BuiltView: Integrating LiDAR and BIM for Real-Time Quality Control of Construction Projects

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Abstract -

Global spending on rework in the trillion dollar construction industry is estimated at $570bn of direct costs and $440bn of indirect costs. The cost of rework is on the rise, and the main cause is rooted in quality deviations from construction design. Real-time or even near real-time remote progress monitoring and quality control has the potential to prevent a large portion of defects and enables quick detection and handling of errors that often go undetected for too long. Current procedure still relies on human visual inspections that are costly, in terms of time and human resources, and is subject to human error. Moreover, existing tools and services are limited in the size of data they can handle, as LiDAR data can be gigabits in size with hundreds of millions of unstructured points. The technology often fails at being robust to occlusions and other noise elements commonly found on construction sites. More sophisticated algorithms exist to perform different parts of the required analysis; however, they require a high level of expertise to implement and tailor to different use cases. In this paper, we present BuiltView, an automated progressive assurance platform that allows users to validate and document construction activities on a daily basis. BuiltView can significantly reduce rework by accurately and efficiently identifying BIM components and detecting discrepancies between the as-designed data and the as-built data, particularly in terms of geometric compliance. BuiltView is a powerful tool that processes billions of LiDAR points in a very efficient manner. Leveraging sophisticated analytical algorithms, BuiltView calculates accurate dimensions and generates comprehensive user-friendly reports to facilitate communication across the business. We show that BuiltView is a valuable tool for automation of quality assurance and quality control, progress tracking and documentation. Using the tool, builders can significantly reduce costly rework, increase productivity and boost transparency between different project stakeholders, thanks to objective, high-accuracy evidence.

Keywords -

LiDAR; BIM; point cloud; progressive assurance; QA/QC; rework; as-built models; project management

1 Introduction

According to McKinsey and Co, most construction projects are expected to run 20% over schedule, and 80% over budget with 25% of profit lost on defects and rework [1]. Moreover, the overall productivity of the construction industry has increased by a mere 1% over the past two decades [2]. The depressed productivity of construction projects is costing the global economy $1.6 trillion each year [3]. For major contractors in the industry, documenting and maintaining a single source of truth is essential for accountability, quality and efficiency of the work. For effective management of construction projects, this data needs to be timely (up to date), detailed and accurate. Autodesk identified frequent information capture of errors, omissions, and defects as the number one key performance indicator (KPI) for construction contractors [4].

Building information modelling (BIM) is widely used in the construction industry to enhance project performance from design to construction and facilities management (FM). Complimenting BIM, point cloud data obtained from LiDAR (Light Detection and Ranging), images, and videos are able to provide accurate and fast records of the 3D geometries of construction-related objects. Point clouds are a set of data points with (X,Y,Z) coordinates along with hardware-dependent additional information, such as reflection intensity, RGB values, and normals. LiDAR, in particular, is able to provide an accurate 3D digital representation of construction site conditions at millimetre level accuracy. The 3D laser scanning market has doubled over the past four years, evaluated now at almost $6bn, and the demand for LiDAR in construction has almost tripled in just four years (approximately 60%) [5]. With recent research showing the efficacy of LiDAR in construction and its capability to reduce rework by 25% [6], there is no doubt that laser scanning is becoming an essential part of the industry.

The value of LiDAR lies in referencing the resultant point clouds to BIM. Despite the fact that there are many existing software and service providers in this space, there is no state-of-the-art framework that can be readily adopted by building design and construction professionals. In this space, BuiltView presents an innovative and unique solution to the integration of LiDAR with BIM for construction projects. BuiltView is a digital tool that automatically conducts deviation analysis between the as-designed model and point clouds based on as-built conditions.

By automating deviation analysis and progress checking, BuiltView has provided significant value to Laing O'Rourke through reduced rework and improved productivity (as depicted in Figure 2). Laing O'Rourke is an international engineering enterprise, with roots tracing back a century and a half. It excels at delivering large scale projects in building, transport, power, utilities, mining, and infrastructure.

Since inception, Laing O'Rourke has showcased numerous innovative research and development achievements. One recent example is BuiltView, which provides automated reports to improve client and subcontractor relationships. BuiltView is a key enabler of future digital tools such as smart contracts [7] and scan-to-BIM [8]. This paper leverages in-house case studies from past and current projects to assess the value of BuiltView compared with traditional approaches such as survey reports, spot checks, site walks, and eye-balling discrepancies for as-built model creation.

