Planning for Scanning in Construction: Optimizing 3D Laser Scanning Operations using Building Information Modelling and a Novel Specification on Surface Scanning Completeness

Md. Humayun Kabir Biswas

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Heriot-Watt University

School of Energy, Geoscience, Infrastructure and Society

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ABSTRACT

Application of Terrestrial Laser Scanning (TLS) technology in the Architectural Engineering and Construction (AEC) industry is gaining popularity because the technology uniquely offers the means to create as-built three-dimensional (3D) models of existing facilities, and conduct construction project progress and dimensional quality measurements. An open challenge with regard to the use TLS for such applications is to efficiently generate effective scanning plans that satisfy pre-defined point cloud quality specifications. Two such specifications are currently commonly used: Level of Accuracy (LOA) that focuses on individual point precision, and Level of Detail (LOD) that focuses on point density. Given such specifications, current practice sees professionals manually prepare scanning plans using existing 2D CAD drawings, some ad-hoc rules (of thumb), and their experience. Yet, it is difficult to manually generate and analyse laser scanning plans to ensure they satisfy scanning quality specifications such as those above. Manually-defined plans may easily lead to over-scanning, or worse under-scanning with incomplete data (which may require the team to go back on site to acquire complementary data).

To minimize the risk of producing inadequate scanning plans, some semi-automated and automated methods have been proposed by researchers that use the 3D (BIM) model generated during the design stage. These methods take consideration for LOA and LOD. However, these are point-based specifications that do not guarantee that a sufficient amount of the surface of each object is covered by the acquired data, despite this aspect being important to many of the applications for which TLS is employed (e.g. modelling existing facilities).

Therefore, this research uniquely proposes a novel planning for scanning quality specification, called Level of Surface Completeness (LOC) that assesses point cloud quality in terms of surface completeness. In addition, an approach is proposed for automatic planning for scanning in the AEC industry that takes both LOA and LOC specifications into account. The approach is 'generic' in the sense that it can be employed for any type of project. It is designed to generate automatic laser scanning plans using as input: (1) the facility's 3D BIM model; (2) the scanner's characteristics; and (3) the LOA and LOC specifications. The output is the smallest set of scanning locations necessary to achieve those requirements.

The optimal solution is found by formulating the problem as a binary integer programming optimization problem, which is easily solved using a branch-and-cut algorithm. To assess the performance of the approach, experiments are conducted using a simple concrete structural model, a more complex structural model, and a section of the latter extended with Mechanical Electrical and Plumbing (MEP) components.

The overall performance of the proposed approach for automatic planning for scanning is encouraging, showing that it is possible to take surface-based specifications into account in automated planning-for-scanning algorithms. However, the experimental results also highlight a significant weakness of the approach presented here which is that it does not take into account the overlapping of surfaces covered from different scanning locations and thus may inaccurately assess covered surfaces.

Keywords: *Planning for Scanning, Terrestrial Laser Scanning, Construction Industry, BIM, 3D Point Clouds*

DEDICATION

This dissertation is dedicated to my beloved parents,
Md. Sakender Ali Biswas & Mrs. Hazera Khatun Biswas

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ACADEMIC REGISTRY

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LIST OF ABBREVIATIONS

2D	two dimensional
3D	three dimensional
4D	four dimensional
5D	five dimensional
6D	six dimensional
AEC	Architectural Engineering and Construction
AEC&FM	Architectural, Engineering, Construction and Facilities Management
BIM	Building information modelling
BIP	Binary Integer Programming
BSI	British Standards Institution
CAD	Computer Aided Design
DOF	Depth of Field
FOV	Field of View
GNSS	Global Navigation Satellite System
GSA	General Services Administration
GUI	Graphical User Interface
IFC	Industry Foundation Classes
LOA	Level of Accuracy
LOC	Level of Completeness
LOD	Level of Density
MEP	Mechanical, Electrical and Plumbing
MIP	mixed integer programming
nD	n dimensional
NBV	Next Best View
P4S	Planning for Scanning
RFID	Radio Frequency Identification
TLS	Terrestrial Laser Scanning

CHAPTER 1: INTRODUCTION

1.1 Research Background

1.1.1 3D Surveying Technology in AEC Industry

Novel technologies are transforming the way activities, such as surveying, progress measurement process and creating as-built three dimensional (3D) models, are conducted in the Architectural Engineering and Construction (AEC) industry. Among those is 3D Terrestrial Laser Scanning (TLS), a surveying technology that uses laser to measure the 3D surfaces of objects densely, automatically and efficiently. TLS thus enables the rapid and accurate acquisition of the as-is (as-built) state of projects, and is particularly advantageous in the cases of inaccessible or hazardous environments [1]. For all these reasons, TLS has been rapidly gaining popularity [2-8].

