Using terrestrial laser scanning technology to assess the quality of prefabricated concrete modules

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ABSTRACT
The main objective of this study was external facade deviation analyses applied to prefabricated off-site concrete modules. This article is decomposed into three main parts: the first part is dedicated to the introduction and the research background. The second part explains and details the construction project, the off-site factory, the modules as well as the use of a terrestrial laser scanner. A Framework and a data acquisition layout are also exposed. The third part elaborates, in addition to the discussion and study limitations, the main key results which were obtained. The bulging effect on the bottom half of the modules can be explained by the fact the greater the quantity of concrete is poured, the more the inside pressure of the formwork increases, exposing the mould's structure to additional deformations.

KEYWORDS
Terrestrial Laser Scanning; Modular construction; Quality Assessment; Deviation Analysis; Prefabricated Prefinished Volumetric Construction;

INTRODUCTION
Modular off-site construction is a building method organised in a repeatable, standardised, and systematised way. In that way, prefabrication, robotization, automation, digitalisation and continuous improvement are often used. Industrialising off-site construction comes with its benefits and drawbacks, with numerous studies documenting the potential benefits of safety, security, site cleanliness, production time, cost, quality, and waste improvements. (Attouri et al. 2022; Bertram et al. 2019; Marte Gómez et al. 2021). The off-site prefabrication processes and technologies have allowed this type of construction to experiment with real projects in Europe, North America, Australia, and Asia.

As of 2020, according to The Prison International Observatory, France had a total of 187 correctional facilities in service (OIP 2020) that all suffer from continuous overpopulation. To address this persistent issue, over 30,000 new places have been built in the last 25 years, representing a 60% growth of the French correctional facilities (OIP 2016). The next step is to increase once again its capacity by 8000 more places by the end of 2027, meaning that the construction sector will have to offer newer and faster building solutions. Modular off-site construction is being considered for the building of new correctional facilities in France.

This article is organised as follows. The research background is first established to identify and assess the research gaps, in the scientific literature, on the use of terrestrial laser scanners in the quality assessment of prefabricated construction. After the research background, the paper presents the data path and the article's case study, which mainly focuses on wall flatness and verticality analyses, as well as a floor flatness analysis. These analyses allow the quality assessment of the concrete modules. The lessons learned from applying the terrestrial laser scanning technique for quality assessment, the limitations of the present research work, and possible future directions for research are presented in the discussion section before concluding.

RESEARCH BACKGROUND

Offsite prefabricated modular elements are rapidly gaining traction in the construction industry as a viable alternative to conventional construction methods. Product quality and dimensional verifications are still being carried out manually. Dimensional and quality traceability are long and tedious tasks. Experience has shown that these methods are insufficient and do not represent, with precision, the true geometry of objects. For these reasons, terrestrial laser scanning technologies are being incorporated into the construction industry.

Terrestrial laser scanning technology evolved from the fusion of Light Detection and Ranging (LIDAR) with photogrammetry technologies (El-Omari and Moselhi 2008). On construction sites, automated data acquisition can be done with the help of technologies, such as IoT sensors, and terrestrial laser scanners that have the potential of monitoring and surveying schedules, costs as well as progress reports. (El-Omari and Moselhi 2011).

On a construction site, once automatic data acquisition technologies are in place on a construction site, as-built deliverables can then be evaluated. Every technique used to capture the 3D of objects or of construction components was studied and compared in terms of accuracy (Golparvar-Fard et al. 2011). The modular construction sector has already trialled the terrestrial laser scanner technologies for case studies, involving; (1) precise positioning of foundations before prefabricated concrete retaining walls were installed (Li et al. 2020), (2) the documentation as well as the comparison of rebar cages and anchor bolts to digital models in the BIM environment (Hajian and Brandow 2012), and (3) quality control for structural analyses and inspections (Randall 2011).

The subject of quality control tolerancing gained popularity with the potential collaboration of BIM and terrestrial laser scanner technologies (Kim et al. 2014). Comparison frameworks between BIM and 3D laser scanning were established. Thus, tolerance control reference systems are being implemented, such as ASTM E1155-20 (ASTM 2020).

MATERIALS & METHODS

Objective

The main objective of this study was external facade deviation analyses applied to prefabricated off-site concrete modules.

