APPLICATION OF DIGITAL TECHNOLOGIES IN THE ASSEMBLY CONTROL OF STEEL STRUCTURES

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ABSTRACT

In the industrialization of the construction of metallic structures, quality control procedures are required, both for manufacture and assembly. The structural control and validation in the construction phase aims to identify the geometric deviations that may occur during its assembly, as well as to ensure the compliance with all requirements and tolerances essential to the operation of the structure. In this context, the application of digital technologies emerges as a resource to support stakeholders in the construction process, since these quality control procedures, although essential, are characterized as being time-consuming, difficult to document and prone to error. After the study of the technologies associated with automation and geometric verifications of the objects, the methodology followed was the analysis of a case study, by comparison of the structural models of manufacture and assembly. A steel structure was analyzed, using computational tools and digital survey technologies. The results obtained allowed to conclude that the use of digital technologies contributes positively to the automation of control procedures and geometric validation of metallic structures, both in the manufacturing and assembly phases.

Keywords: *Steel Structures, Digital Technologies, Geometric Validation.*

1 INTRODUCTION

Currently, the use of digital technologies on the market is required by the simultaneous demand for a decrease in production costs and an increase in productivity. This paradigm is part of the so-called fourth industrial revolution, the so-called Industry 4.0, whose benefits are visible in several areas, including civil engineering. Consequently, there is a need to adapt and reinvent the methods of work, with the aim of reducing the difficulty of performing tasks and their cost, as well as increasing profitability and productivity. In the field of civil engineering, steel structures are one of the solutions used in the construction of buildings. However, to ensure the quality of the execution of these structures, a strict control and verification procedures should be carried out at different stages of the construction process. The first verification is related to the manufacturing phase of the structural elements and aims to ensure the conformity according to design. The second is related to the construction phase, with the aim of ensuring that any deviations that may occur during on-site assembly comply with the requirements and tolerances provided by NP EN 1090-2:2020 standard. It is considered that the application of digital technologies in the management of geometric information, such as BIM and the automation of geometric survey on site, support technicians in the necessary structural checks, in a more effective way, with less probability of error and in less time, both in the manufacturing phase and in the assembly phase. This study aims to highlight the importance of the parameterization and automation of the control procedures associated with the verifications and validations mentioned above. To achieve the defined objective, and based on a case study, comparative analyses were made focused on the assembly phase of metallic structures with the support of digital technologies. Specifically, checks were performed by comparing the digital model of the assembly on site with the digital model of the project.

2 STEEL STRUCTURES AND DIGITAL TECHNOLOGIES

2.1 Steel Structures

Currently, we can say that the execution of metallic structures is defined through two essential processes - manufacturing and assembly - both provided by the NP EN 1090-2:2020 standard. This standard also specifies the technical requirements for the execution of steel structures, with the aim of ensuring adequate levels of mechanical strength, stability, usability, and durability. In (CT 182, IPQ, 2020; Santos & Silva, 2011; Alves, Francisco, 2021), the requirements for the execution of hot-rolled steel structures are provided, addressing the classification of steels, purchase, reception, traceability, cutting, drilling, straightening, factory assembly, welding, manufacturing control, tolerances, non-destructive testing, corrosion protection, on-site assembly, among others. For the validation of the structural model of manufacture and assembly it is essential to have knowledge of the acceptable geometric tolerances at each stage of the structural execution process. NP EN 1090-2:2020 distinguishes essential tolerances from functional tolerances. The essential geometric tolerances are defined as the fundamental limit to be met to respect the mechanical strength and stability of the structural design. Meanwhile, functional geometric tolerances are defined as the limit to be met to respect its structural function, excluding mechanical strength and stability and despite the appearance or geometric fit.

2.2 Digital Technologies

The process of assembling a steel structure requires a high number of tasks in the execution, subject to error and / or deviations from diverse origins and from geometric origin. Thus, the conformity of the structural model of the assembly requires validation with its structural model of manufacture. Automation and the use of digital technologies that allow structural surveys may be a more accurate resource in the identification of dimensional and geometric deviations, reducing the time required for structural validation. According to (Seungho, Sangyong, & Dong-Eun, 2020; BIM, Task Group, 2013; Autodesk, s.d.) there are digital technologies that allow the performance of precise surveys of objects and spaces, through the generation of point clouds, with the recording of 3D geospatial data. These authors also present some rules for greater accuracy in the survey.