1.1.2 BIM and its Convergence with TLS

Building information modelling (BIM) is a modern solution to support the collaborative design and management of building projects over their entire lifecycle. The uptake of BIM is growing rapidly internationally, sometimes with governments taking the lead by mandating its use, such as in the UK [9]. BIM is revolutionizing the way the AEC industry operates. At the heart of BIM is the Building Information Model (hereafter *BIM model*) that is a virtual representation of the physical and functional characteristics of the facility, creating a shared source of information for decision making by project delivery and operation teams.

Numerous researchers have highlighted the convergence between TLS (and similarly other reality capture technologies) and BIM [10-13]. The integration of TLS and BIM could improve the delivery of as-built BIM models as well as the control of construction quality and progress. *Scan-to-BIM* (creating a 3D BIM model from a reality point cloud) and *Scan-vs-BIM* (comparing a reality point cloud with a 3D BIM model) are the two approaches that are increasingly referred to in relation to these applications [14-16].

1.1.3 Planning for Scanning

Although 3D measuring technologies are changing the AEC industry in terms of design, construction control and visualization, the applications they support, such as Scan-to-BIM or Scan-vs-BIM, require that the point cloud data be of sufficient quality, for example in terms of point precision, or point density. Notwithstanding, conducting scanning operations is time-consuming and expensive, so it is important that the point cloud data be acquired in an efficient manner, that is with the minimum number of scans possible. These requirements altogether demonstrate the need for planning for scanning.

Planning for scanning can be formally defined as: the process of defining the optimal set of scanning locations to capture the desired objects while satisfying various scanning criteria and specifications. Planning for scanning in construction is commonly conducted by professional surveyors, in an ad-hoc manner, based on experience (tacit knowledge), and even sometimes simply upon arrival on site [17-20]. Figure 1 shows two laser scanning plans as typically generated manually by a professional surveyor using a Computer Aided Design (CAD) drawing of the facility. The problem with such approach is that it may inadequately consider critical factors that can impact TLS data quality, such as incidence angle or surface materials. Furthermore, this process is typically conducted in 2D, which may lead to additional issues being overlooked, such as 3D occlusions of external objects on the ones of interest. Overall, current practice can lead to the following performance deficiencies:

- **Insufficiently precise scans:** the acquired data has insufficient single point precision (i.e. uncertainty in each point's 3D coordinates). Note that single point precision is the first metric currently widely used for specifying laser scanning jobs. *Level of Accuracy (LOA)* is the formal term used to refer to this specification.
- **Insufficiently dense scans:** the acquired data has insufficient point density (i.e. space between points). Note that point density is the second metric currently widely used for specifying laser scanning jobs. *Level of Density (LOD)* is the formal term used to refer to this specification.
- **Under-scanning (incomplete data):** the acquired data insufficiently covers the surface of some objects of interest. This can be important to confidently and accurately model that object. For example, to confidently and accurately

model a pipe, data must be acquired all along its length and for a large portion of its curvature [21]. An important observation is that current practice does not consider any sort of specification regarding surface completeness. The author suggests to refer to such (at this stage hypothetic) specification as *Level of Surface Completeness (LOC)*.

- **Over-scanning (over-complete data):** in contrast, the acquisition of an unnecessary number of scans can result in an unnecessarily large dataset that has to be processed, which can take time (and significant computing resources). Since laser scanning should be conducted in clean, non-intruded environments, over-scanning also means that other activities that need to occur in that environment must be delayed an unnecessarily long time. Over-scanning is commonly due to the limitations of current practice for planning for scanning mentioned above. Indeed, to prevent the risk of having insufficiently precise data, insufficiently dense data and/or insufficiently covered surfaces, surveyors are likely to conduct many more scans than would actually be necessary if more accurate planning for scanning methods were available.

The issues above indicate that there is a need for more scientific and robust approaches to planning for scanning in construction.

