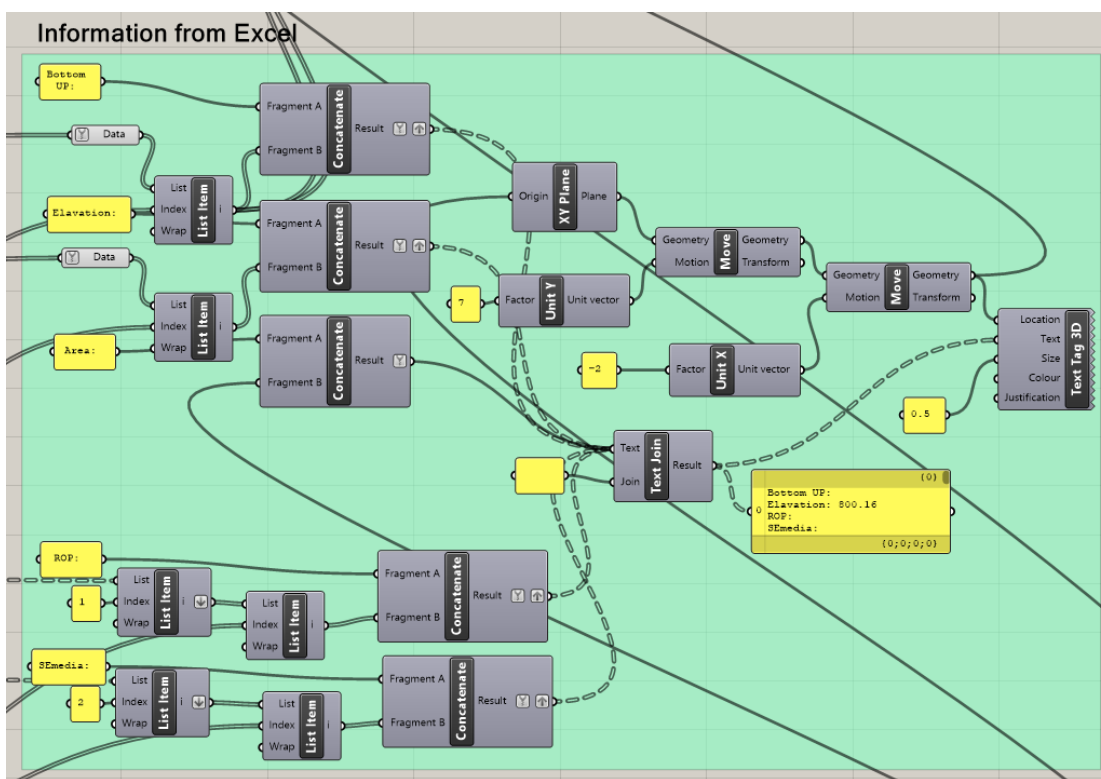


Figure 57 - - Manage Information from Excel

One of the key and foundational steps in the process of integrating data from an Excel sheet into Grasshopper script is to locate, organize, and name the data obtained from the Excel sheet. This preparatory phase sets the stage for effective data manipulation and analysis within Grasshopper. Including Data Identification and Selection, Data Structuring and Labeling, Data Extraction, Data Naming, Data Organization, Data Alignment, and Integration.

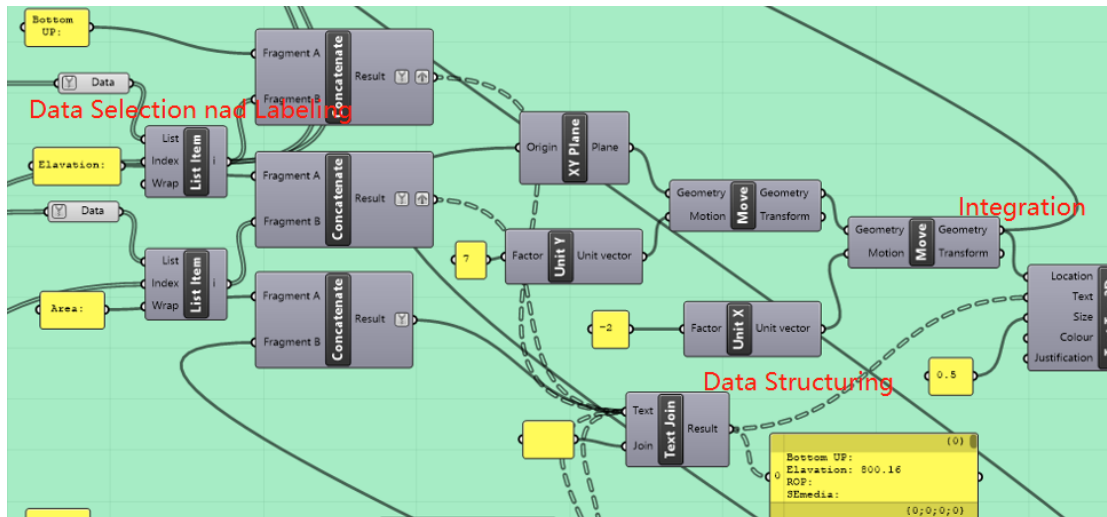


Figure 58 – Data Structuring and Interaction

4.3. Case Study- Avrieux ventilation shafts

4.3.1. Introduction of the case study

The Avrieux shafts are ventilation shafts for the base tunnel of the Lyon-Turin railway line. These shafts provide the connection between the Modane safety site, and the ventilation plant located on the Avrieux platform. Access to the bottom of the Avrieux shafts is via the Villarodin-Bourget/Modane downhill tunnel and then through a connecting gallery. A ventilation gallery connects the bottom of the shafts to the smoke extraction shafts connected to the main tubes. These consist of 4 galleries called smoke extraction shaft heads and 4 vertical smoke extraction shafts which connect the shaft heads to the Base Tunnel. The shaft P1 was used in this paper for the case study.