A point cloud is a set of geometric points, which are defined as a digital model of a structure. It provides information regarding the detected object, space or structure, since each point contains the geospatial coordinates and color, in case they are photographed by the equipment (Mois, 2020; Sousa, 2021; Razali, Ahmad Firdaus; Majid, Zulkepli; Mohd, Farid ;, 2022; Campelo, Tiago, 2020). It can be achieved through two digital technologies that involve the use of high-quality optical systems, namely, LIDAR (*Light Detection And Ranging System*) and Photogrammetry. The LIDAR system allows remote laser measurements to be made. The LIDAR sensor is a laser that does remote scanning sensing. It is widely used to obtain geospatial information, as it can measure and obtain the actual distance between the different constituent objects of the swept space. It is characterized by the survey and measurement made *in situ* by laser scanning and the subsequent three-dimensional digitization of its information. The characteristics and properties of the scanned objects are obtained due to the existence of a 3-coordinate internal detection system (Campelo, Tiago, 2020).

Terrestrial laser scanning (TLS) is a 3D scanning in which tripod-mounted laser scanners are used to capture large objects and environments. The technique is already used in construction, topography, and other disciplines. Also known as long-range laser scanning, TLS involves deploying a scanner in a static location, while other laser scanners can be portable or mounted on vehicles to capture data from various perspectives. These 3D scanners are often called LIDAR scanners, although ground-based scanners are not the only type of scanner to use the technology.

TLS scanners can record the various points in two different ways: 1) Through the emission of laser beams, the device measures the distance traveled, considering the time it took for the beam to return to the emitting origin, after being reflected; 2) By emitting the pulsation of laser beams, the device measures its wavelength. Sweep lifting can be performed using one of the following techniques: i) Triangulation-based laser measurement; ii) Rotation of the reflection mirror of the TLS, which rotates around an axis, covering several angles, while the laser is rotating. In the point cloud processed by the laser scanner, each point represents the object/space/structure where the laser was reflected and has the 3D coordinates known as *X, Y, and Z*. Although no geographical or geometric information is provided when defining the point cloud, it is possible to obtain the Cartesian coordinates of a plane, the length, width and height of the swept object and its color (Seungho, Sangyong, & Dong-Eun, 2020; BIM, Task Group, 2013; Leica, 2022, s.d.). With the use of laser scanners, different digital models can be obtained, such as: drawings or 2D views; 3D models; point cloud; 360° photographs; detection of inconsistencies between models; Videos; augmented reality.

According to (Campelo, Tiago, 2020) in the use of a laser scanner is essential to consider the following steps: a) Preparation - Prior visit to the site to know the dimensions of the structure to be raised, in order to define a forecast of the execution of the works, i.e., to know how many surveys will be necessary for a correct reading and where the scanner will be located; Definition of the density mode of the point sweep according to the dimensions and characteristics of the structure; b) Use – Recognition of the limits of the equipment to be used, so as not to make it difficult to obtain the points to be raised ; Placement of in *situ targets* for subsequent georeferencing; c) Information processing – Verification of the connection of the different point clouds, georeferencing of the targets placed and export processing; d) Error Control – Check the error report of the software used in the processing of the information collected and verification of the digital model through different visualizations; e) Precision control in modeling and export - Comparison between the various models, recording of deviations between them and export of the final model.

3 METHODOLOGY

The methodology adopted in this work allowed to analyze and evaluate the application of digital technologies to a case study, related to the construction of a steel structure of an industrial building.

For the comparison between the manufacturing and assembly models of the steel structure studied, the Revit software was used for the 3D modeling of fabrication and the BLK 360 laser scanner for the point cloud survey of the model of the structure assembled on site.