2 BuiltView

In this section, we present the workflow for BuiltView, its key distinguishing features and how it is of value to a multitude of parties of the construction industry, from subcontractors to site engineers to project managers, clients and stakeholders.

2.1 BuiltView: Main Components

BuiltView is a platform that leverages LiDAR and BIM technologies to provide up-to-date information on as-built conditions compared with the as-designed model requirements. BuiltView's value lies in automating quality checking to enable improved productivity and certainty, reduced rework, faster as-built model creation and improved decision making. The main workflow structure is as follows:

1. *Data acquisition*: The data acquisition phase is not limited to any particular hardware and can range from terrestrial laser scanners to drones and handheld mobile devices. The accuracy of the hardware relates directly to the use case it can serve. For instance, photogrammetry cannot yet support millimetre-level floor flatness analysis. Moreover, progress tracking may not require the high accuracy of survey-grade laser scans.

2. *Data Processing*: The data collected is referenced (or geo-referenced) to existing models and analysed in terms of matching objects and geometric compliance.

3. *Quality Assessment*: Quality is assessed through calculated geometric variances between the point clouds and the model, surface deviations and displacement.

4. *Progress Estimation*: Progress is estimated by comparing the amount of work completed with the amount of work planned, while taking into consideration the quality of the work and any rework required on potential defects.

5. *Visualisation*: Customised reports and dashboards are generated to tailor the visualisation of the results to the audience, e.g. project managers will be interested in overall percentages, whereas engineers will be interested in particular activities.

2.2 BuiltView: Key Innovations

There are commercial software packages and algorithms under research and development that aim at detecting and calculating variances between point clouds and models, or between point clouds themselves. With varying features, integrations and pricing models, we have found BuiltView to be the preferred solution in the following areas.

- *Accurate Metrological Algorithms*: BuiltView leverages proprietary deviation analysis algorithms that are capable of detecting objects in point clouds, in the presence of partial occlusions or other noise elements. It is a uniform platform that is independent of the method of capture. The accuracy of the calculated deviations lies solely in the accuracy of the data.

- *Intelligent Referencing and Geo-referencing*: Anyone familiar with point clouds will admit to the difficulties in referencing point clouds to models manually or even using semi-automated tools. The process is theoretically complex and empirically a combination of trial and error. BuiltView leverages intelligent algorithms that can identify different features in point clouds, for example surfaces, corners, beams, and pipes, to better register the point cloud to the model. This is a game changer for use cases where geo-referencing based on survey-grade control points is not possible, for example, in manufacturing facilities (see Section 3).

- *Intelligent Object Categorisation*: The required point cloud quality parameters are highly dependent on the construction-related element classes. For instance, building tolerances of steel beams are not the same as those of pipes or electrical services. BuiltView has built-in intelligence that allows it to produce conformance reports that are specific to every object class.

This saves engineers a tremendous amount of time in translating the results to tangible actions.

- *Robust Data Processing*: While most existing tools and services are limited in the size of data they can handle, BuiltView works with LiDAR data of the order of hundreds of millions of unstructured points with great ease by leveraging proprietary hierarchical data structuring algorithms for efficient processing and storage.

2.3 BuiltView across the Construction Project Life Cycle

Here we present a closer look at the use of BuiltView across a project's life cycle, as illustrated in Figure 1.

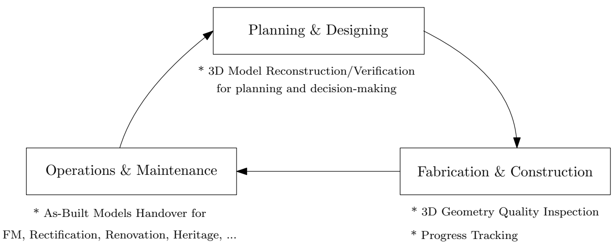

Figure 1. The benefits of BuiltView across the different phases of a construction project