Materials
The case study, evoked in this paper, is based on a modular complex. This new facility will be built, to a percentage, from prefabricated modules made off-site in a separate temporary factory. This inside-project experiment was also a pilot study to outline the feasibility of using offsite construction.

A temporary prefabrication factory was created to build the modules off-site. The factory's building is a warehouse capable of hosting the 3D concrete module's production line. Each module, 25 tons for the heaviest, had to be moved along the production line to be completed. An overhead crane was also needed to carry the modules, pieces of equipment, and materials along the assembly line. The warehouse's floor also had to be well-dimensioned to receive the load of the heavy modules (sufficient surface area and flat).

The modules were built symmetrically to one another, facilitating and creating dedicated accessible connection spaces for the electrical, plumbing, and water evacuation ducts. For safety and durability reasons, concrete was used.

To gather numerous point clouds of the as-built modules, a terrestrial laser scanner, the Trimble X7, was used. During the data collection phase, the terrestrial laser scanner was mounted on a lightweight tripod at 1.5m from the ground level. The scans were performed with the maximum available accuracy in the "Standard" scan mode. The picture quality was on the "quality" setting. Each scanning operation took 8 minutes and 39 seconds to complete, creating 125 million-point clouds per scan. Moreover, the scanner has the ability to level itself, meaning it compensates for any errors due to the positioning of the equipment on the ground.

Methods
Automated quality evaluations of precast concrete components utilising a terrestrial laser scanning device were previously studied (Wang et al. 2016). The use of laser scanning with the BIM for dimensional and quality examination, on full-scale precast concrete objects, has also been demonstrated, through a six-step process, for comparing, extracting, and evaluating laser scanning to the BIM data (Kim et al. 2016).

For compatibility and convenience, the software solution utilised for the study was also from the same company as the laser scanner (Trimble RealWorks). The method proposed in this case study is based on the two previously-cited papers. The proposed framework has been adapted to correspond to the Trimble workflows and recommendations. Moreover, for confidentiality reasons of the module's digital model, the comparison between the as-built modules and the as-designed modules is not yet studied. This part had to be cut out from the existing frameworks.

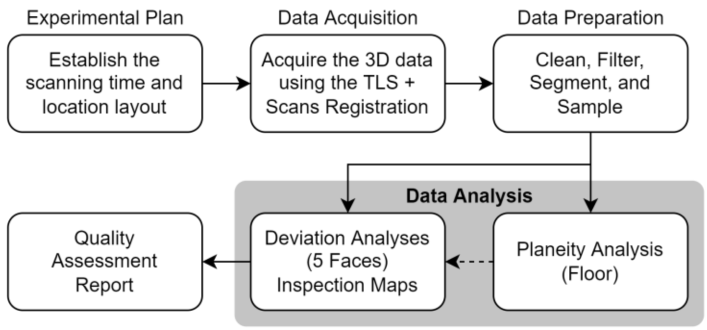

Figure 1: Proposed framework

The steps proposed in **Figure 1** are the following:

1. Establish scanning time and location layout to be able to scan the modules and gather enough data to examine the external surfaces of modules;
2. The terrestrial laser scanner is used to acquire the 3D data, followed by the scan registration process merging all the captured data together;
3. In order to obtain a usable dataset, the 3D data has to be cleaned (areas that are not studied), filtered (points corresponding to noise), segmented (by faces), and sampled to reduce the size of data while keeping the meaningful information in the point cloud;
4. The data analysis step covers the floor, walls, and ceiling deviations analyses of a module;
5. Finally, a quality assessment report can be generated for each element, then aggregated for each module.

RESULTS

Data Collection

Most of the time, the modules were idle because the modules were not continuously moving along the production line. The work presented in this article only focuses on controlling the exterior properties of the modules. To avoid the quality control being biased by the workers during scanning, the most appropriate time was chosen for the data collection, which was after the concrete floor had been poured and cured because the modules were empty and raw (only concrete).