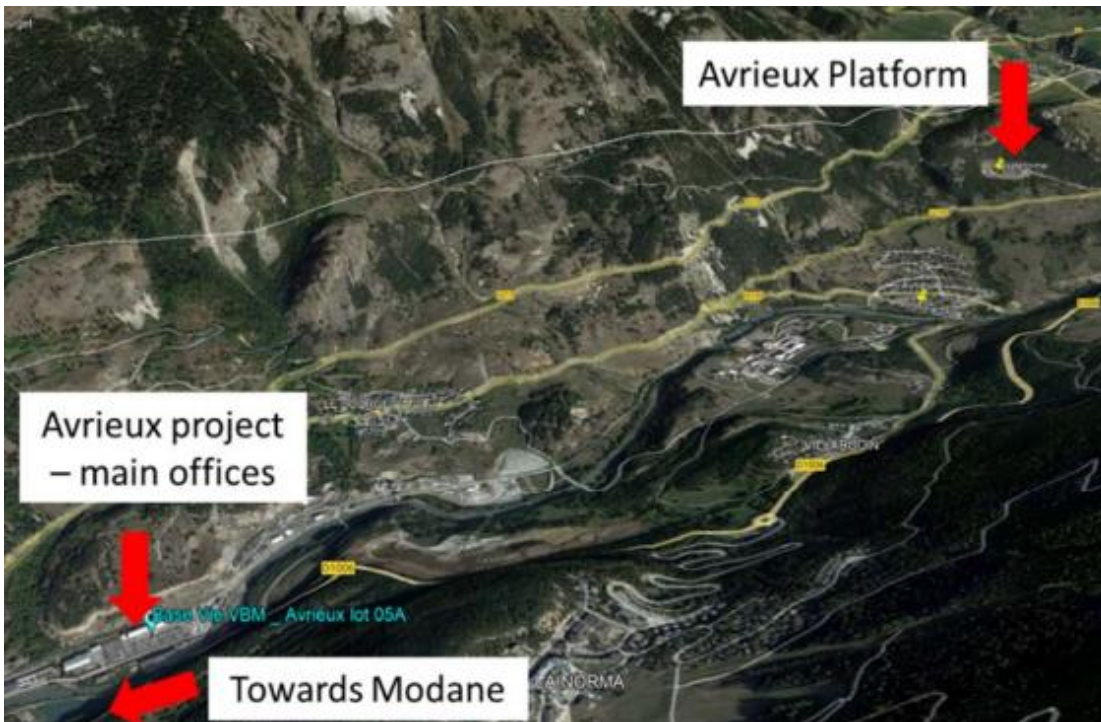


Figure 59 - Location of Avrieux Platform



Figure 60 - Picture of the Avrieux Platform

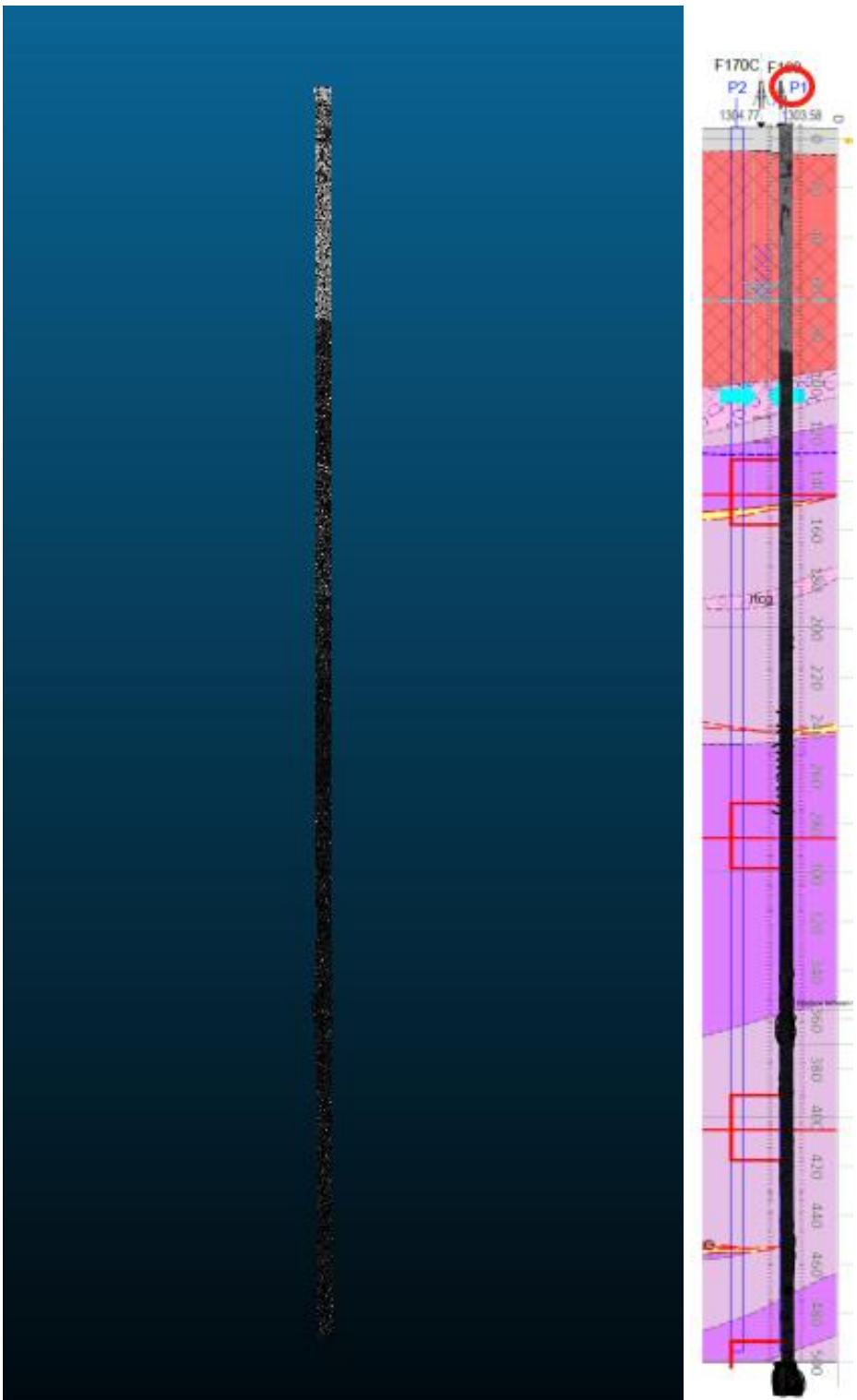


Figure 61 - Point Cloud of the Ventilation Shaft P1

4.3.2 Generated Result

Marking all points that fall beyond the defined tolerance with a distinct color is an effective visualization strategy that enhances clarity and ease of analysis. This color differentiation makes it visually apparent which points or elements deviate from the expected criteria, allowing users to quickly identify and focus on areas that require attention or further investigation.

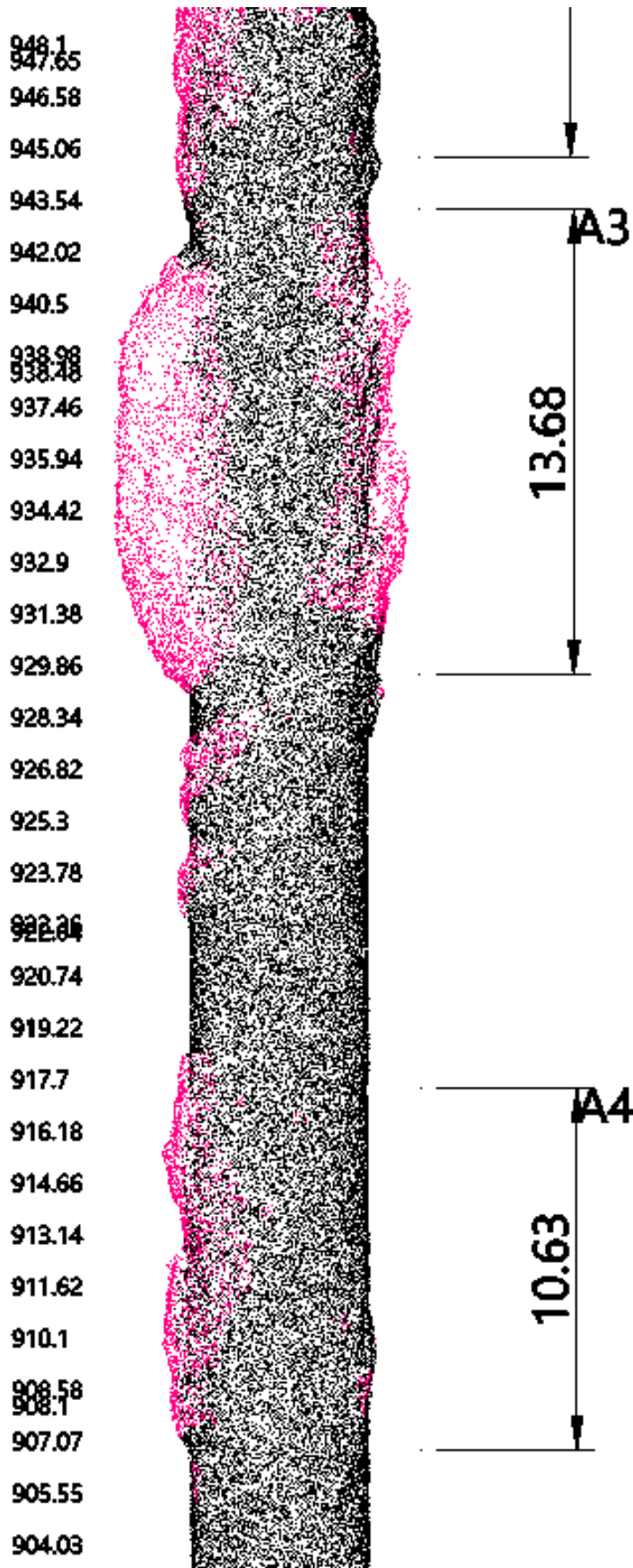
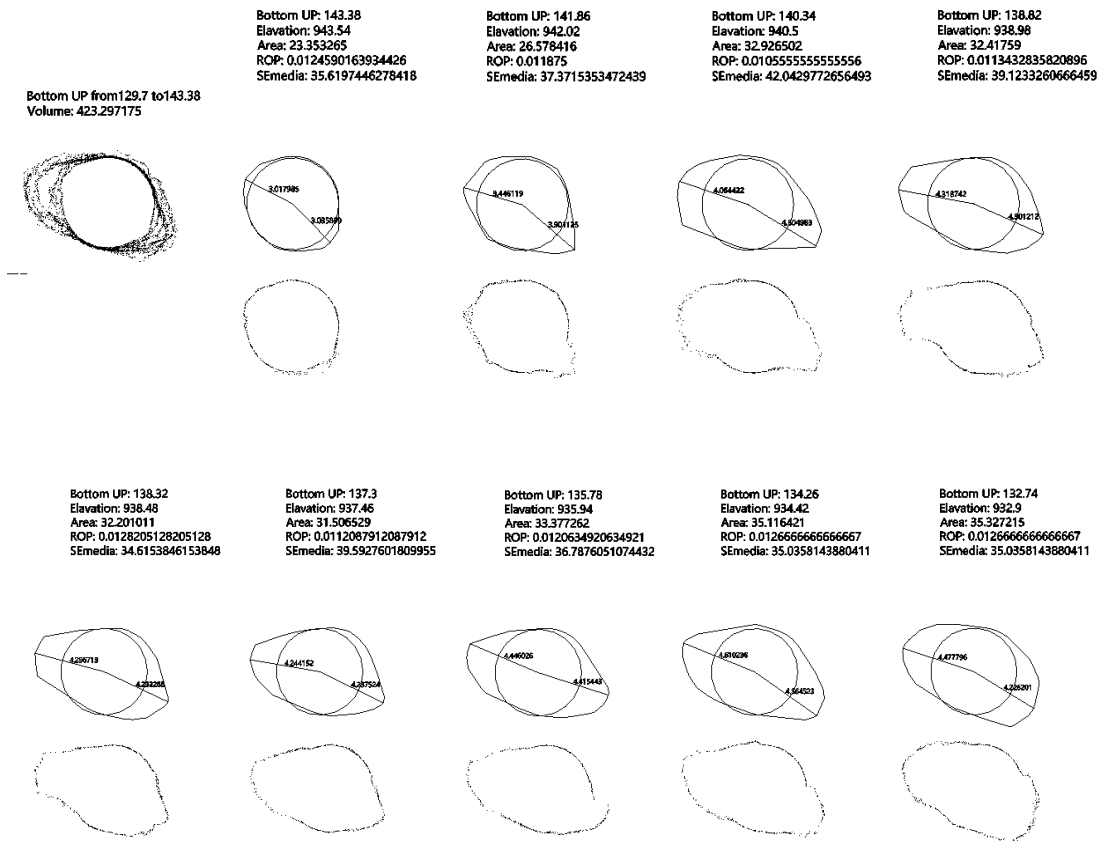


