

## LiDAR-Based Framework for Scaffolding Design Rule Compliance and Health Management

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In the construction industry, scaffolding is a temporary structure used to support equipment or workers at height. Scaffolding, a temporary yet critical structure, plays a significant role in ensuring workers' safety. During the installation of scaffolding, specific design rules related to spacing, fall protection, spindle adjustment, and overall geometry are followed to ensure its stability. However, during use, the scaffoldings are often modified either intentionally or unintentionally, which might compromise its stability and safety. Currently, visual inspections are commonly performed by site managers or accredited personnel, which can be tedious. These manual inspections can be prone to error and may fail to detect gradual modifications that deviate from compliance, thereby compromising structural integrity. This paper proposes a data-driven framework for assessing the health and design rule compliance of scaffolding structures. LiDAR scans are used to capture the as-built geometrical structure of scaffolding on a construction site. The objective of this paper is to assess compliance with scaffolding design rules by processing and analysing information obtained from 3D point cloud data. Relevant parameters are extracted from the acquired point cloud data and compared with the original required design rules. The proposed framework is verified using representative design rules and demonstrates the feasibility of quantitative assessment for scaffolding structures. This work enables a way for automated compliance verification and assistance during manual inspection, thereby enhancing overall safety on construction sites.

*Keywords:* LiDAR point cloud data, Design rule compliance, Health management framework, Construction site safety.

### 1. Introduction

Structural design rules are established to mitigate safety risks; however, when such rules are not strictly followed, structures may become vulnerable to instability and failure. European occupational accident statistics show that the construction sector accounts for a high number of fatal workplace accidents, with falls from height remaining a leading cause of serious and fatal injuries. Temporary access structures, such as scaffoldings, are frequently the cause of such incidents due to their direct interaction with workers at height (Eeckelaert, 2025). Scaffolding structures are widely used on construction sites to perform their required function of providing safe

access and working platforms for the erection, maintenance, repair or demolition activities (SS-EN 12811-1, 2004). Despite their temporary nature, scaffolding structures constitute a safety-critical asset due to their direct impact on worker safety and continuity of construction.

Scaffolding structures are assembled, modified, and dismantled repeatedly throughout a project lifecycle to accommodate evolving site conditions. During their use, intentional or unintentional deviations from prescribed design rules might be common (Halperin & McCann, 2004; Mohammad et al., 2023). Even minor geometric deviations can significantly disrupt structural stability, thereby increasing the risk of

structural failure or falls (Goh & Chua, 2010; Halperin & McCann, 2004). Nevertheless, scaffolding structures are often treated as transient installations, resulting in limited emphasis on systematic health assessment once they are put into service (Ramezantitkanloo et al., 2024). Field studies on European construction sites indicate widespread scaffolding non-compliance and associated safety risks (Rubio-Romero et al., 2013). Currently, scaffolding monitoring practices are predominantly manual, periodic and visual, conducted by trained personnel. As a result, scaffold conditions are commonly assessed at discrete points in time without objective metrics to support continuous evaluation or trend analysis (Ramezantitkanloo et al., 2024).

The health of the scaffolding structure needs to be maintained in order to perform its required function. Prognostics and Health Management (PHM) provides a systematic approach by integrating sensing, health assessment, diagnostics, and prognostics to support informed decision-making based on the evolving condition of the structure (Hu et al., 2022; Zio, 2022). PHM emphasizes the use of quantitative indicators to enable proactive rather than reactive health management strategies (Hu et al., 2022; Jardine & Tsang, 2021). Health management is the process of decision-making and implementation of actions based on the state of health derived from monitoring and expected future use of the system (IEEE 1856, 2017). While PHM methodologies have been widely adopted in manufacturing, aerospace, and energy systems, their application in the construction domain, particularly for temporary, reconfigurable, and safety-critical assets such as scaffolding, remains limited (Biggio & Kastanis, 2020).