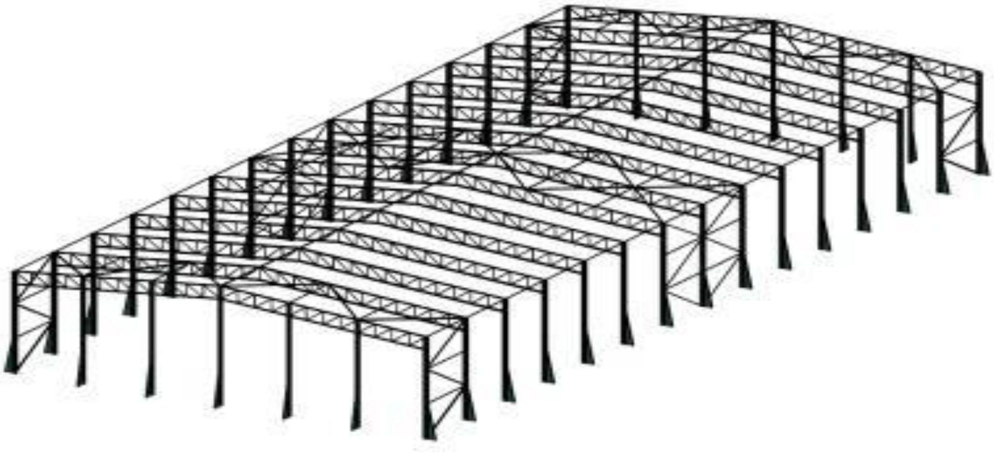
For the evaluation of the automation of control and verification procedures in metal structures, the manufacturing and assembly tolerances referenced in NP EN 1090-2:2020 were considered.

4 RESULTS

4.1 Case Study

In the scope of the case study, a metallic structure of an industrial building under construction was analyzed, whose 3D structural scheme is presented in Figure 1.

Figure 1 – 3D model of the steel structure



The industrial building studied has a rectangular geometry of 46x105m^2 in plan, a variable height between 13m and 15m and a two-sides roof. The metallic framed structure consisting of metallic columns in IPE/HEA/HEB profiles, founded in reinforced concrete, and truss metallic with ropes in HEA/IPE profiles and diagonals in tubular profiles in CHS/SHS. Aiming at the functional and overall behavior of the structure, for the validation of the various structural elements, the criteria, parameters, and permissible assembly tolerances were previously defined. As for the geometric tolerances of assembly, the NP EN 1090-2:2020 standard was adopted, namely those indicated in its Annex B. Then, summary tables were elaborated in Excel sheets to record the deviations found in the different structural elements under study and after the survey carried out on site.

4.2 Laser Scanner Survey

The survey of the steel structure mounted on site was carried out using LIDAR technology (TLS) by Leica's BLK 360 laser scanner. BLK 360 laser scanner (Figure 2) is an equipment that differs by having: an independent wireless connection; ability to collect information at a 360° angle; three digital cameras with HDR (High Dynamics Range) imaging; internal storage capacity of 64 GB; maximum laser range is 60m and the minimum distance is 60cm; scanning capacity of 360,000 points/second; three levels of density modes (Figure 3).

Figure 2 – BLK 360

Source: LEICA (Leica, 2022, s.d.)

Figure 3 - BLK 360 density modes

Density Mode	Resolution (at 10 m)	Scan Duration (Min)
Low	20 mm	02:55
Average	10 mm	03:30
High	5 mm	05:20

Source: CAMPELO (Campelo, Tiago, 2020)

In summary, the BLK 360 laser scanner captures the world around with 3D panoramic images superimposed on a high-precision point cloud. Through Leica Cyclone Field software, BLK 360 transmits images and digitized data from point cloud to a mobile device in real time.

The steps referred in section 2.2 were followed in the survey of the steel structure of the case study. Given the geometric dimensions of the industrial building, to ensure a high density in the resolution of the point cloud, and to optimize the time required for the digital survey, it was planned to survey only the frame of one of the façades of the industrial building, in an extension of 46m, as shown in Figure 4.

The use of BLK 360 at the construction site should not be initiated without the marking of targets, placed on the columns (Figure 5), which posteriorly were georeferenced by a local survey. The purpose of georeferencing the targets is to serve as a support when exporting the point cloud processed by BLK 360.

Figure 4 - Planned scans for the façade survey (based on a plan view of structural scheme of the industrial building)

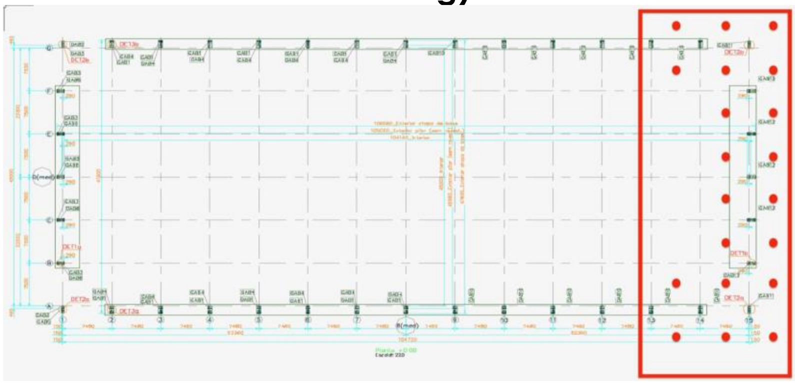


Figure 5 – Target 1 marked on a column

After the placement of the targets, photographs of the structure were taken *in situ*, either through the BLK 360 (Figure 6) or through a photographic camera (Figure 7).