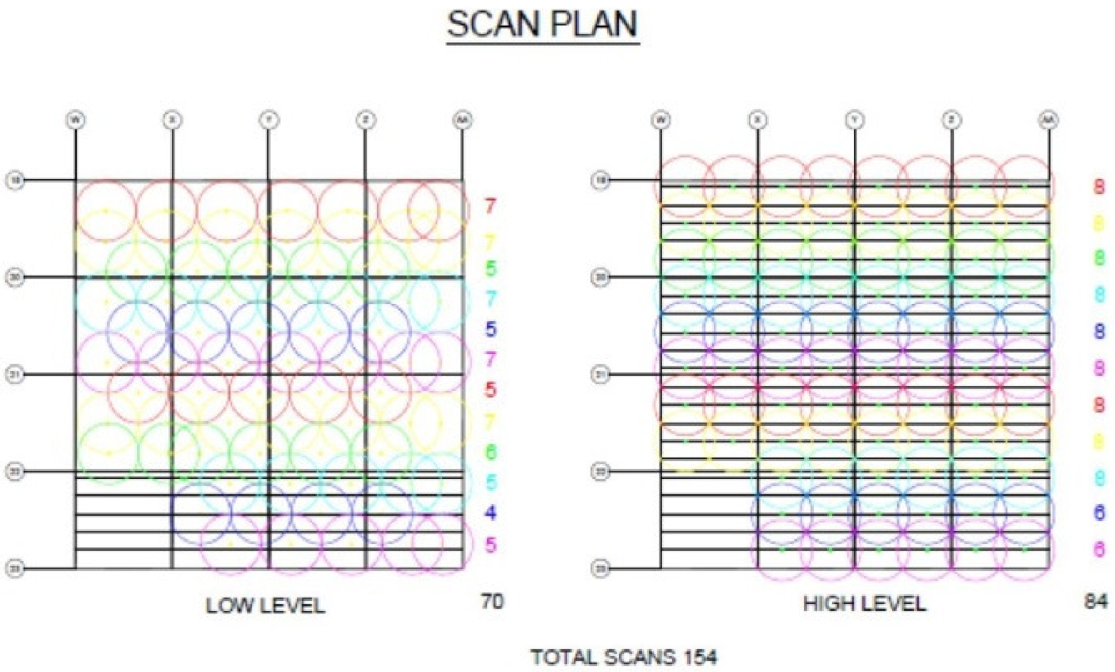


Figure 1. Low-level and high-level scanning plan

A few authors have already attempted to develop more scientific methods to planning for scanning, some using existing (e.g. as-designed) facility 3D BIM models [4, 5, 19, 20]. But, a detailed review of these methods (see Chapter 2) shows that there is no fully automatic planning for scanning method that (1) achieves a global optimization, (2) is 'generic' in the sense that it is not developed to be used in only certain contexts, and (3) that takes LOC specifications into account. This study contributes a novel solution that aims to fill this gap.

1.2 Research Aim and Objectives

The aim of this research is to investigate, implement and validate an approach for automatic planning for scanning in the context of the AEC industry. This novel approach shall automatically generate an optimal laser scanning plan (i.e. the minimum necessary scanning locations) given scanning specifications and an (as-designed) 3D BIM model of the facility to be scanned. The approach shall not be specific to a certain type of 3D structure so that it can be applied in a wide range of construction contexts. The approach shall also achieve a global optimisation, i.e. without starting with a manually pre-defined set of scanner locations. This is important because manually pre-defining a set of locations is a very hard problem requiring significant expertise. In fact, that process alone would suffer from the same limitations that entirely manual approaches suffer from (insufficiently precise scans, under-scanning, over-scanning), and so it would not constitute a valuable solution to the identified problem. It is thus important that new approaches for planning for scanning seek to achieve global optimisation. In terms of scanning (quality) specifications, the approach shall uniquely take into account an LOC specification that defines scanning quality in terms of covered surface per object. As mentioned earlier, LOC is a new type of specification proposed by the author that is not considered in current practice (despite its clear value) and that has not been considered by any previous research. Ultimately, this approach shall improve the efficiency and quality of the acquisition of point clouds employed in Scan-to-BIM and Scan-vs-BIM processes.

In order to achieve this aim, the following objectives are identified:

I. Review the key subjects related to the identified planning-for-scanning problem in the construction industry in particular BIM and TLS technologies, and explore how similar problems may have been investigated in other industries.
II. Design a mathematical model for optimizing the 3D scanning operations, i.e. establishing an optimal scanning plan given the design BIM model as well as LOA and LOC specifications for objects of interest.
III. Implement the developed solution in a prototype system and validate the performance of the proposed model experimentally.

1.3 Research Scope

This research focuses on the problem of automatic planning for scanning in the context of the AEC industry (not in other domains such as in manufacturing). In addition this research aims to develop an approach that is generic to any construction context, not specific cases such as straight tunnels with circular cross-sections in [4].

1.4 Methodology

To gain a better understanding of the identified problem (Objective I), a thorough literature review is conducted to find and assess existing research that directly relates to the identified problem, and to explore existing research that partially relates but may contribute to solving the problem. Various databases are explored, including journal articles, e-books, and other library and Internet resources.

Objective II is achieved by designing a (theoretical) mathematical model for globally optimizing the positioning of the laser scanner given the input project's as-planned 3D BIM model, scanning goals, scanner characteristics and scanning LOA and LOC specifications.

To achieve Objective III, a prototype software package is implemented to demonstrate, validate and assess the performance of the proposed approach. To design this prototype, open source libraries and software are considered. The performance of the proposed approach is assessed experimentally in terms of effectiveness, efficiency and robustness using realistic case studies. For this, quantitative metrics are used alongside with some more qualitative assessment.

1.5 Thesis Structure

The thesis consists of six chapters. The first chapter (the current one) provides a general background to the research leading to the identification of the research need. The research aim, objectives and scope are then defined, together with a brief discussion on the research methodology.

Chapter 2 presents the detailed literature review on BIM, Terrestrial Laser Scanning (TLS) and planning for scanning. This literature review further clarifies the research gap, i.e. the need for improved methods for planning for scanning in the AEC industry.

Chapter 3 presents and justifies the research methodology designed to achieve all objectives, in particular Objectives II and III. The proposed novel approach for planning for scanning is then presented in Chapter 4.