Framing scaffolding design rule compliance within a PHM framework allows scaffolding to be treated as an evolving structure with measurable health states, rather than static structures subject only to periodic visual inspection. In this context, violations of prescribed design rules can be

interpreted as indicators of degraded health or increased safety risk. Point cloud data acquired through Light Detection and Ranging (LiDAR) offers a robust and repeatable means to capture the as-built geometry of scaffolding. The extracted geometric parameters from the acquired data can be directly mapped to specified design rules, forming the basis for quantitative health indicators that describe the compliance and structural condition of the scaffolding throughout its service life.

The main contributions of this paper are:

1. Development of a LiDAR-based framework for scaffolding design rule compliance assessment.
2. Verification of the proposed framework using real construction site data, demonstrating its applicability for safety-oriented decision-making.

## **2. Background and Related Work**

### ***2.1. Scaffolding systems and structural configuration***

A typical scaffolding system consists of standardized components, including vertical standards, horizontal ledgers, diagonal braces, base plates, decks, guardrails, toe boards, and anchoring elements, as shown in Fig 1. Connections between standards, ledgers, and braces are achieved through a rosette-based wedge system, which enables fixed and variable angular configurations. Rosettes are positioned at regular vertical intervals along the standards, enabling modular three-dimensional assembly, and defined load paths between components (Yu et al., 2003).

Loads applied to the working decks are transferred through ledgers and standards to the base plates and subsequently to the ground. System stability is achieved through diagonal bracing and anchoring to adjacent structures (Layher Allround scaffolding, 2018). Due to their modularity and repeated reconfiguration, scaffolding systems are particularly susceptible to geometric deviations during use.

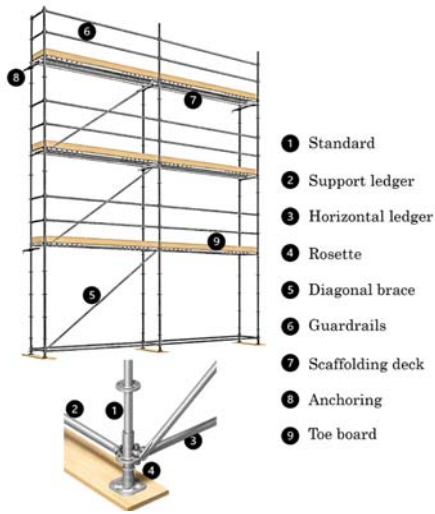


Fig 1. Scaffolding structure, adapted from (Layher Allround scaffolding, 2018)

## 2.2. Scaffolding design rules

Scaffolding safety is governed by a set of prescriptive design rules intended to limit fall hazards and ensure overall structural stability during use. European standards for temporary works, notably (SS-EN 12810-1, 2004) and (SS-EN 12811-1, 2004), specify requirements for geometric configuration, access, load classes, and collective fall protection systems. To support objective assessment, some of the key scaffolding design rules (Layher Allround scaffolding, 2018; MonZon, 2023; SS-EN 12811-1, 2004) are summarized in Table 1.

Non-compliance with the design requirements, particularly missing intermediate rails and toe boards, strongly correlates with an increase in fall incidence (Rubio-Romero et al., 2013). Some of these rules can be expressed as measurable geometric constraints, making them suitable for quantitative verification.

Table 1. Scaffolding design rules

Design rule	Quantitative requirement	Purpose
Distance to façade	$\leq 30$ cm	To prevent fall hazards
Top guardrail height	$\approx 1.0$ m	To provide fall protection by restraining workers
Intermediate guardrail spacing	$\leq 50$ cm	To reduce the risk of workers or objects passing through
Toe board	Continuous	To prevent tools and materials from falling
Diagonal bracing	Every 5 <sup>th</sup> bay	To ensure global stiffness and lateral stability
Platform continuity	Gap $\leq 25$ -80 mm	To avoid tripping hazards and ensure safe movement
Base support	$<$ maximum spindle extension	To maintain load bearing capacity
Anchorage	Height, load, and environmental conditions are dependent	To resist scaffold sway, overturn under operational or environmental conditions