Figure 6 – Photograph of the structure with BLK 360

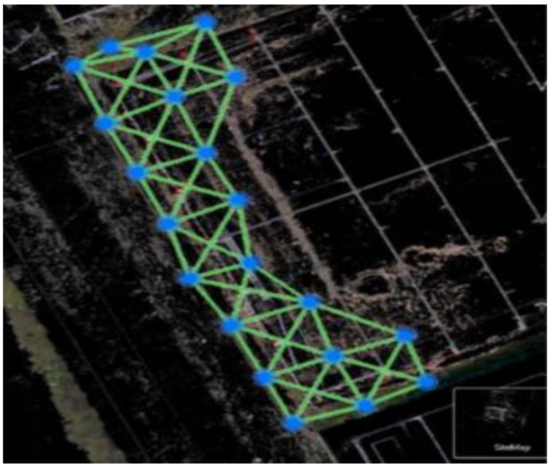
Figure 7 - Photograph of the structure with camera

The survey made with the BLK 360 was supported with the use of Leica's Cyclone FIELD 360 application installed on an iPad. Independently of the changes on the location of BLK 360 station, the links between the various scans are processed in the Cyclone FIELD, identifying any resolution inaccuracies. This methodology facilitates the processing of the point cloud, avoiding the repetition of the in-situ survey. In this case study, 21 scans were performed (Figure 8).

This was followed by the information processing, Information processing followed, targets were georeferenced, errors were controlled, and scans were exported. All the processing of the information collected *in situ* was performed at office, through a high-performance computer, since the survey made generated 25 GB. To ensure a point cloud with the highest possible resolution, the connection between the various scans was performed, joining all those that are nearby. This link is digitally visible through a green line segment (Figure 9).

Figure 8 – Mapping of scans performed in *situ*

Figure 9 – Mapping of scans after analysis of the various connections

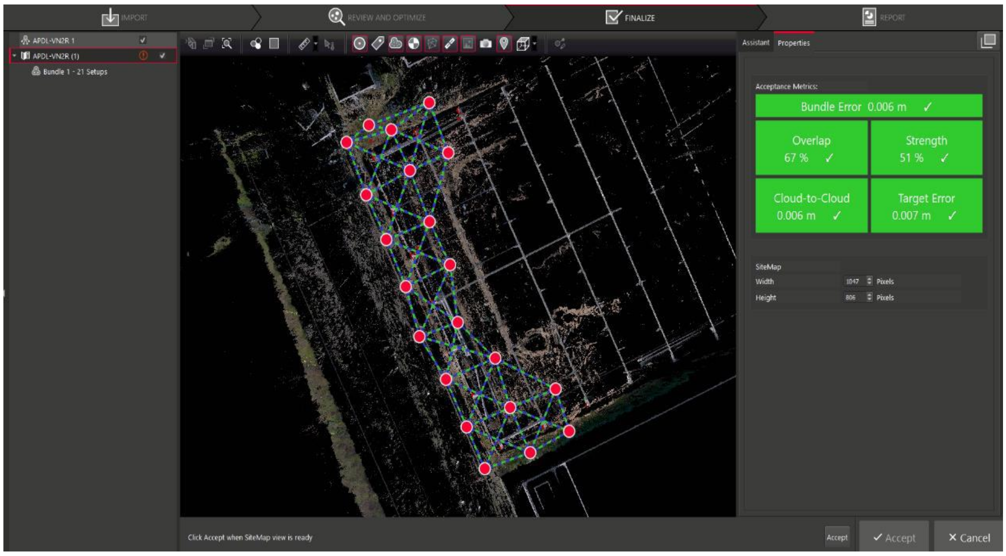


In the Cyclone Register, the points corresponding to the targets, whose topographic coordinates were referenced and marked. Each target and corresponding x, y, z coordinates were encoded and referenced by the surveyor using an automatically imported .txt file (Figure 10).