1. *Planning & Design*: This is commonly known in the literature as "Scan-to-BIM", where laser scanning is conducted during the pre-construction phase for site design. This step is crucial for many projects to kick-off the design process with accurate and detailed information. Even when as-built models exist (from previous clients), we find that BuiltView is still invaluable to verify the models quickly, which will serve as a basis for all designs to come. This will be covered in detail in Section 5.
2. *Fabrication & Construction*: BuiltView continues to provide value during the construction phase as a powerful tool to document progress, defects and overall milestones. The nature of the data facilitates communication between different systems (mechanical, electrical, HVAC, etc.) and remote collaboration. The nature of the data, being free of human-error and subjectivity, also facilitates conflict resolution and accountability. This will be covered in Sections 3 and 4.
3. *Operations & Maintenance*: The advantage of laser scanning and the main goal of BuiltView is to close the loop. Laser scanning captures a very high level of detail, and this helps create a permanent as-built record for both owners and facility managers. In the end, this data can help with building operations, renovations, retrofits and future building additions and even demolitions. This will be covered in Section 5.

In the remaining part of this paper, we focus on the three main use cases of BuiltView, namely Quality Assurance and Quality Control (QA/QC), Progress Tracking and Documentation. An overview of the impact BuiltView has had on Laing O'Rourke's projects is depicted in Figure 2.

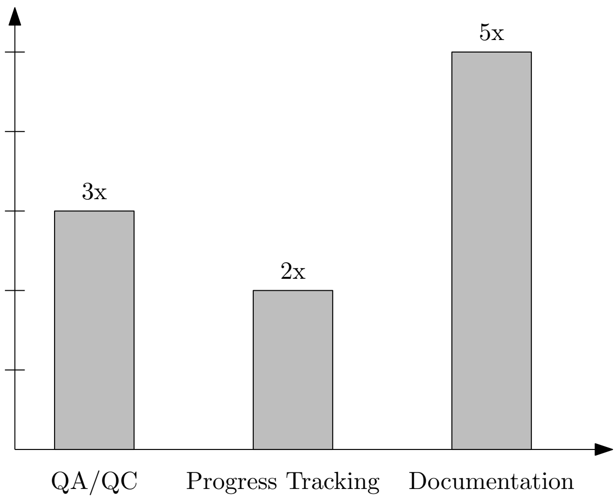

Figure 2. The time savings offered by BuiltView on Laing O'Rourke's past and current projects

3 Quality Assurance and Quality Control

3.1 Traditional QA/QC Workflow

Early identification of defects is critical for quality control because, on average, 6 to 12% of construction cost is wasted due to rework. This is exacerbated when defective components are detected late in the construction process [9]. Traditionally, QA/QC is carried out by periodic site walks and random spot checks that are documented in red-line mark-ups on 2D drawing print-outs. These hard copies are later translated manually in the office into as-built CAD drawings. In other instances, surveyors are sent out to site to check particular areas. The latter is notoriously expensive and is often subject to long turn-around times, leading to delayed detection of defects.

3.2 QA/QC Automation

With BuiltView, LiDAR scans captured with a single site walk can serve a multitude of use cases that can be automatically checked. Laing O'Rourke has successfully

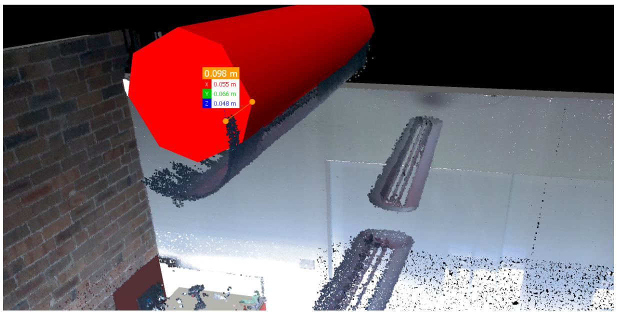

Figure 3. An example of a traditional QA/QC workflow, where deviations are eyeballed in software and measurements are prone to human error.