Figure 62 - Anomalous Segments, Marked in Pink

The script's ability to automatically generate sections of a specific area, such as A3 (spanning from elevation 943 to 929), by inputting the elevation values (929 and 943) is an efficient and user-friendly feature. This automation streamlines the process of obtaining sections, saving valuable time and effort. Furthermore, the integration of information within these sections with data from Excel enhances the script's analytical capabilities. Users can access and analyze integrated data, facilitating comprehensive investigations. This function of the script is very useful when identifying and addressing specific project aspects like over-excavated areas, enabling a focused and data-driven approach to problem-solving within the broader context of the project.

No	Activity	Date	Start	Minutes	Rod Serial No	Length m total	Bottom UP	Per. m/h	RPM	RPM max	Torque	torque m/s	Load	load m/s	Cuttings	Operator	ROP	SEM	SEmax	SEmedia
257	1741	reaming	2023/02/26	14:48	102	30889	1.52	353.09	0.99	3.0	500	260	260	41.94	SN	0.014902	39.78		39.78	
258	1743	reaming	2023/02/26	16:37	73	30889	1.51	354.1	0.94	3.0	500	160-290	210	41.67	SN	0.020888	21.45		21.45	
259	1745	reaming	2023/02/26	17:57	85	31133	1.52	356.42	1.07	3.0	500	305	305	41.94	SN	0.017885	4.82		34.82	
260	1747	reaming	2023/02/26	19:29	82	31082	1.52	357.94	1.11	3.0	500	310	310	41.94	SN	0.018531	33.94		33.94	
261	1749	reaming	2023/02/26	20:58	27	38953	0.45	358.09	1.00	3.0	500	305	305	12.42	SN	0.016667	36.63		36.63	
262	1751	reaming	2023/02/27	06:51	84	38953	1.07	359.45	1.05	3.0	500	300	300	29.53	JH	0.012784	41.94		34.94	
263	1753	reaming	2023/02/27	08:22	117	40553	1.52	360.0	0.78	3.0	500	290	290	41.94	JH	0.012599	44.16		34.16	
264	1755	reaming	2023/02/27	10:28	122	39032	1.52	362.1	0.78	3.0	500	300	300	41.94	JH	0.022458	56.62		56.62	
265	1757	reaming	2023/02/27	12:39	128	39361	1.52	364.0	0.71	3.0	500	310	310	41.94	JH	0.011877	37.37		37.37	
266	1759	reaming	2023/02/27	14:55	144	30020	1.52	365.5	1.03	3.0	500	340	340	41.94	SN	0.010598	2.04		42.04	
267	1761	reaming	2023/02/27	17:26	134	31089	1.52	367.01	0.88	3.0	500	350-300	325	41.94	SN	0.011341	31.12		39.12	
268	1763	reaming	2023/02/27	19:46	99	50446	0.5	367.5	0.77	3.0	500	290	290	13.80	SN	0.012821	44.62		34.62	
269	1766	reaming	2023/02/28	06:46	91	50446	1.02	368.53	1.37	3.0	500	350	350	28.15	JH	0.011208	39.59		39.59	
270	1768	reaming	2023/02/28	08:24	126	40679	1.52	370.1	1.05	3.0	500	330	330	41.94	JH	0.010398	36.79		36.79	
271	1770	reaming	2023/02/28	10:38	120	38872	1.52	371.63	0.76	3.0	500	330	330	41.94	JH	0.012065	35.04		35.04	
272	1772	reaming	2023/02/28	12:45	120	31160	1.52	373.11	1.02	3.0	500	330	330	41.94	JH	0.012665	35.04		35.04	
273	1773	reaming	2023/03/01	09:06	100	39073	1.52	374.63	1.13	3.0	500	290	290	41.94	SN	0.015511	39.20		39.20	
274	1777	reaming	2023/03/01	10:53	111	37216	1.52	376.39	1.07	3.0	500	340-340	290	41.94	SN	0.010398	32.41		32.41	
275	1779	reaming	2023/03/01	12:51	113	30936	1.52	377.1	1.03	3.0	500	230-370	300	41.94	SN	0.013435	3.99		32.99	
276	1783	reaming	2023/03/02	06:56	131	40673	1.52	379.3	0.70	3.0	500	330-280	295	41.94	SN/KC	0.011002	38.25		38.25	

Figure 63 – Integrated Excel Data



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5. CONCLUSION

This paper introduces two innovative methods within the pipeline, each offering a unique approach to computing progress in construction monitoring. Method 1 stands out by taking a novel route: it aligns the densities of the as-designed and as-built point clouds, enabling a comparison with the as-designed model. This departure from the traditional practice of directly comparing two point clouds results in a significant reduction in computational time. Consequently, project managers gain access to real-time progress information without compromising accuracy. Method 2, on the other hand, takes progress analysis to the next level by utilizing the as-built mesh for comparison with the as-designed model. This method not only enhances analysis speed but achieves a remarkable improvement, with processing times exceeding a hundredfold compared to conventional approaches. This substantial acceleration in analysis allows project managers to make timely and informed decisions. In summary, these two methods offer efficient and effective tools that can revolutionize construction progress monitoring, streamlining project management processes and ultimately contributing to successful project outcomes.

In Chapter 2, a novel approach for element analysis based on point clouds is presented. This approach not only enables the identification of anomalous parts within elements but also offers the capability to automatically generate sections as required. Furthermore, it seamlessly integrates data from various sources into these sections. The result is a substantial improvement in the efficiency and speed of tasks related to point cloud processing and analysis. This innovative method holds promise for enhancing construction monitoring processes by providing a comprehensive and unified view of construction elements.