## 2.3. Manual inspection

Traditional scaffolding inspection practices rely on periodic, manual, and visually driven assessments conducted by trained personnel (Prabhu et al., 2025). These inspections are typically guided by standardized checklists derived from regulatory frameworks and focus on verifying component presence, connection integrity, anchorage conditions, and overall geometric conformity (Cho et al., 2018; Halperin & McCann, 2004). Such approaches are inherently subjective and episodic, often requiring the inspectors to rely on memory or records of prior assessments. As a result, gradual geometric changes and undocumented modifications may remain undetected between inspection intervals, limiting their effectiveness for proactive safety management.

## 2.4. Automated safety checking

To address the limitations of manual inspection practices, automated rule-based safety checking is extensively investigated, primarily within Building Information Modelling (BIM) environments and more recently, using reality-capture techniques. BIM-based approaches encode safety regulations as machine-readable rule sets to detect hazards such as unprotected edges, openings, and missing protective elements (Kim & Teizer, 2014; Shou et al., 2015; Vilventhan Aneetha and Mohapatra, 2023; Zhang

et al., 2013). Despite advances in BIM, its support for temporary structure remains limited (Kim & Cho, 2015).

Recent research attention has shifted toward reality-capture-based approaches, particularly using LiDAR and images. A point-cloud-based framework combining semantic segmentation and encoded safety rules is proposed to automate scaffold inspections and detect missing platforms or abnormal installations (Kim et al., 2024). An image-based deep learning approach is proposed for component-level completeness checks, such as detecting cross-bracing or guardrails (Lin et al., 2025). However, existing automated approaches are largely limited to safety assessment at isolated time instances, leaving continuous health management based on design rule compliance unexplored.

### **3. Methodology**

This paper follows the Design Science Research methodology (Hevner et al., 2004; Vom Brocke et al., 2020). This approach develops and evaluates the design knowledge through the interaction between a problem space and a corresponding solution space, with evaluation serving as the link between the two. In this paper, the problem space is the need for objective methods to assess the scaffolding design rules compliance during use. Guided by this perspective, regulatory scaffolding standards, particularly (SS-EN 12810-1, 2004; SS-EN 12811-1, 2004), are analysed to identify design rules that can be expressed as measurable geometric constraints.

The solution space consists of a framework that translates regulatory scaffolding design rules into quantitative, geometry-based indicators derived from LiDAR-acquired point cloud data. The proposed framework is instantiated and evaluated through a real construction site case study.

LiDAR is used to capture a 3D representation of the construction site, including the scaffolding and surrounding environment. The raw point cloud data is processed to extract the object of

interest. The processing steps include noise filtering and spatial segmentation to remove ground points, façade regions, and surrounding site elements not relevant to scaffolding assessment. Planar features, such as façade surface, are identified using model-fitting techniques such as RANdom Sample Consensus (RANSAC) (Prabhu et al., 2025; Rui et al., 2022), while efficient neighbourhood queries are supported using KD-Tree (Lin et al., 2020; Prabhu et al., 2025). Density-based clustering methods, DBSCAN are used to group structural elements and to suppress noisy point clusters arising from occlusions (Kim et al., 2024; Prabhu et al., 2025).

From the processed point cloud, rule-relevant geometric parameters are extracted, which are compared against the threshold values defined in a knowledge base derived from applicable standards and installation guidelines. Compliance or non-compliance is determined by comparing measured values with prescribed tolerance limits for each design rule. From a health management perspective, deviations from the design rules are interpreted as indicators of degraded scaffolding health or increased safety risk. The resulting compliance indicators support safety-oriented decision-making by providing objective, quantitative evidence that can assist site managers and inspectors.

### **4. Results**

This section presents the proposed framework to assess scaffolding design rule compliance using LiDAR-based geometric data. The framework is verified through two safety-critical design rules: the distance between scaffolding and façade, and the spacing between guardrail elements. The results demonstrate the feasibility of translating 3D point cloud data into quantitative compliance indicators that can support decision-making.