A prototype software package implementing the proposed optimization approach is presented and detailed experimental results reported and analysed in Chapter 5.

Finally, Chapter 6 summarises the research contributions and provides recommendations for future works.

CHAPTER 2: LITERATURE REVIEW

This Chapter presents a comprehensive review of literature. First, the chapter reviews technologies recently introduced to the AEC and Facilities Management (AEC&FM) industry to increase the efficiency and quality control of construction projects. Building Information Modelling (BIM) is reviewed in Section 2.1. Section 2.2 initially discusses Terrestrial Laser Scanning (TLS) and its application, particularly in relation to BIM. It then reviews point cloud quality specifications typically considered in the AEC&FM sector, and conducts an analysis of the factors impacting TLS point cloud quality. Section 2.3 provides a detailed review of existing works in the field of planning for scanning, with specific focus on the AEC sector. Finally, Section 2.4 concludes this Chapter with an analysis of those prior works leading to the identification and articulation of the research need that this dissertation aims to address.

2.1 Building Information Modelling (BIM)

Building Information Modelling (BIM) is a rapidly growing procedural and technological change in the AEC&FM industry [22]. It appeared in the 1970 with the development of information technologies for construction project management. BIM is an approach to digitally and collaboratively model and manage a construction project over its entire life cycle from briefing through to design, construction, operation and maintenance and finally repurposing or demolition [23, 24]. BIM aims to provide all stakeholders with a unique set of information that is interoperable among various technology platforms. There is no unilaterally agreed definition of BIM, but some organizations that have been playing crucial roles in its development do provide well-informed definitions. In particular, the British Standards Institution (BSI) defines BIM as *"a suite of technologies and processes that integrate to form the system which is a component-based three dimensional (3D) representation of each building element"* [25], while the international BuildingSMART organization defines it as a *"business process for exchanging building data and information to design, construct and operate the building during its lifecycle"* [26]. BIM can assist in the development of a more integrated design and construction process that delivers better quality with predictable (even lower) cost and time.

The benefits of BIM are expected to be so significant that it has gained world-wide interest from both public and private organizations. In the UK, the government has mandated that all public projects be delivered with BIM Level 2 by 2016 [27]. The following sections detail what the BIM model is and review important applications of BIM in practice, particularly in conjunction with TLS.

*2.1.1 **BIM Model***

The BIM model is a digital representation (a file, set of files or database) of a building that gathers all life-cycle information or data about it. The BIM model contains *"all kinds of information, from spaces and geometry, to costs, programming, specifications and other information types"* [28]. This includes geometry and other semantic information on performance, planning, construction and operation. Each building component is created from a product library and has embedded semantic information about it. BIM models significantly differ from CAD models as they are object-based with the particular implication that each of the objects has a type (e.g. wall, door, floor). In contrast, CAD models only contain geometric information, lacking any semantic information such as the type of each 3D object.

Despite the great progresses made by present BIM technologies to enhance data management and communication in the AEC&FM sector, one important remaining challenge is the limited interoperability among data models produced by the numerous software packages that are used over the life cycle of projects and even within each one of its stages. To address this issue, the industry is looking to develop open data standards for data exchange and BIM modelling. The Industry Foundation Classes (IFC) is the most significant BIM open data standard (actually a set of standards) which is developed and promoted by BuildingSMART.

*2.1.2 **Application of BIM***

BIM is aimed to support a wide range of tasks over a building's life cycle. Some tasks commonly mentioned include quantity take-off, cost estimating and conducting energy consumption simulations. With BIM, these tasks can be efficiently (sometimes automatically) updated/repeated when changes are made to the BIM model. Such feature is not available to designers working with two-dimension (2D) or three-dimension (3D) CAD tools that produce drawings or other documents that are merely disintegrated hand-offs lacking semantic information [29]. BIM also helps avoiding, or detecting and correcting, design conflicts, thereby helping project team members coordinate their discipline-specific models throughout the project [30-33].

Many of these tasks are commonly referred to by the terms 4D, 5D and 6D BIM. By linking scheduling information (i.e. the dimension of time) to the 3D BIM model, a 4D model is created that enables the simulation of the construction process and the identification of dynamic conflicts that would not be identifiable with the 3D model alone. The 5th dimension of BIM is commonly considered to be ‘cost’. The information required for facilities management, although wide in scope, is often collectively called the 6th dimension of BIM [34]. But, numerous additional ‘dimensions’ may also be considered, leading to the BIM model effectively becoming an ‘nD model’. According to Eastman [29], BIM models could support the following applications:

- Developing project specification information associated with each building components;
- Data analysis related to performance levels and project requirements for procurement, fabrication and Mechanical, Electrical and Plumbing (MEP) services;
- Progress tracking within the supply chain (procurement, installation and testing) by maintaining the design and construction status of every element digitally within the BIM model.