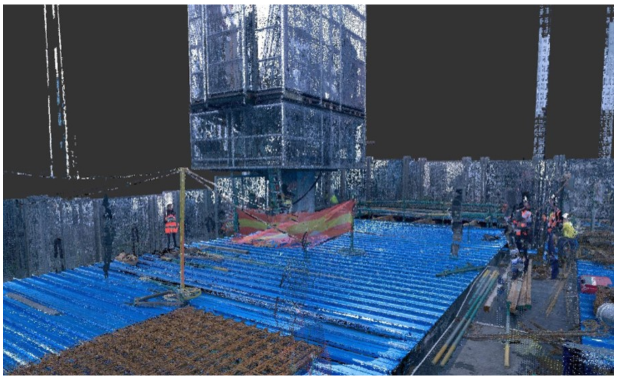

Figure 4. A scan of a 44 level high-rise under construction by Laing O'Rourke.

deployed BuiltView for a number of QA/QC checks listed below.

- *Floor Flatness and Floor Levelness*: BuiltView is capable of replacing manual slab flatness spot checks, based on spirit level and tape measure, with an automated LiDAR-based solution.
- *Reinforcement Steel Bars*: On many projects, BuiltView demonstrated extraordinary capabilities for rebar detection, identification and spacing calculation.
- *Precast Elements*: Precast elements can be checked for quality issues prior to leaving a manufacturing facility - preventing site delays and accelerating rectification.
- *Geometrical Compliance*: Most structural concrete objects - column, beam, wall and slab, and mechanical objects, pipe, duct and cable - can be accurately checked for geometric compliance using BuiltView.

3.3 QA/QC Automation Benefits

- *Floor Flatness and Floor Levelness*: By utilising BuiltView on the 44 level high-rise in North Sydney, Laing O'Rourke mitigated much of the risk associated with the works that followed structural works, for example carpet laying. A scan of the building is shown in Figure 4
- *Reinforcement Steel Bars*: BuiltView demonstrated extraordinary speed and accuracy in counting rebar, computing bar diameter and inter-distances on a large power generation project. The project consisted of 3 million tons of concrete and a total reinforcement weight of 200,000 tons In this environment, assurance checks with minimal labour was highly valued.
- *Precast Elements*: Due to time consuming manual QA processes, it is estimated only 5%-10% of precast units are surveyed in manufacturing facilities prior to delivery. An example of these units is depicted in Figure 6. With BuiltView, this percentage can reach 100% at no additional cost. In practice, BuiltView was used to run automated quality checks on bridge culverts that were scheduled to be installed on a $240 million train bridge project. By detecting defects in a single culvert early in production, BuiltView prevented defects in the remaining 40 precast replicas - preventing rework-related costs and delays.
- *Geometrical Compliance*: By leveraging BuitView as an in-house digital tool for automatically checking geometric compliance (see Figure 5), Laing O'Rourke reduced the turn-around time on as-built validation. Typically, surveyors' reports are based on spot checks of less than 10% of object area. With BuiltView, this percentage can increase to 100% at no additional cost. Moreover, with BuiltView these comprehensive and automated checks allow for a proactive approach to defect identification, allowing for an indirect reduction in total defects and consequent schedule delays.

4 Progress Tracking

4.1 Traditional Progress Tracking Workflow

The process of progress monitoring is traditionally a laborious in construction. Foreman record the work performed on construction sites on a daily and/or weekly basis. Filed reports provide a wide range of data on the available resources, the potential risks, inventories, etc. Nonetheless, these reports cannot capture 3D aspects of the construction work completed and to be completed. They are also prone to human error and aren't frequent

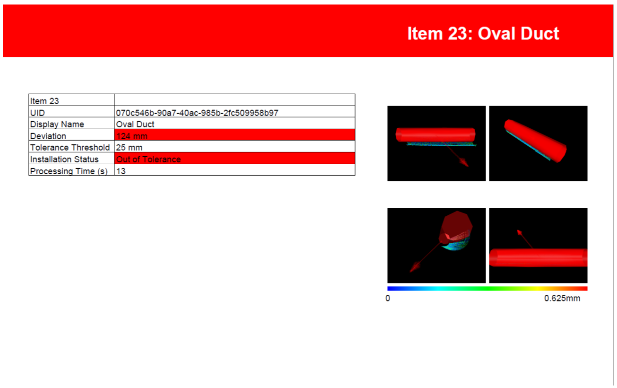

Figure 5. An example of a BuiltView's QA/QC workflow, where deviations are automatically calculated, removing subjectivity in measurements.