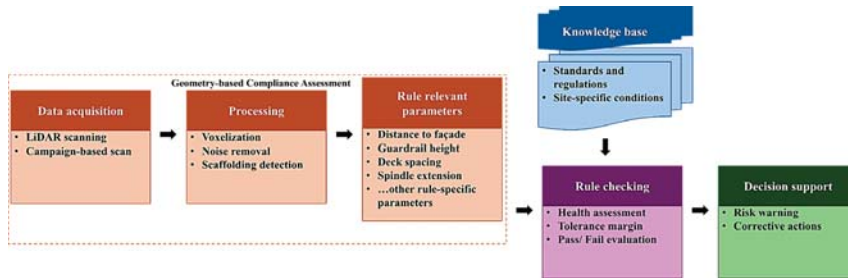


Fig 2. Framework for scaffolding design rule compliance using LiDAR-based geometry extraction and rule checking to support safety-oriented decision-making

#### 4.1. Framework for design rule check

The proposed framework for scaffolding design rule compliance assessment is shown in Fig 2. The framework integrates LiDAR-based data acquisition, pre-processing, extraction of rule-relevant parameters, rule checking, and health management. LiDAR is used for data acquisition, generating dense point cloud representations of scaffolding structures on construction sites. Campaign-based scanning allows the same structure to be captured repeatedly over time, supporting continuous monitoring of its geometric condition. The acquired point cloud data consists of millions of points and includes noise and surrounding objects that are not relevant to scaffolding assessment. Therefore, processing is required to remove noise and isolate the object of interest. This step ensures that subsequent analysis is performed only on geometrically meaningful data.

From the extracted scaffolding structure, rule-relevant parameters are computed as quantitative values. In parallel, a knowledge base provides the reference information required for compliance assessment, including applicable standards, regulations, and installation rules.

The extracted quantitative parameters are then compared against the design rules stored in the knowledge base. Based on predefined tolerance limits, the health state of the scaffolding structure is evaluated, and determines whether it complies with the rules or exhibits deviations. From a health management perspective, these deviations are interpreted as indicators of degraded structural condition. These outcomes support risk warning assessment and safety-oriented decision-making by assisting site managers and inspectors in the implementation of corrective actions.

#### 4.2. Verification of scaffolding design rule

The proposed framework is verified using two scaffolding design rules: the distance between

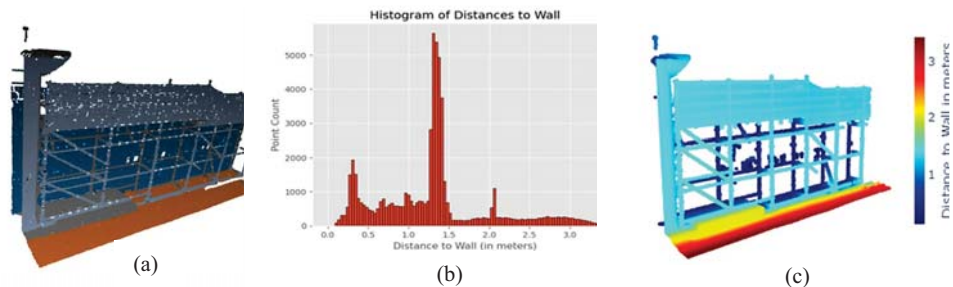


Fig 3. Raw point cloud data and assessment of scaffold-to-façade distance

scaffolding and façade ( $\leq 30$  cm) and the spacing between guardrail elements ( $\leq 50$  cm). Fig 3(a) shows the raw LiDAR-acquired point cloud data of the scaffolding structure, which is used to verify both the design rules.