Many of the applications of BIM, require the BIM model to be used in combination with various other technologies. For example, the following technologies have demonstrated huge improvements in material and resource management, cost monitoring, quality control, progress tracking and equipment operator training:

- Radio Frequency Identification (RFID): This technology is used to receive and transmit data from tags fixed to components. RFID is useful for material identification and tracking.
- Global Navigation Satellite System (GNSS): GNSSs provide global geographical positions with no infrastructure required beyond a receiver. Like RFID systems, GNSSs are used for tracking construction components, but also equipment, as well as for land surveying.

- Terrestrial Laser Scanning (TLS): TLS is also gaining popularity. It is a 3D imaging system to capture large scenes in the form of dense 3D point clouds. It is used on construction sites for example for as-is modelling of existing structures.

Automatic progress tracking systems have been investigated by numerous researchers [10, 16, 35]. It is noted in [35] that, for effective project performance tracking, dynamic and reliable survey information is needed to enable effective comparison of the as-built state of projects against their as-planned (or as-designed) state [10, 36] (see *Scan-vs-BIM* in section 2.2.2.2). The 3D BIM model is increasingly used as representing the as-design state. Accurate TLS data is also required in the case a 3D (BIM) model has to be generated from scratch from a TLS point cloud of a given site (see *Scan-to-BIM* in section 2.2.2.1). These two applications (*Scan-to-BIM* and *Scan-vs-BIM*) highlight the convergence between TLS and BIM [14] and are discussed in more detail in Section 2.2.2.

Section 2.2 below first describes the TLS technology and its application in the AEC&FM, and then more specifically analyses the potential value that can be derived from its integration with Building Information Modelling (BIM). This is followed by a discussion of the TLS data quality specifications currently used in the AEC&FM sector and the various factors that impact TLS data quality.

2.2 **Terrestrial Laser Scanning (TLS)**

TLS is a recent 3D surveying technology that is based on the latest laser technologies for distance measurement, and is increasingly used in the AEC industry since the beginning of the 21st century. TLS is valuable for its rapid acquisition of dense and accurate 3D point cloud data that can be used for measurement as well as accurate object modelling [37, 38].

*2.2.1 **TLS Principle***

There are different types of terrestrial laser scanners that differ by their distance measurement principles. Currently, three popular technologies are used: time-of-flight measurement, phase-based measurement (strictly speaking a form of time-of-flight technology), and optical triangulation. Laser scanners used on construction sites employ either time-of-flight or phase-based principles (Figure 2). Phased-based technology measures the phase shift between the emitted and return signal to establish the time of flight and therefore the distance travelled. In contrast, time-of-flight technology measures the time taken for an emitted pulse to return to the scanner, and infers the distance travelled from that time. The different measurement principles used means that phase-based technology enables faster scanning but at limited range (under 100m). In contrast, time-of-flight technology allows scanning at distances of a kilometre and more, but has typically shown to be slower [37].

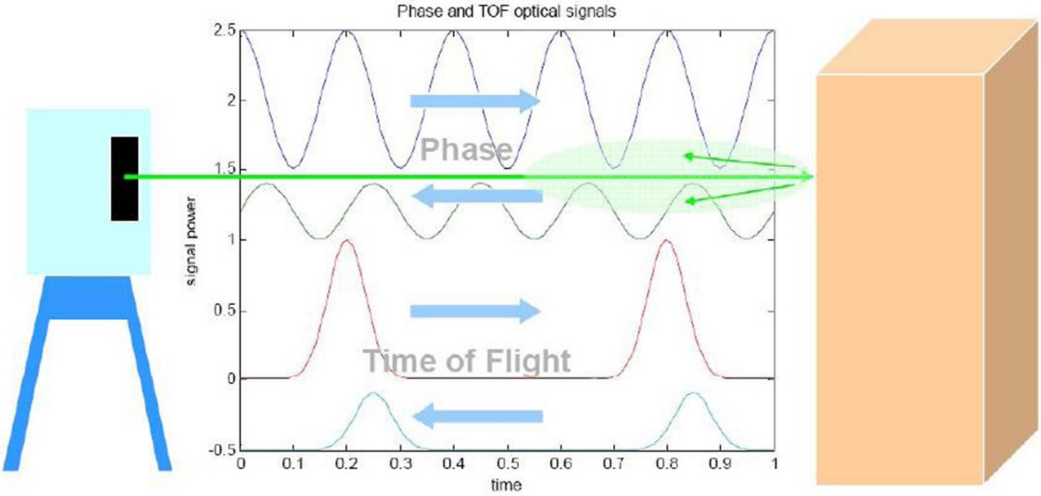


Figure 2. TLS phase-based and time-of-flight principles [39]

A terrestrial laser scanner is made up of two significant components, a laser probe and a two-axis pan-and-tilt mechanism device. As a result, a laser scanner natively acquires the position of each 3D point in spherical coordinates, i.e. with an azimuthal (horizontal) angle φ, a polar (vertical) angle θ and a range distance ρ (see Figure 3). Trigonometric functions are then used to transform the point's spherical coordinates (φ, θ, ρ) into Cartesian coordinates (x, y, z). All those coordinates are provided in the inner coordinate system of the laser scanner.