In conclusion, the use of point cloud-based analysis in construction offers a rich array of applications, allowing for a thorough understanding of complex projects and facilitating data-driven decision-making. The choice between point cloud-based and model-based analytics depends on the specific requirements and objectives of the analysis, with each approach offering unique advantages in the construction industry.

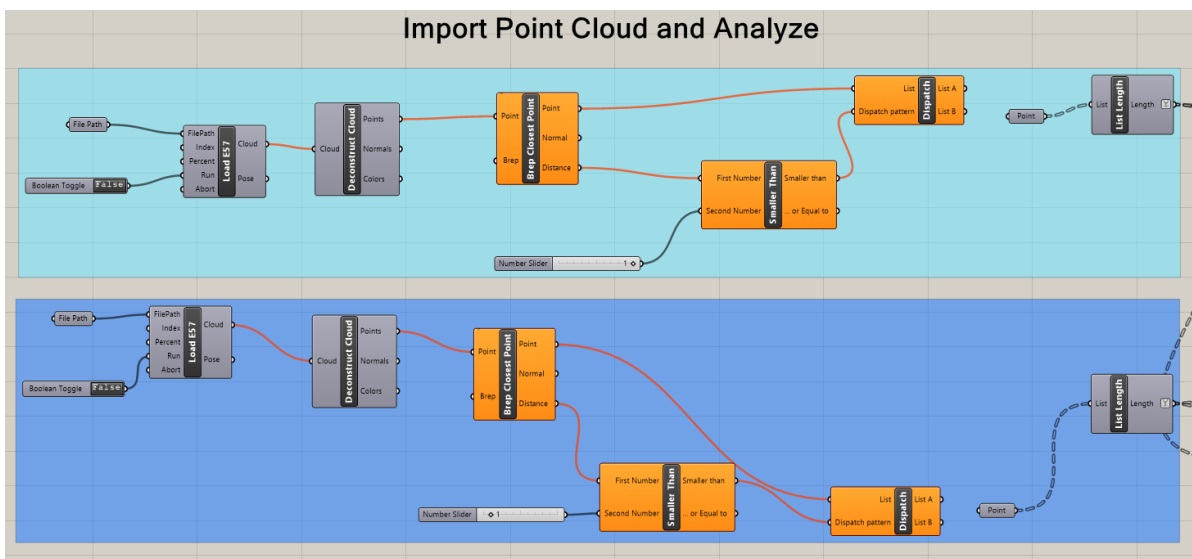