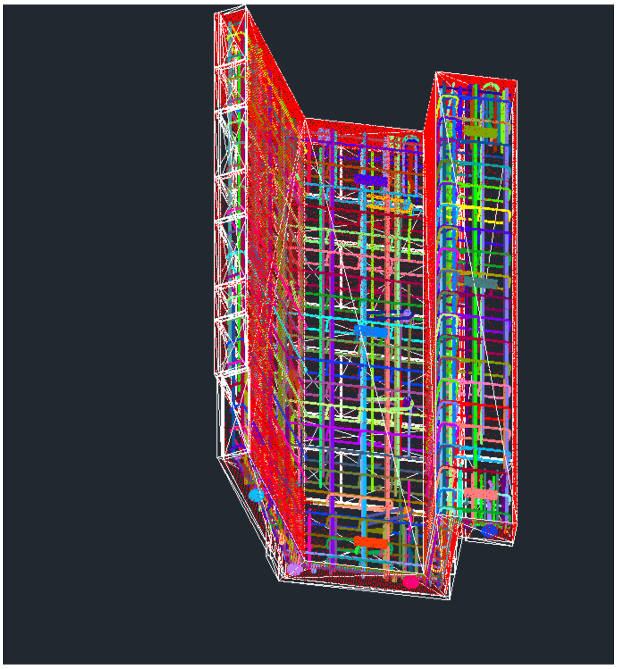

Figure 6. An example of a precast moulds processed by BuiltView for Quality Checks at Laing O'Rourke's manufacturing facility, Explore Industrial Park, UK

enough due to time and cost constraints. This is especially true when multiple site visits are required to collate all data and correct any inaccuracies. Furthermore, significant schedule delays can occur before progress reports can be analyzed and acted upon.

Taking photographs on site is another traditional method of capturing a visual record of on-going progress. Nonetheless, this 2D information is not detailed and comprehensive as 3D geometric data of as-built conditions of construction sites. Consequently, many researcher have directed their work toward generating 3D point clouds from captured photographs, with the aid of photogrammetry and computer vision. The meshes or models generated can be compared with 3D design models and used for automated progress monitoring. However, the capture & analysis process can be laborious.

4.2 Progress Tracking Automation

The traditional process for monitoring progress often prevents corrective actions from taking place in a timely manner, which eventually leads to schedule delays. BuiltView replaces most of these reports (or at least supplements them) with as-built 3D geometric information to minimise delays. By providing reliable progress data of on-site activities, Laing O'Rourke has been able to identify issues that may have caused significant delays. This information is a crucial component of a progress monitoring process as it is timely, detailed, objective, and repeatedly queried at no additional cost. [10].

4.3 Progress Tracking Automation Benefits

BuiltView provides an innovative progress tracking framework that integrates LiDAR and 4D BIM (3D BIM + schedule) [11] as well as 5D BIM (3D BIM + schedule + cost) [12]. Even when BIM is not present in an appropriate format, which is a common aspect of infrastructure and linear projects, BuiltView provides scan to scan comparisons using proprietary point-based algorithm to report temporal changes on projects[13].

Aside from the traditional progress checks of built elements, Laing O'Rourke was successful in tracking earthworks using BuiltView on a 155 km highway upgrade project, one of the largest public infrastructure projects in Australia. By running daily scans and progress checks, the project was capable of accurately detecting schedule delays and make data-based decisions to rectify the issues, boosting overall productivity and mitigating potential budget overruns.

5 BuiltView for Fast, Accurate and Timely Documentation

Data acquisition time for LiDAR in comparison to multiple site walks can be 2-10x faster [14] depending on the hardware used (terrestrial tripods, drones or mobile scanners). As a result, construction professionals are potentially able to document 10x the amount of information [14]. Intuitively, with more high-quality information, data-based decision making becomes easier and more efficient. With BuiltView's high-end processing capabilities, the data size can be reduced by half through de-noising and de-cluttering point clouds and by creating meshes and

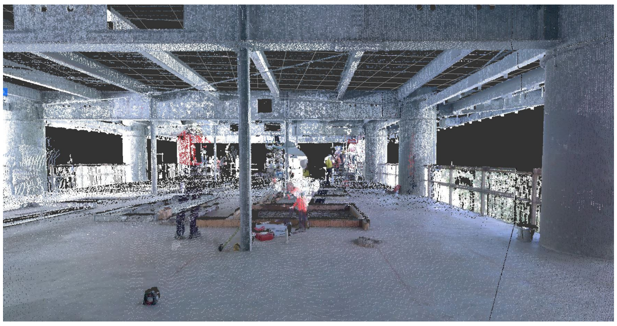

Figure 7. An example of point clouds of construction sites, cluttered with equipment and moving personnel.

as-built models. An example of cluttered point clouds is shown in Figure 7.