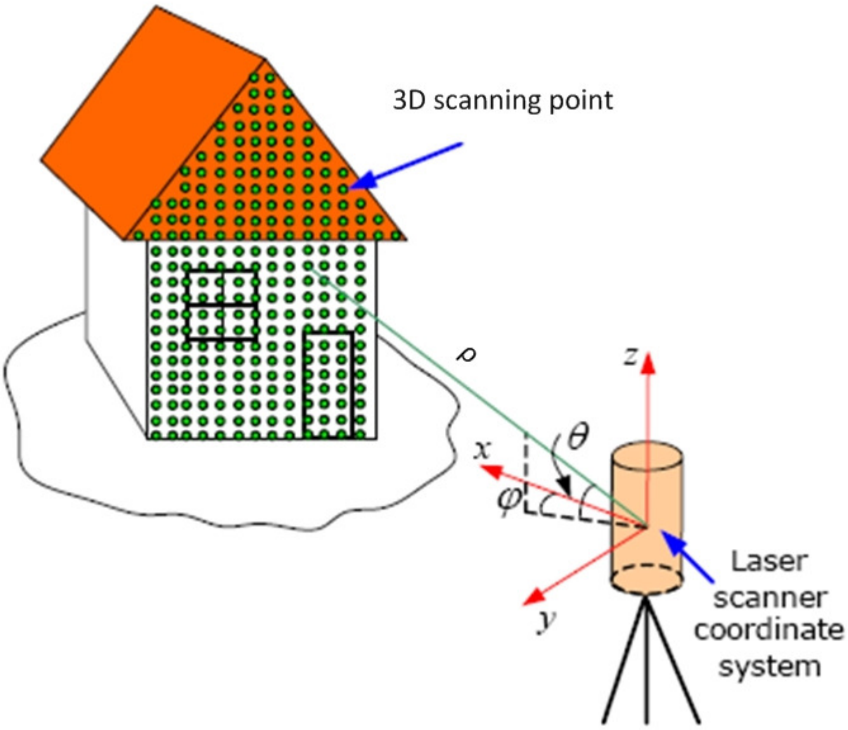
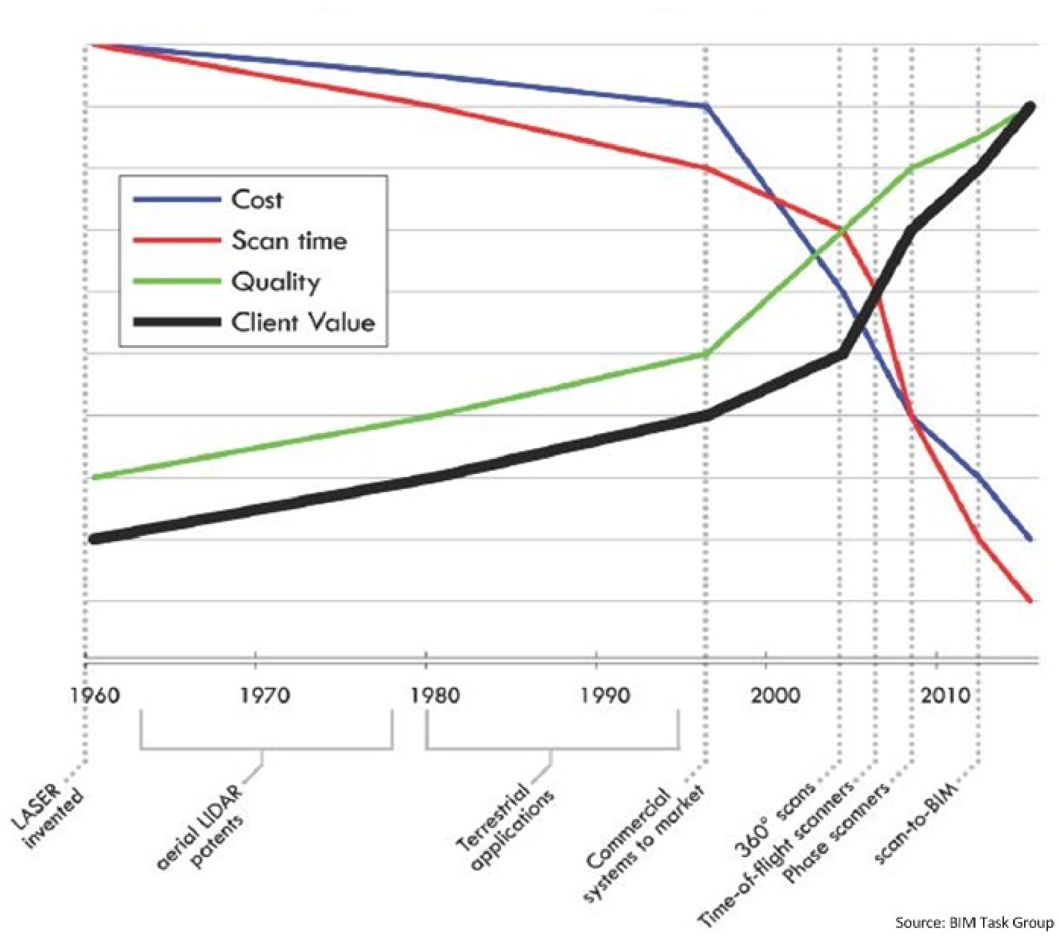