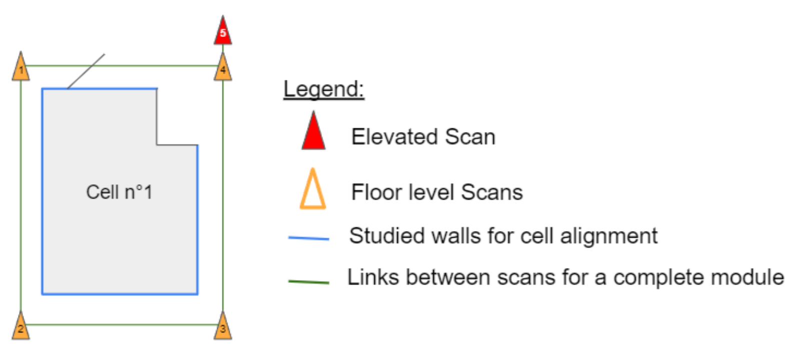

Figure 2: Scanning location layout

Figure 2 shows the exterior location layout for the scans of a module. The first four ground-level scans, at each of the corners, scans n°1 to 4, allow for each wall to be documented. The fifth scan, elevated compared to the others, scan n°5, allows the ceiling to be examined. The module underside will be extracted by a proxy measurement of the factory's floor.

Data Preparation

Registration

The field registration process of the laser scanning measurements begins with the data being brought into a common coordinate system (Gergana, 2015). Registering the scans to one another is now an embedded functionality within the software solutions.

Filtering

The registered point clouds of the factory, englobing numerous modules, comprised 3 billion points from 24 scans. 33.000.000 points correspond to the factory's floor laying area, and an average of 60.000 data points were retrieved for each studied module. Only the main interest points, such as the mould, the floor laying area and the modules, were adequately scanned, meaning that the distances between the scanner and the studied elements were always reasonable (less than 5m).

Segmentation and Cleaning

For the study, a segmentation was needed to break up the modules into their four walls and ceilings. Then, the sub point clouds were cleaned. All points which weren't useful or out of the scope of this experiment were eliminated, such as (a) the barred windows, (b) the embedded lifting and anchoring brackets, (c) the surface where the technical connections are, (d) any tools and materials lying around, and (e) the door and its frame. This step was to ensure that the deviation analyses were only considering the concrete surfaces without anything else interrupting or falsifying the measures.

Spatial Sampling

Finally, a spatial sampling of each element, with a resolution of 7 mm, was performed to homogenise the point cloud throughout the surfaces. The sampled versions of modules have, on average, one-fourth of the quantity of the initial point cloud.

Data Analysis

Ground Planeity Analysis

The level of flatness of the underside of a module was obtained by proxy measurements to the floor pouring area under the same module. This flatness level indicates the risks of the modules being not correctly installed once they are stacked on top of one another. No general slopes were observed for the entire factory's floor pouring area. However, when considering the area under the module itself, deviations were measured. The Z deflection values are -0.57mm, +0.09mm, +5.05 mm, and -0.85 mm on the four ends of the module floor, i.e. 6 mm over the 8.5 meters length of the module. This is a bias that has to be considered in the next sections.

Faces Deviation Analysis

For our case study, five of the external sides were directly studied. Data from the underside of the modules couldn't be gathered because of safety concerns and potential delay for in the construction process. As told before, module undersides are the direct symmetries of the factory's pouring floor.