**4.2.1. Distance between scaffolding and façade**

Using LiDAR-acquired point cloud data, the façade surface is identified as a dominant planar feature within the scene. A robust plane-fitting approach enabled reliable separation of the wall surface from the surrounding structural elements. Following wall surface identification, point-wise distances between the scaffolding structure and the façade are computed. The distribution of these distances is analysed using a histogram, as shown in Fig 3(b). The majority of scaffolding points are observed to lie within the prescribed tolerance limit of 30 cm, indicating general compliance with the design rule. To further analyse spatial variations, a distance-based heat map is generated, as shown in Fig 3(c). The heatmap shows that the scaffolding structure is within the prescribed limits; however, points shown in red colour are associated with ground level, rather than violations of the design rule.

**4.2.2. Spacing between guardrail elements**

The second verified design rule focuses on the spacing between guardrail components. Fig 4(a) shows the extracted scaffolding point cloud with the work platform identified (orange colour), which serves as the reference level for guardrail analysis. All point cloud data above the platform level is isolated to focus on the guardrail system, as illustrated in Fig 4(b). Guardrail elements are extracted through clustering and geometric filtering, with small or sparse clusters removed to reduce noise arising from occlusions and limited data density. Structural joints along the vertical guardrail posts are then identified, as shown in Fig 4(c), allowing the vertical spacing between successive guardrail components to be measured. The extracted measurements provided quantitative distances between the work platform and the first intermediate rail, between successive

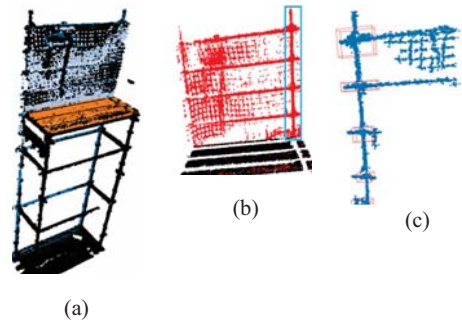


Fig 4. Assessment of the vertical spacing of the guardrail system

intermediate rails, and between the uppermost rails. These measurements provide direct quantitative indicators for evaluating compliance with guardrail spacing requirements, as shown in Table 2. The measured spacing marginally exceeds the 50 cm design limit due to occlusions caused by safety nets, which affects the point cloud density. This result highlights both the feasibility of design rule verification and the need for improved data acquisition to enhance measurement accuracy.

Table 2. Measured vertical spacing between guardrail elements

Guardrail element spacing	Measure distance
Work platform - intermediate rail 1	47.3 cm
Intermediate rail 1 – intermediate rail 2	48.2 cm
Intermediate rail 2 – handrail	51.1 cm
Handrail – top rail	47.6 cm

**5. Conclusion and Future Work**

This paper presents a framework for assessing scaffolding design rule compliance by translating as-built geometric data into quantitative compliance indicators. By framing design rule verification within a PHM perspective, scaffolding structures are treated as evolving, safety-critical assets whose health can be assessed over time rather than evaluated through isolated visual inspections.

The proposed framework integrates point cloud data, geometric processing, rule-relevant parameter extraction, and design rule checking

against a standard knowledge base. The applicability of the proposed framework is demonstrated using real construction site data through the verification of two design rules: the distance between the scaffolding and the façade, and the vertical spacing of guardrail elements. The results show that geometric parameters can be reliably mapped to prescribed design rules, enabling objective compliance assessment and supporting safety-oriented decision-making. The guardrail spacing design rule verification highlights practical challenges associated with in situ data acquisition, such as occlusions caused by safety nets and reduced point cloud density. Nevertheless, the results demonstrate that design rule compliance can be verified even under non-ideal site conditions. The proposed framework is intended to assist site managers and safety inspectors by providing quantitative information for decision-making.

This paper is limited to the verification of a small set of design rules using data from a single construction site. While the framework is generalizable, its applicability across diverse scaffolding structures has not been evaluated.

Future work might focus on extending the proposed framework to incorporate additional scaffolding design rules, particularly those related to bracing configuration and global stability. Further efforts will address enhanced data acquisition strategies, multimodal sensing methods, and advanced deep learning approaches for feature extraction and design rule evaluation.

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