Figure 3. Spherical coordinate system of a 3D point [40]

2.2.2 ***Application and Uptake of TLS***

The use of TLS is growing fast in various industries as an alternative to traditional survey methods [2, 7, 8, 41]. For example, it is applied in the mining sector for volume calculations and in forensics investigations to record and analyse traffic accident scenes. In the construction industry, it is mainly used to create as-built or as-is documentation (e.g. industry facility, housing, cultural heritage) [42]. But, its use is still growing with increasing interest for monitoring construction activities.

Figure 4 illustrates the development of TLS technology in terms of scanning time, cost, quality and client value [43]. It shows that TLS was not much used before the 1990’s (low client value), and this seems (in fact it was) correlated to its high cost, long scanning time and low data quality. The 1990s have however seen disruptive changes in the underpinning technologies which have led to simultaneous and dramatic improvements in data quality, acquisition time and cost, altogether resulting in the rapid uptake of TLS across industries [7, 8].



Source: BIM Task Group

Figure 4. Development and value of TLS technology over time [43]

TLS is now increasingly used in the AEC sector for various applications. In particular, the integration of TLS and BIM could significantly improve design and construction performance. TLS technology is able to capture the as-is (including as-built) 3D status of a construction project. TLS can thus be used to support the generation of 3D BIM models of existing facilities, a process commonly called *Scan-to-BIM*. Furthermore, when an existing (e.g. as-designed) 3D BIM model of a facility is already available, then the TLS data can be compared to it to identify discrepancies, a process that can be called *Scan-vs-BIM* [16]. The following sections detail these two main types of processes that integrate TLS and BIM.

2.2.2.1 Scan-to-BIM

The process of creating a 3D BIM model from point cloud data is often called *Scan-to-BIM* (Figure 5). In this process, recognizing and reconstructing objects from point clouds are very complex tasks due to the sizes of the points clouds and the vast quantities of information needed to describe the environment [44]. For this reason current Scan-to-BIM techniques require significant manual operation [45]. However, significant research efforts are currently put in developing new algorithms and processes for at least semi-automating this process [10-12, 14, 15, 46].

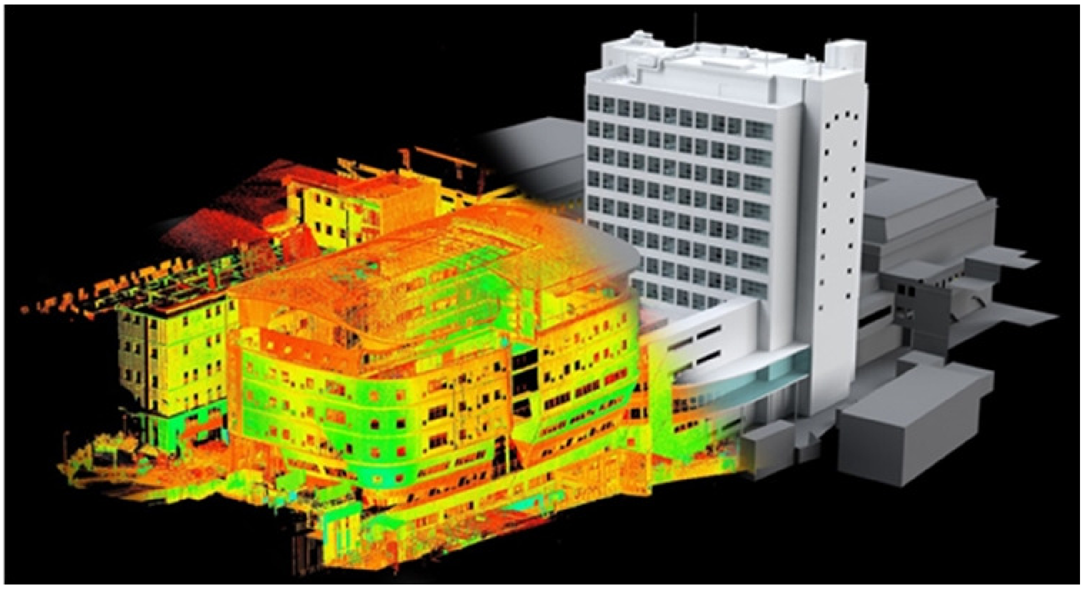


Figure 5. Illustration of the Scan-to-BIM process [47]

2.2.2.2 Scan-vs-BIM

The process consisting in comparing as-built TLS data with existing (e.g. as-designed) BIM models can be called *Scan-vs-BIM*. According to Bosché [10], integrating TLS and BIM in Scan-vs-BIM processes can be beneficial for progress and quality control, and even 3D as-build BIM model delivery. At the core of the Scan-vs-BIM process is the registration of TLS data in the coordinate system of the 3D BIM model.