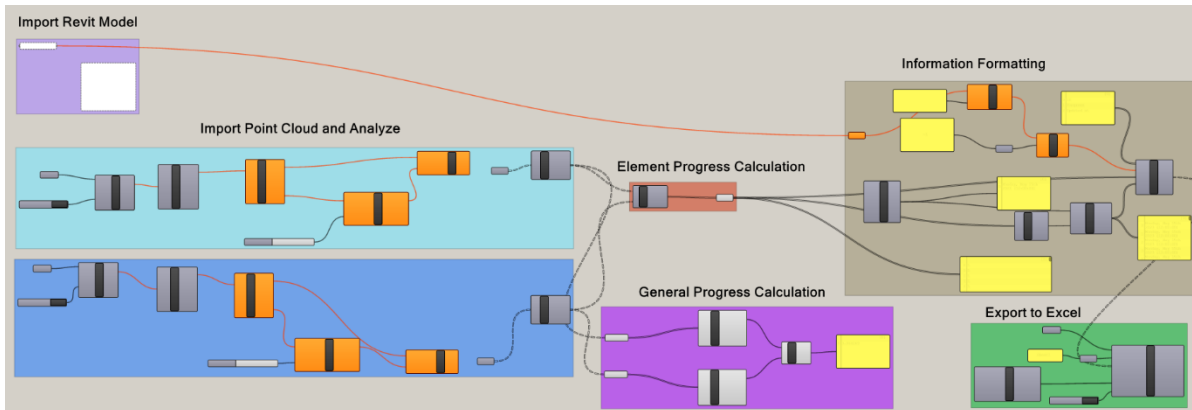
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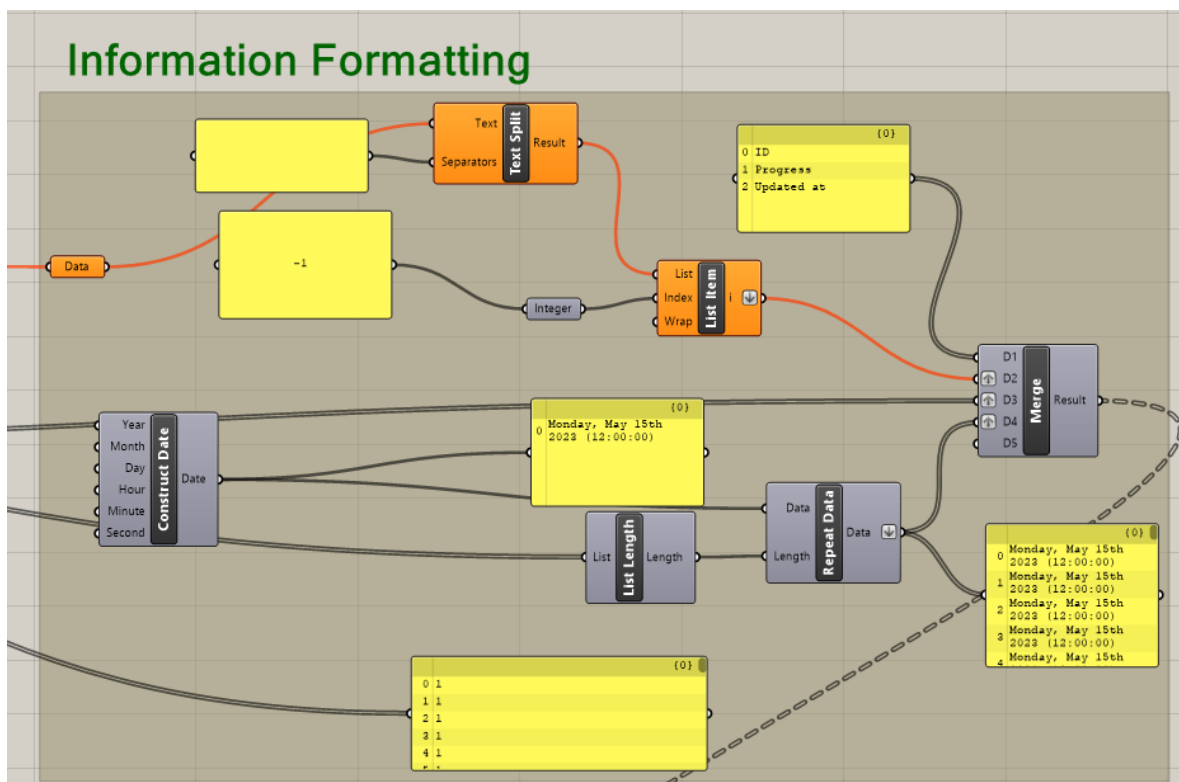
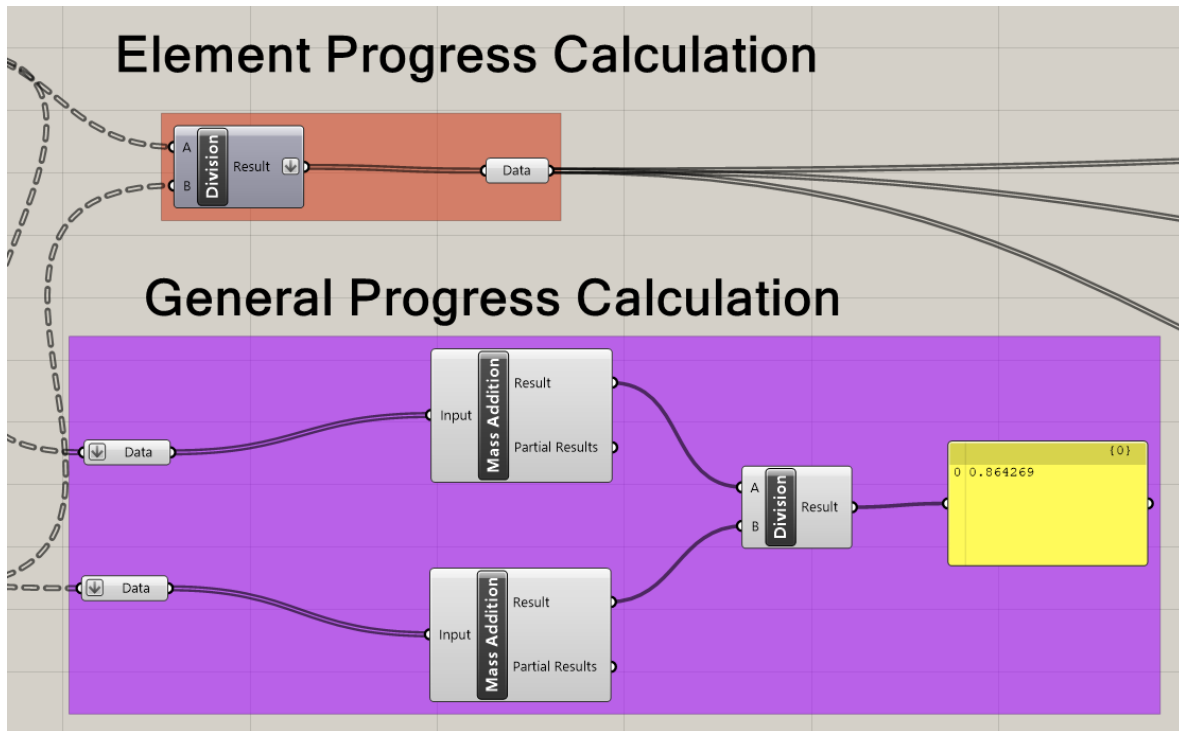
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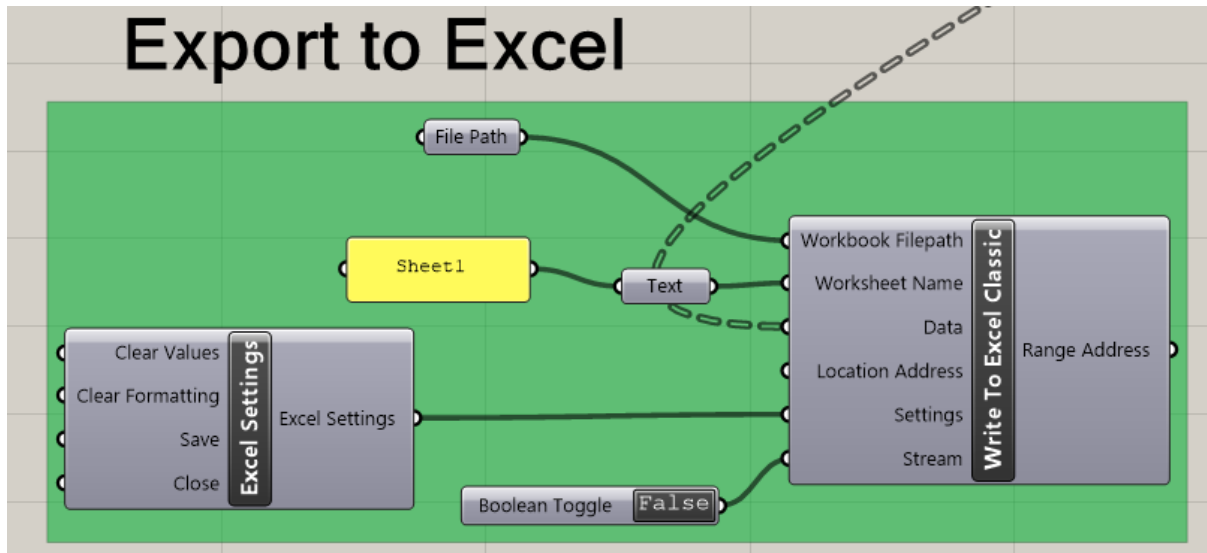
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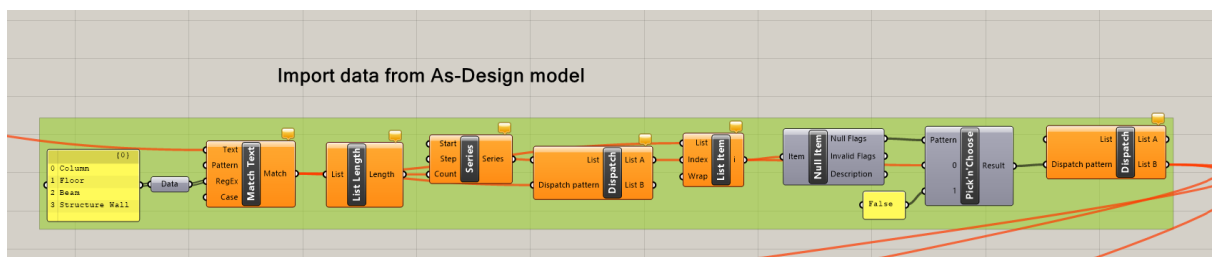
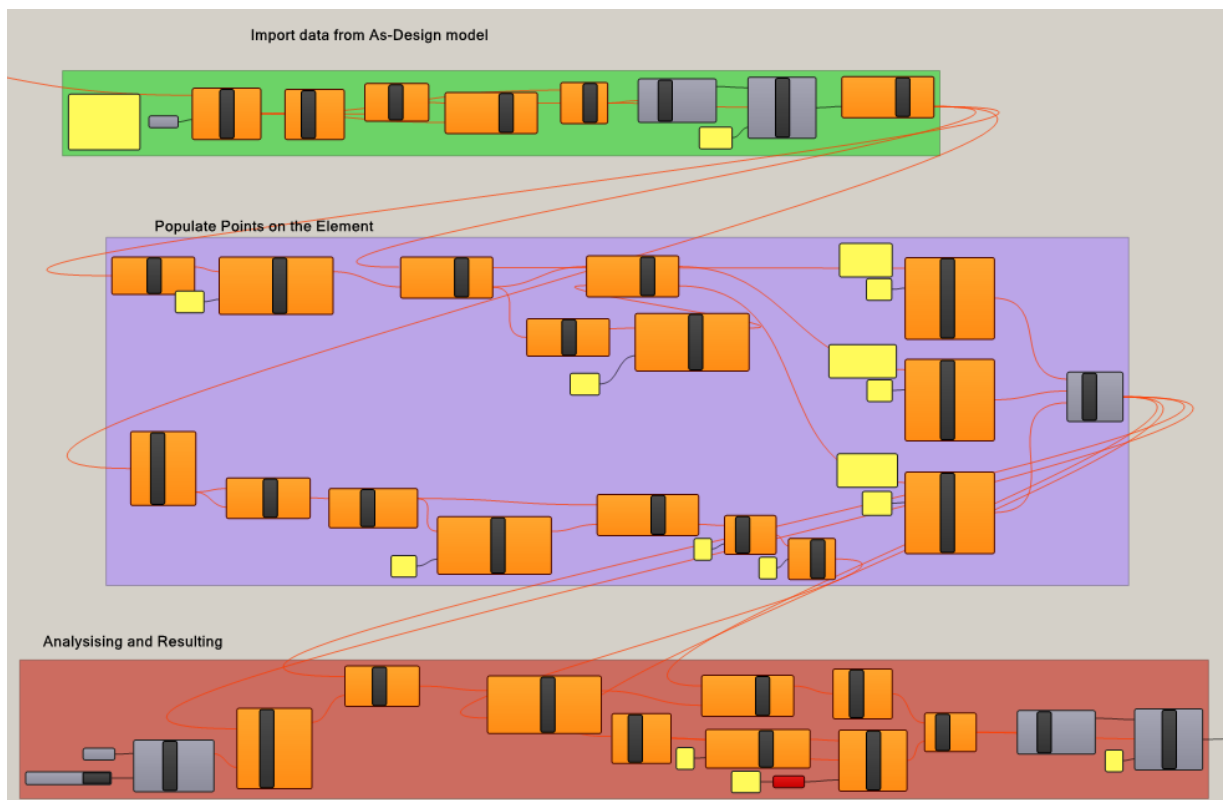
APPENDIX 1: GRASSHOPPER - METHOD 1