Figure 10 – Targets marked in the Cyclone Register software

This was followed by the error control stage, where the error report generated in the Cyclone Register derived from the processed point cloud was analyzed. In this stage, the accuracy of the digital model was controlled through visualizations in cut and plan views of the structure assembled *in situ*, giving due attention to the error rate (Figure 11).

Figure 11 – Point cloud error report



Acceptance Metrics:
Bundle Error 0.006 m ✓
Overlap 67 % ✓
Strength 51 % ✓
Cloud-to-Cloud 0.006 m ✓
Target Error 0.007 m ✓

SiteMap
Width 1047 Pixels
Height 806 Pixels

Click Accept when SiteMap view is ready

🟩 Max error of 0.015 m. 🟨 Max error of 0.020 m. 🟥 Error greater than 0.020 m.

After controlling errors and the accuracy of the modeling, the next step was the export. The format ". *rcp*" was chosen for the exported file, so that it can be used in Revit. In addition to the exported file, an error report was generated to identify the errors in the connection between the various scans, to allow better interpretation of the model of the scanned structure. Figures 12 and 13 show two views derived from the export of the point cloud generated in this case study.

Figure 12 – Exported as-is model: overview of the assembled structure

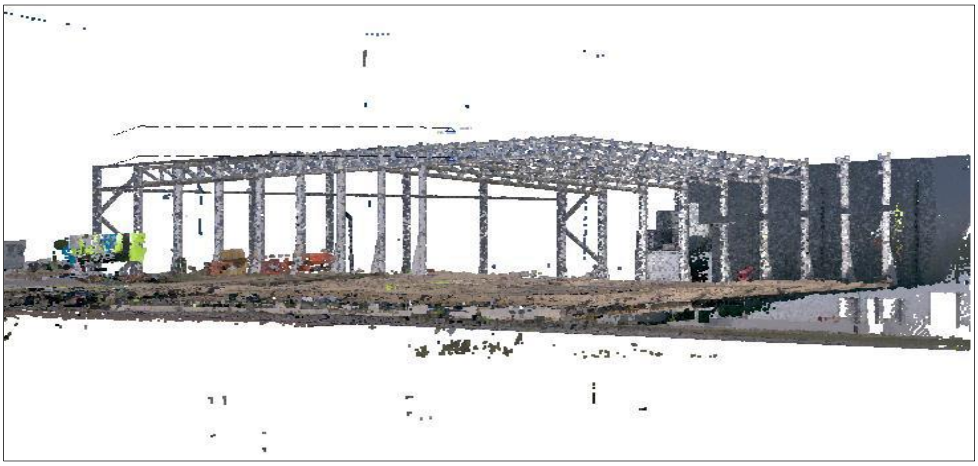
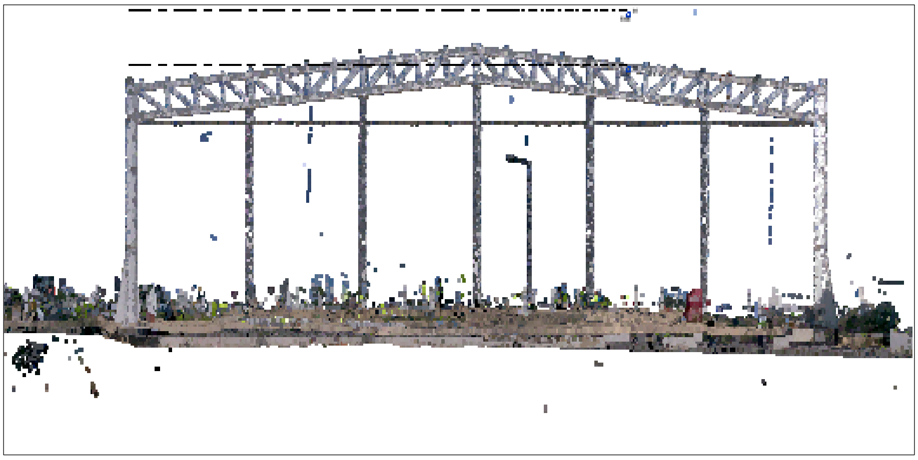


Figure 13 – Exported as-is model: view of the façade frame of the structure



4.3 Verification of structural models

Without losing the focus of the main objective of this study, it was performed the analysis and comparison between the structural models of manufacture and assembly.