5.1 As-Built Models for Pre-construction Phase

During the pre-construction phase, the various parties involved in a project collectively define the milestones of the project, based on the expected duration of completion and the available budget. With LiDAR data, heritage buildings were captured with great detail on a number of Australian heritage buildings renewal programs. BuiltView's fast and accurate validation of existing as-built models prior to construction using LiDAR data was invaluable, as it served as the foundation for all works to come. Capturing the intricate architecture of these legacy buildings would have otherwise proven prohibitively slow.

In short, the engineering and risk analysis conducted before starting construction is significantly improved by leveraging accurate as-built data. BuiltView's intelligent system is capable of facilitating the production of as-built models, which clearly improves project performance. In fact, according to recent studies [15], when project definition work is conducted properly, both project schedules and costs are reduced by approximately 20%.

5.2 As-Built Models during Construction Phase

There is a growing requirement for contractors to deliver as-built models during the construction phase or projects, as they progress from one milestone to the next. To streamline this, BuiltView provides a semi-automated workflow for updating the position of BIM components based on point clouds. Compared with manual updates, BuiltView is capable of quickly producing accurate conformance reports that reduce the amount of time designers need to spend eye-balling point clouds to detect variances (see Figure 3. It also reduces the amount of time project engineers have to spend verifying the resulting as-built model from weeks to a few days.

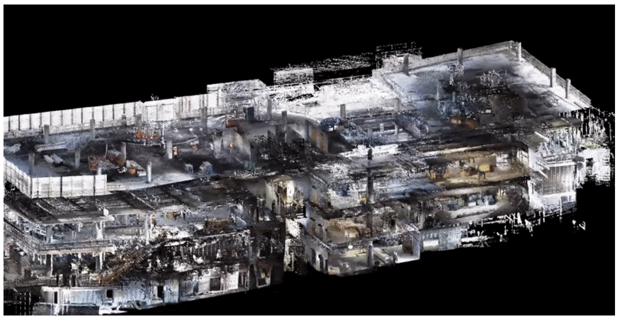

Figure 8. Multi-Level Buildings can be captured in one day with terrestrial LiDAR scanners, and in under an hour with mobile LiDAR scanners (see Figure 8). Using the correct hardware for the correct use case is a key reason for Laing O'Rourke's success in implementing BuiltView

5.3 As-Built Models for Post-construction Phase

It is evident that handover of 3D as-built documentation, whether in the form of a model or a point cloud, is becoming increasingly common in construction contracts. As research and case studies continue to prove the value of objective as-built data, this trend will no doubt continue to grow. As a facilitator of this data, BuiltView is invaluable for closing the loop on learning from one project to the next. We expect opportunities will continue to arise for BuiltView to reduce rework costs, improve productivity and facilitate transparency and accountability within construction. Most recently, following the devastating 2019 Australian Bushfire Season, LiDAR was used to rapidly capture a massive geographic extent for detailed mapping and documentation of the impact of these fires [16]. Laing O'Rourke was appointed by the New South Wales Government of Australia to undertake the first phase of fire recovery clean-up works, and it will leverage BuiltView to rebuild the local community assets with extraordinary performance.

6 Conclusion

In this paper we presented BuiltView, a digital progressive assurance tool that provides construction projects with accurate and timely verification of as-built conditions when compared with design. The tool leverages LiDAR and BIM technologies to provide insights that have been proven useful across multiple project phases and disciplines. Through real-life use cases undertaken at multi-million dollar projects for the international contractor Laing O'Rourke, we showed how BuiltView has been an invaluable asset for reducing rework, boosting productivity, and providing indisputable documentation. By providing an accurate, regular digital representation of as-built conditions, we believe BuiltView will be a key enabler for digital twins in the near future. Moreover, by providing an accurate, objective measure of construction progress, we forecast that BuiltView will play a key role in enabling the industry-changing efficiencies of smart digital contracts.

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