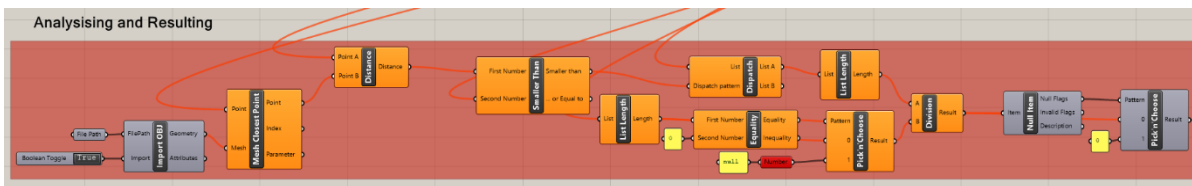
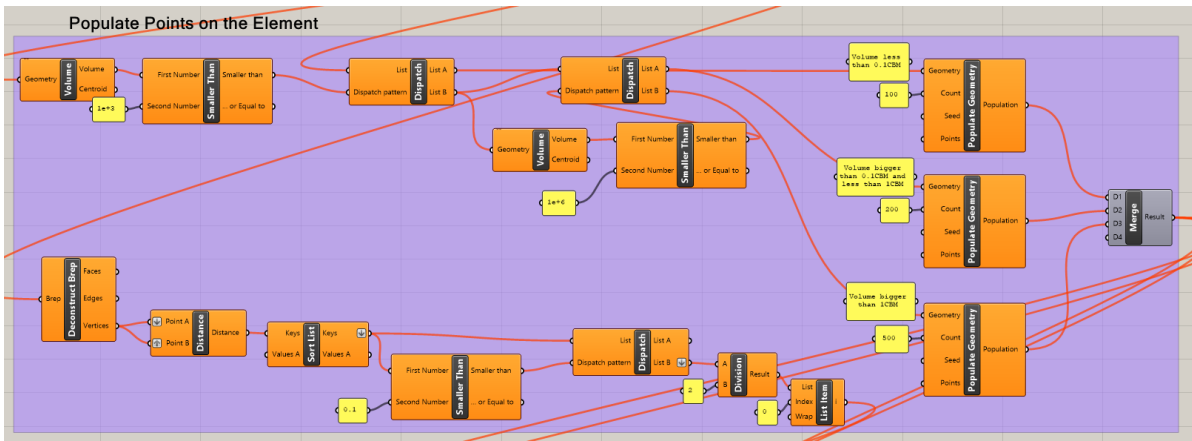




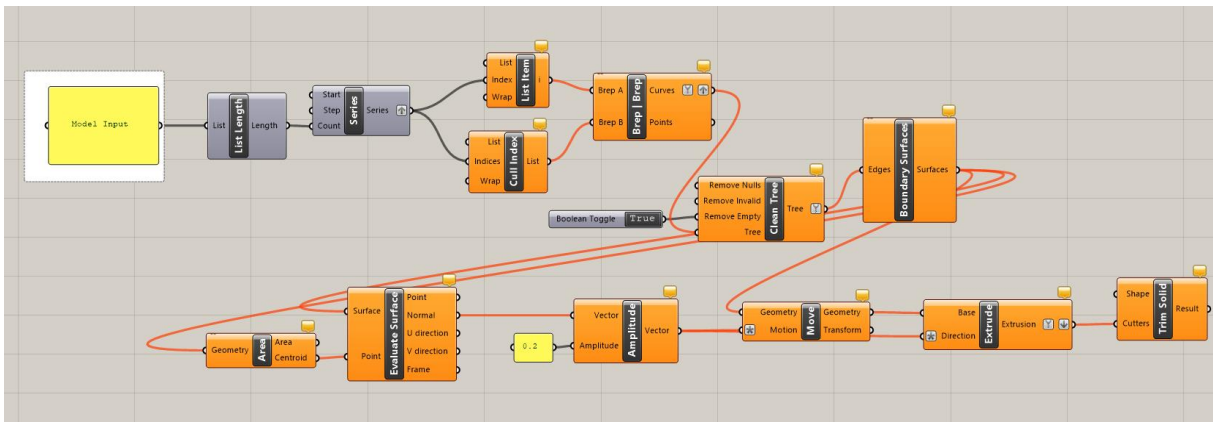


APPENDIX 2: GRASSHOPPER - METHOD 2

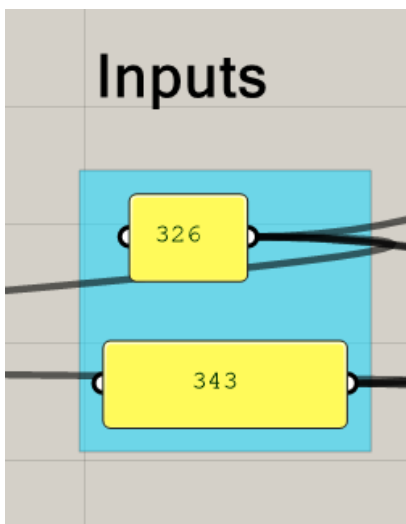
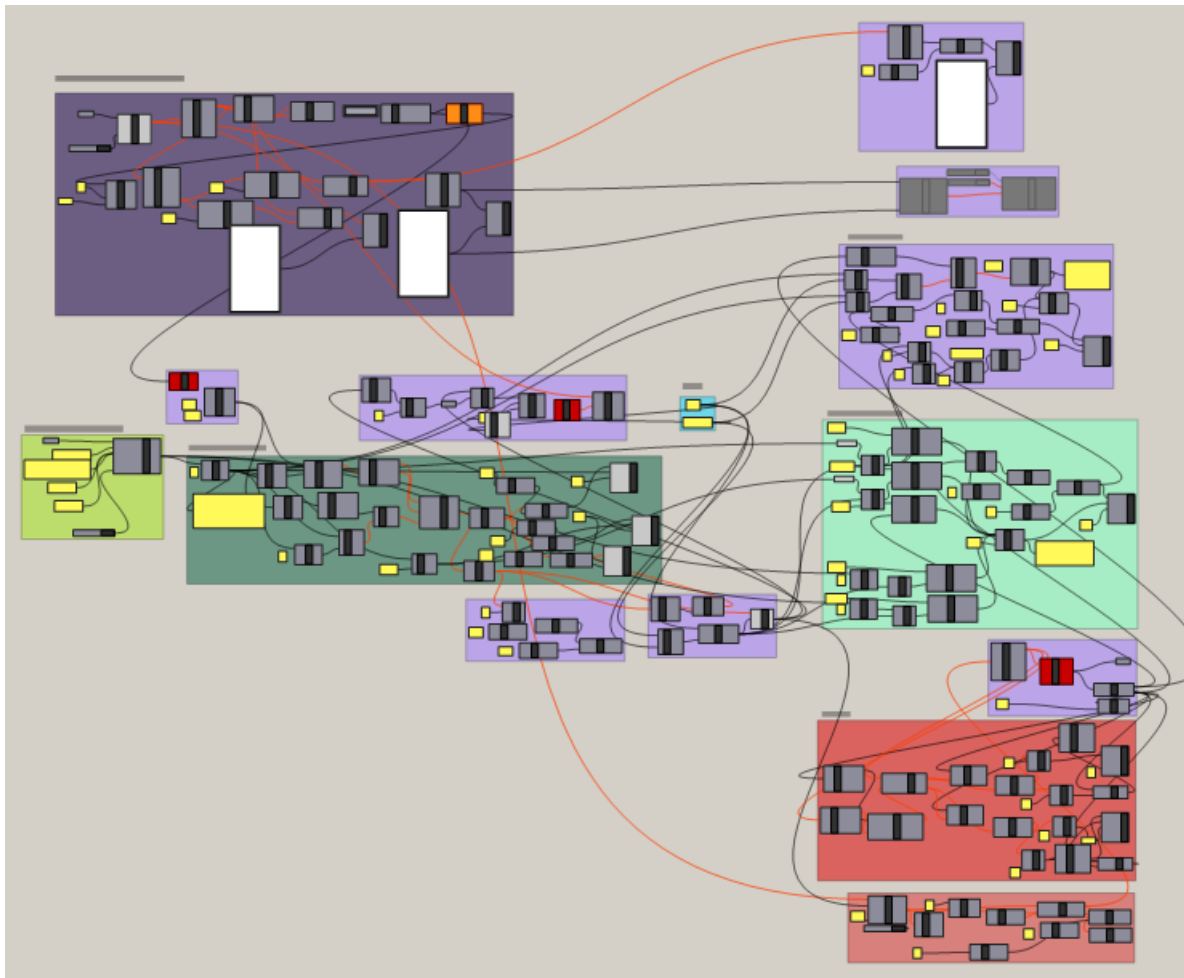