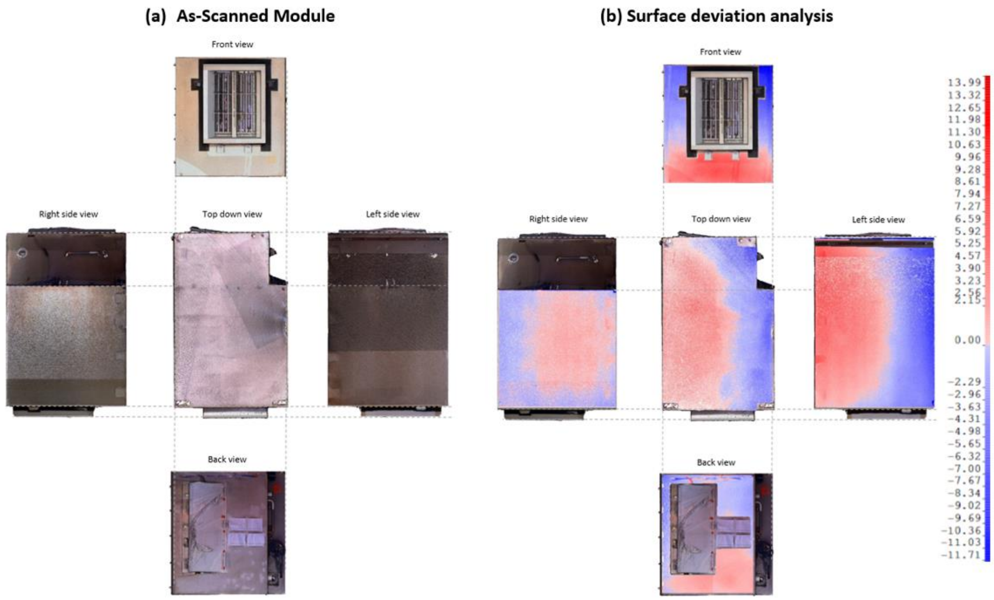

Figure 3: Steps for data processing the scans

Figure 3. shows the two steps of the data processing phase. Each step is shown through an aggregate of the five studied surfaces (left, right, top, front, and back). Part (a) shows the laser scanner acquired and registered data of a modular module. Part (b) illustrates the deviation analysis applied to each surface.

On average, the overall quality of the studied module surfaces respected the tolerances fixed by the construction team. However, at first glance of part (b), apart from the back wall, slight bulges appeared on the lower half of each wall. Parallel slopes were also observed, which could be explained by the orientation default identified in the previous section. The left side wall, which is also the longest, was the one showing the most positive deviations. 3% of the front wall of this module suffered a negative bulge exceeding a -10 mm threshold, identifiable in the top right-hand corner. This single deviation could be explained by an erroneous manual adjustment of the formwork. On the studied sample of modules, few required some more attention and none have yet been rejected.

DISCUSSIONS & LIMITATIONS

The registration phase was tedious because of the complexity, resilience, and repetitiveness of the factory's dynamic environment. The automatic registering of the scans would often fail, asking the user to manually initiate the registration process, causing an increase in operation time. Furthermore, some of the scanning positions were unreachable. The placements of the modules within the factory very close to each other, and the 0.6m radius buffer zone of the TLS did not allow for optimal data acquisition. Spacing out the modules, in a specific area for quality assessment, to a minimum required distance of 1.2m, would be sufficient to ease of the data collection. However, the current storage capacities of the factory would be impacted.

During the scanning process, off-the-shelf software and hardware solutions from a single editor were used. These solutions had some smart functionalities that were neither presented nor studied in this article. A comparison between off-the-shelf solutions illustrating the different approaches towards quality control should be done. The entire off-site construction industry could also beneficiate from these new data collection methods if, one day, they appear to be included in the building assessment regulations.

The bulging effect on the bottom half of the modules can be explained by the fact that the greater the quantity of concrete is poured, the more the inside pressure of the formwork increases, exposing the mould's structure to additional deformations (Gamil et al. 2021; Ovarlez and Roussel 2006).

CONCLUSIONS & PERSPECTIVES

The adapted framework proposed in this article was tested in our case study during an on-site, or rather factory, experiment. The results indicate qualitative and quantitative data extraction from a terrestrial laser scanner, providing useful information on the quality assessments for a carceral facility case study. The analyses of the modules show regular deformities in the lower half of the structures. Our work has confirmed that the use of terrestrial laser scanners to improve on traditional tolerance guidelines in international standards. These new tools provide the construction industry with better and more accurate data.

The work presented in this article only shows the analysis of a single module. This module's results illustrate the expected deviations and qualities which are to be expected from the current formwork. The results generally show the bottom half of the walls are bulging. A total of 6 fully scanned and precise modules have been extracted from the main factory's point cloud. The scalability of the quality control with the proposed method is also possible, with the addition of two extra scans per consecutive module to the proposed scanning layout.

As a perspective of this research work, BIM models of the designed modules could be used to compare the point clouds of each module to a reference model. Consequently, a full 3D analysis could be performed. Not only the surfaces could be analysed, but also the angles between two consecutive faces and the position of the technical connections. A full 3D compliance of the as-built module with the as-designed module could then be achieved. Finally, automating the whole data acquisition process is also a perspective of this work.

ACKNOWLEDGEMENT

We would like to thank the industrial partner Bouygues Construction for supporting the research done in the Construction 4.0 Chair of Centrale Lille. This industrial research chair is also co-financed by the European Metropolis of Lille and the European Union with the European Regional Development Fund.

We also thank the construction team of the factory, Amaury MASSIN and Philippe BAILLY for their time and knowledge sharing, as well as Ludovic REVERDY for having initiated the work.

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