The analysis was carried out in two stages: the overlap and the verification. The first stage consisted of overlapping the point cloud model of the structure assembled *in situ* with the 3D model of the manufacturing structure. It was found that the point cloud contained export errors that prevented a perfect overlap between the *in situ* and 3D structure models. However, it was possible to obtain the digital model of the overlap, as shown in Figure 14, as well as the digital models of details 1 to 5 marked and illustrated in Figures 15, 16, 17, 18 and 19.

Figure 14 - Overlapping of point cloud and design models

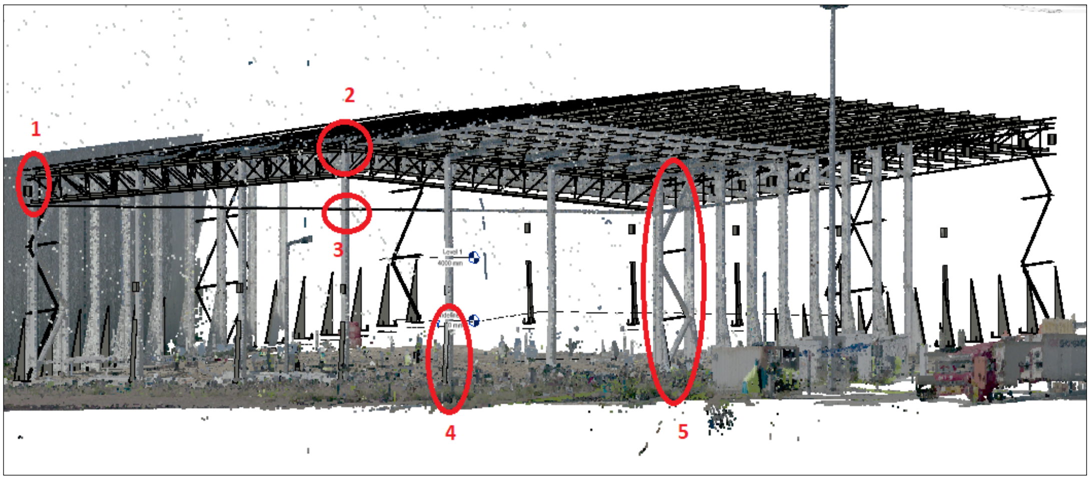


Figure 15 – Detail 1

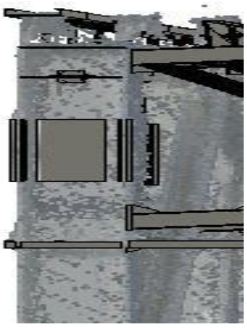


Figure 16 - Detail 2

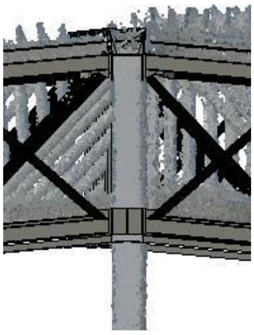


Figure 17 - Detail 3

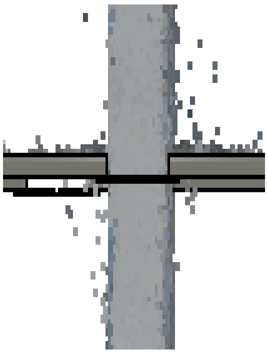


Figure 18 – Detail 4

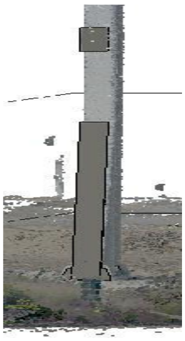


Figure 19 – Detail 5

In the second stage, the Excel generated tables were used in the verification, where the criteria and parameters contained in the NP EN 1090-2:2020 standard are indicated. These criteria are related to the columns and overall structure. Regarding the beams, given their altimetric levels, it was not possible to obtain an acceptable resolution. In the context of the parameters related to the overall framed structure, Table 1 presents the allowed and found in *situ* deviations.

Table 1 - Permitted and found *in situ* deviations - overall framed structure

Criterion	**Parameter**	**Deviation permitted in functional tolerances Δ**		**Deviation found**
		Class 1	**Class 2**	
Height (h)	h ≤ 20m	Δ = ± 20 mm	Δ = ± 10 mm	Δ = 15,7 mm
Column connection	Unintended eccentricity (For any axis)	Δ = 5 mm	Δ = 3 mm	Δ = 7,0 mm
Columns base	Base level of the column to its axis in relation to its intended position (IP)	Δ = ± 5 mm	Δ = ± 5mm	Δ = 2,7 mm

Within the parameters related to columns belonging to one-story structures, Table 2 presents the deviations allowed in the essential and functional tolerances and those found in *situ*.