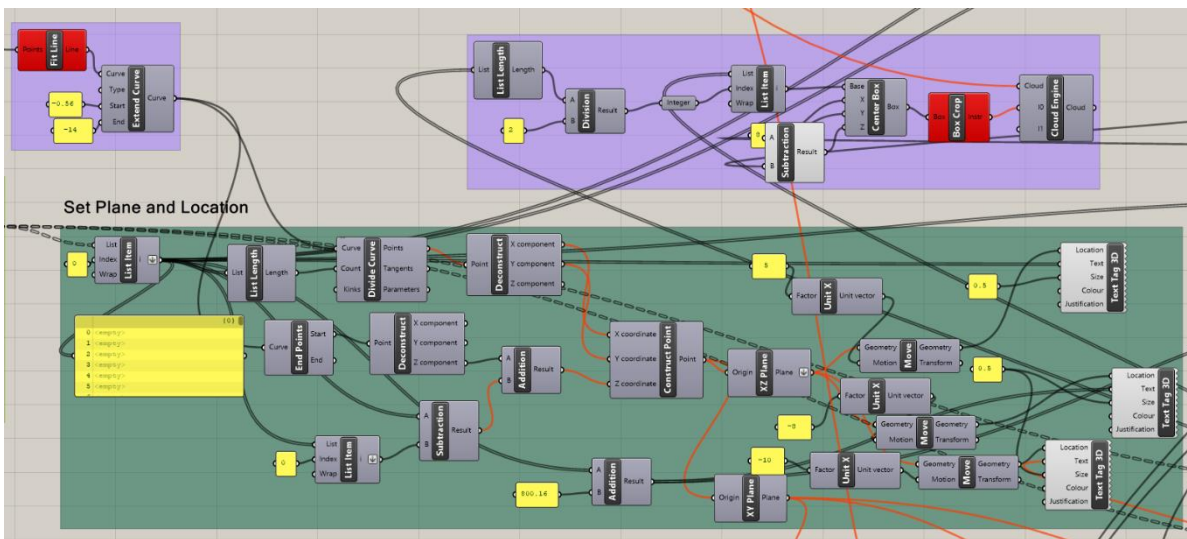
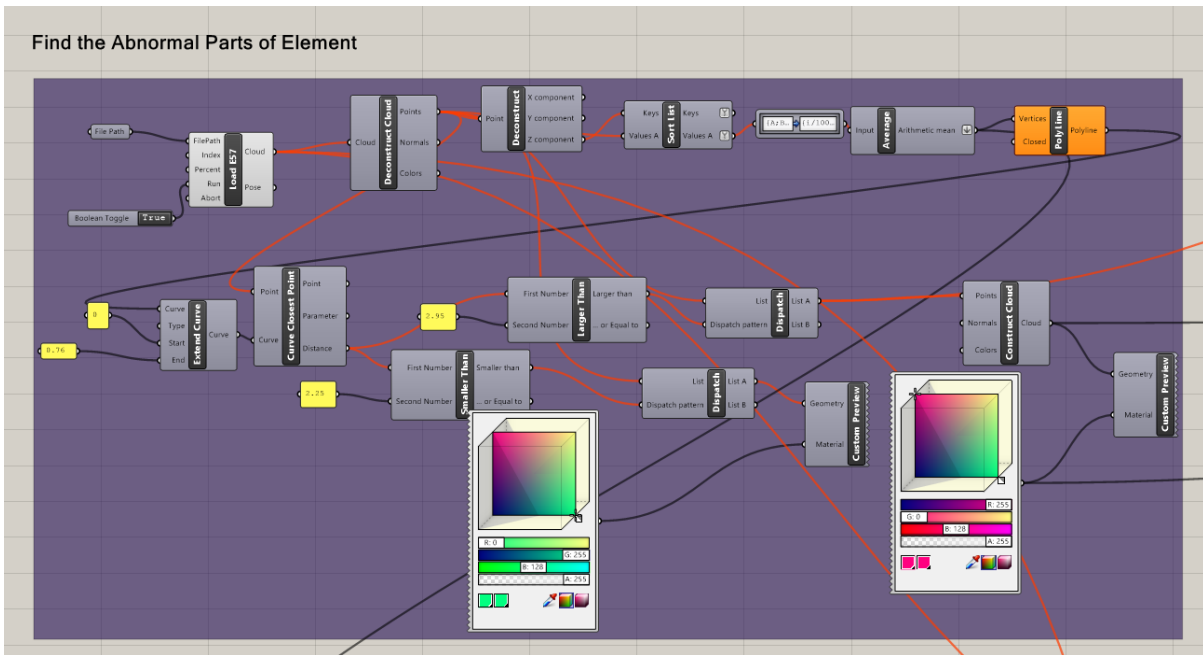


APPENDIX 3: GRASSHOPPER - REMOVE UNDESIRABLE SURFACE

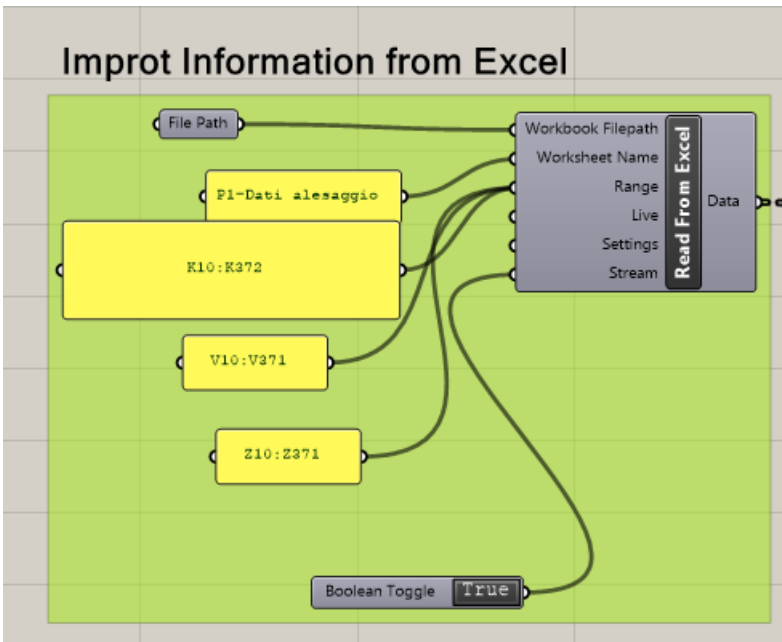


APPENDIX 4: GRASSHOPPER - ELEMENT ANALYSIS

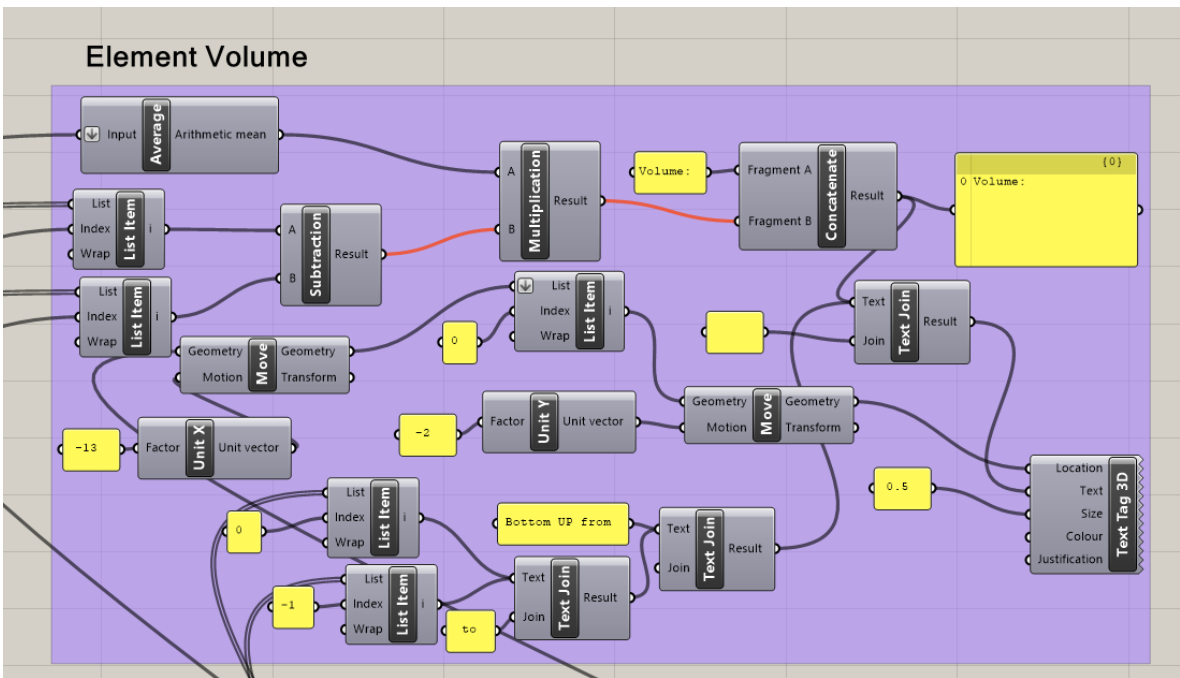


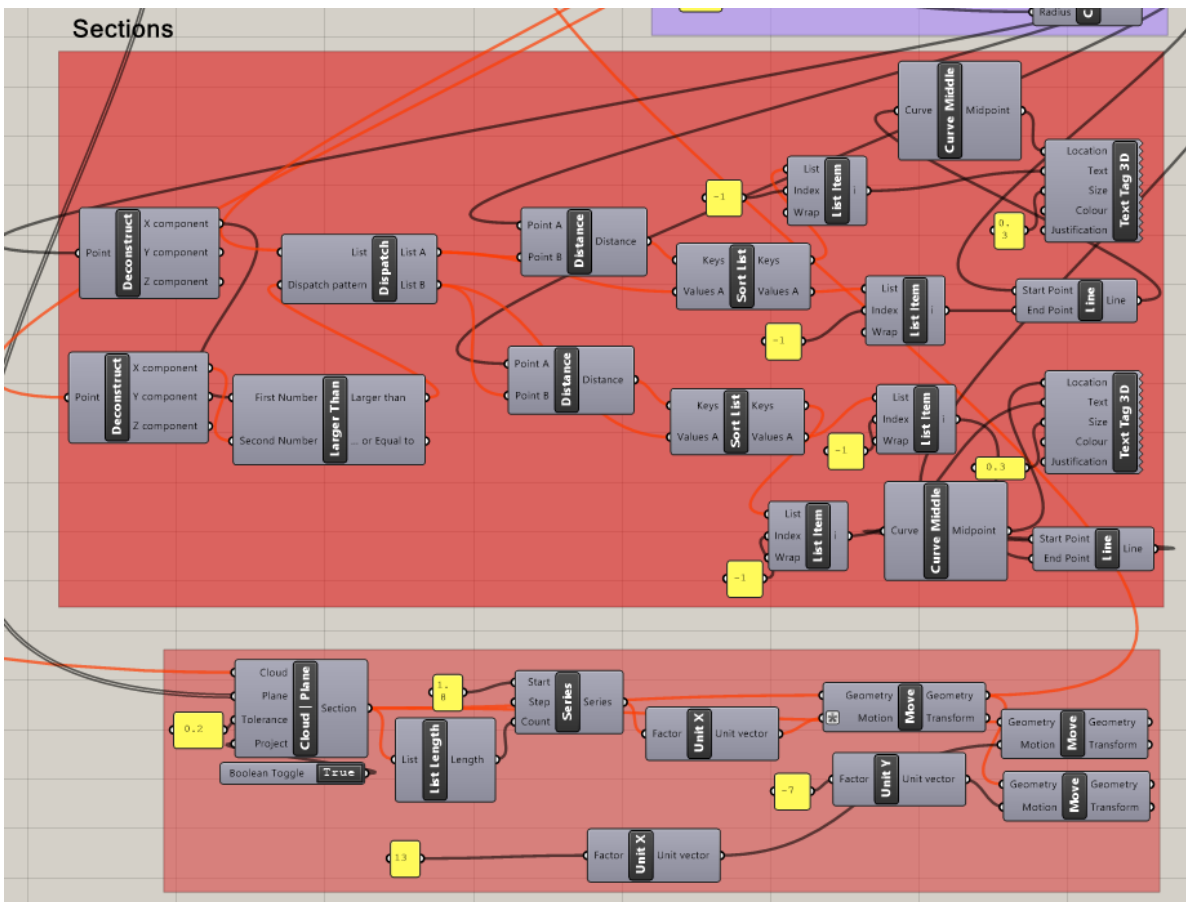
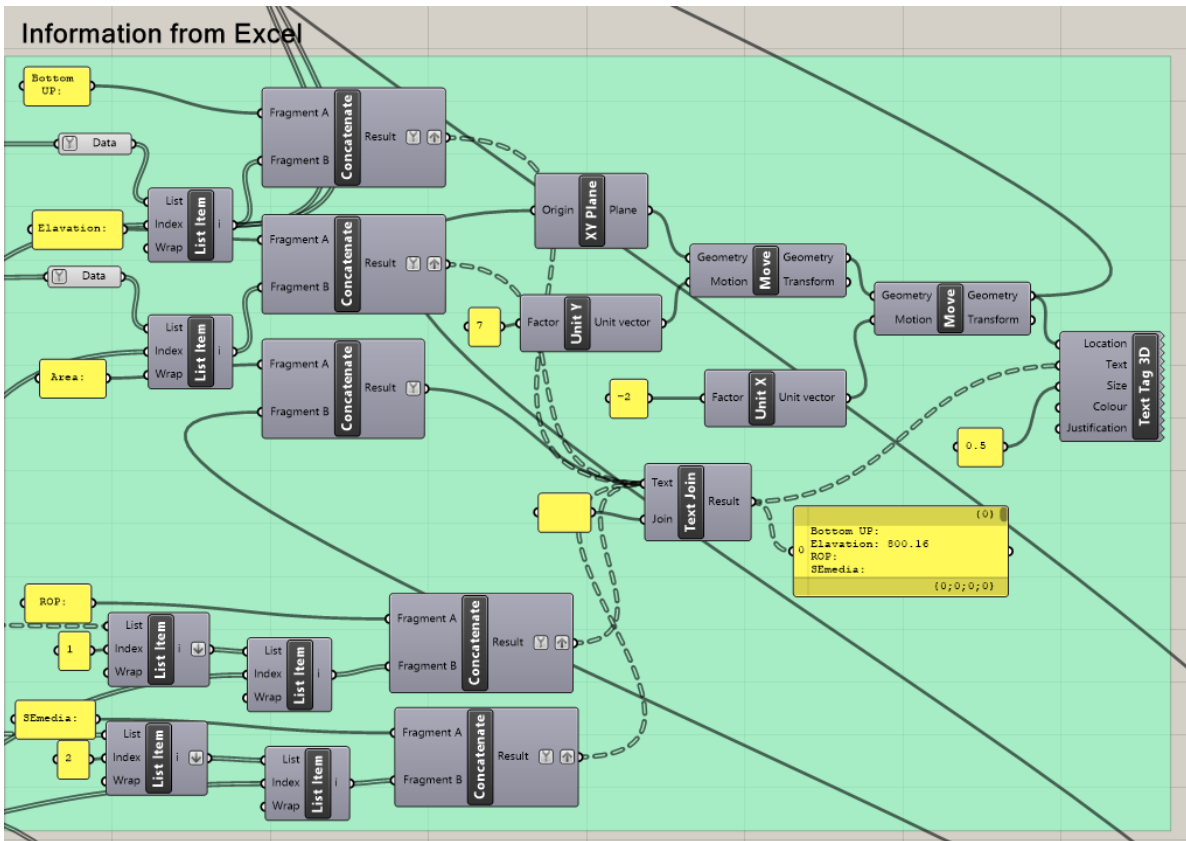


Improt Information from Excel



Element Volume





APPENDIX 5: DYNAMO - INFORMATION MANAGEMENT