Table 2 - Permitted and found deviations – one-story building columns

Criterion	Parameter	Deviation permitted in essential tolerances Δ	Deviation permitted in functional tolerances Δ		Deviation found
			Class 1	Class 2	
Slope of individual columns, in one-story buildings, with inclined girders	Column slope Δ= Δ1 ou Δ2	No requirements	Δ = ± h/150 = 86,7 mm	Δ = ± h/300 = 43,3mm	8,0 mm
	Average slope of all columns in the same frame: Δ = (Δ1 + Δ2) / 2	Δ = ± h/500 = 26,0 mm	Δ = ± h/500 = 26,0 mm	Δ = ± h/500 = 26,0mm	(8,0+23,0) /2 = 15,5 mm
Rectilinearity of a column, of a one-story building	Position of a column in the plane, relative to a straight line defined between the reference points at the base and the top	Δ = ± h/1000 = 13,0 mm	No requirements	No requirements	8,0 mm

In the scope of the parameters related to the positioning of columns, Table 3 presents the deviations allowed in the functional tolerances and found in *situ*. The digital overlap between the 3D model of the industrial building and the point cloud model of the structure assembled *in situ*, not having the best resolution, conditioned the quantification of the deviations found.

Table 3 - Permitted and found deviations - position of columns

Criterion	Parameter	Deviation permitted in functional tolerances Δ		Deviation found
		Classe 1	Classe 2	
Location	Position of the axes of the columns at the base of the columns in relation	Δ = ± 10,0 mm	Δ = ± 5,0 mm	7,0 mm

	to the position of a reference point			
Total length of the building	Distance between external columns in each of the alignments at the base level $30 \text{ m} < L = 46 \text{ m} < 250 \text{ m}$	$\Delta = \pm 0{,}25\,(L+50) = \pm 24{,}0$ mm	$\Delta = \pm 0{,}20\,(L+50) = \pm 19{,}2$ mm	7,6 mm
Spacing between columns	Distance of adjacent columns at base level $L = 7{,}5 \text{ m} > 5{,}0 \text{ m}$	$\Delta = \pm 0{,}20\,(L+45) = \pm 10{,}5$ mm	$\Delta = \pm 0{,}20\,(L+30) = \pm 7{,}5$ mm	8,0 mm
General alignment of columns	Position of a column axis, at base level, relative to an established column alignment	$\Delta = \pm 10{,}0$ mm	$\Delta = \pm 7{,}0$ mm	5,5 mm
Alignment of a perimeter columns	Position of the face of a perimeter column, at the level of the base, in relation to the alignment of the faces of the adjacent columns	$\Delta = \pm 10{,}0$ mm	$\Delta = \pm 7{,}0$ mm	5,5 mm

It should be highlighted that the measurement of the deviations found was performed through Revit, using the *Measurement* function. Considering the deviations found and recorded in Tables 1, 2, and 3, it was stated that some are outside the range of the tolerance values defined in NP EN 1090-2:2020. Moreover, in this case study, the checks carried out took place on a very small-scale values (millimeters), which *per si* conditioned the probability of error.

However, it was considered that the processing of a parametric script for the verification of such deviations would reduce or eliminate the above error.

5 CONCLUSIONS

The study developed, as well as the underlying experience, enabled the learning and knowledge of some digital technologies applicable to the AEC sector and to the validation of metallic structures in the assembly phase. Regarding the verification between the structural models of manufacture and assembly, it was concluded that the process of lifting the structure *in situ*, using the BLK 360 laser scanner, was enriching in terms of the knowledge acquired, regarding the LIDAR technology (TLS). On the

other hand, the tolerances referred to in the NP EN 1090-2:2020 standard facilitated the identification of the criteria and parameters controlled in the digital models. This allowed us to conclude that the digital technologies used are a resource of help to consider in this verification.
Regarding the application of the laser scanner, it was concluded that the quality and density of the point cloud depend on the local and dimensional conditions of the structure and the work. In resume, this study considers that automation and the use of survey digital technologies are a crucial support in the identification of dimensional and geometric deviations in metallic structures.

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