The potential of Scan-vs-BIM approaches has been investigated in the case of structural work progress control, Mechanical Electrical and Plumbing (MEP) work progress control, tracking of temporary (e.g. scaffolds) or secondary (e.g. rebar in the case of concrete structures) objects, dimensional quality control both on-site and during pre-fabrication [10, 16, 48-52]. While encouraging results have been obtained, further developments remain under way to make those promising approaches more robust and efficient.

One of the main constraints to the good performance of Scan-vs-BIM approaches for supporting the applications above (as-built/as-is BIM modelling, dimensional quality control, etc.) is the quality and completeness of the input TLS data. The following sections detail the TLS data acquisition process, and the factors that can impact TLS data quality and completeness.

2.2.3 ***TLS Point Cloud***

A laser scanner generates a collection of 3D points collectively called a *point cloud* [38]. A point cloud may be in the form of unorganized (or unstructured) 3D points, it may also be in the form of organized 3D points (within a 2D matrix), in which case it is often called a *range image*; in a 2D range image, each ‘pixel’ corresponds to one 3D points, with the pixel location in the image corresponding to a unique scanning direction defined by a pair of azimuthal and polar angles, and the pixel value is the range. Laser scanned 3D points are described at least by three coordinates (x, y, z) defining their location in space, but may also contain other parameters such as colour (R, G, B) and intensity (I). As discussed earlier, point clouds may be used as-is or as an intermediary representation for object recognition and reconstruction [53].

2.2.4 ***Point Cloud Quality Specifications***

The quality of point cloud data can be assessed using various criteria [19]. However, two main criteria are commonly used in practice in the AEC sector:

- **LOA (Level of Accuracy):** point cloud specification that specifies the tolerance of positioning accuracy of each individual point, this ultimately specifies the positioning accuracy of the scanned objects. LOA is typically defined as the maximum allowable distance (in millimetres) between the measured and true location of each point.
- **LOD (Level of Density):** point cloud specification that defines the minimum object size that can be extracted from the point clouds. It relates to how dense the points are scanned on object surfaces. LOD is thus typically defined as a distance in millimetre specifying the maximum allowable distance between neighbouring scanned points.

The General Services Administration (GSA) in the United States has for example developed a set of levels of scanning quality that refers to different levels of LOA and LOD requirements. Table 1 summarises those Levels.

Table 1. LOD requirements standardized by GSA [5]

GSA Level	**LOA (Tolerance)** ***mm (inch)***	**LOD (Data Density)** ***mm × mm (inch × inch)***
1	±51(±2)	152 × 152 (6 × 6)
2	±13(±1/2)	25 × 25 (1 × 1)
3	±6(±1/4)	13 × 13 (1/2 × 1/2)
4	±3(±1/8)	13 × 13 (1/2 × 1/2)

While the two criteria above are widely used (e.g. LOD and LOA data quality metrics are employed by the US General Services Administration (GSA) when they procure laser scanning works), the author notes that the following criterion could also be additionally considered:

- **LOC (Level of Surface Completeness):** point cloud specification that requires that a minimum amount of the surface of an object of interest has been scanned. LOC should specify the minimum amount of the object surface, and possibly even which parts of that surface, that need to be acquired. This criterion is important as it is often difficult to acquire the entire surface of an object; but a sufficient amount of this surface could suffice for the intended purpose. For example, Kim et al. [54] proposed a method to automatically model pipes from 3D as-built point. The local surface curvature information is used to identify each pipeline's location and size. In their research, they show that it is necessary that data be acquired from one third of the pipe curvature to be able to confidently automatically compute the pipeline.

  It is noted that LOC is introduced in this dissertation as a completely new scanning specification that has never been taken into an account, not even discussed, by previous research. Yet, as discussed above, the LOC specification does appear important. It is supposed that LOC was not taken into an account by previous research, because this specification is complicated in comparison to LOA and LOD specifications. Indeed, LOA and LOD specifications are focused on points and so can be assessed individually for each point; in contrast LOC is focused on surfaces that require considering large numbers of points at once, which makes the tack more complex. This complexity is particularly high when considered in the context of current manual planning-for-scanning processes.

2.2.5 *Factors Impacting TLS Measurement Quality*

The LOA, LOD and LOC criteria are defined because TLS does not return points from everywhere and with perfect accuracy. It is thus important to review what the different factors are that impact TLS measurement quality in relation to the LOA, LOD, and LOC criteria.

A first set of factors simply impact whether a point can be physically acquired or not. They include:

- *Line of sight:* An important limitation of laser scanners is that they can only measure points with line of sight. This line of sight limitation means that, for example, only a portion of a pipe can be scanned from a given location due to occlusions by other objects (e.g. other pipes or columns) as well as self-occlusions (the other side of the pipe cannot be scanned from that location alone).
- *Depth of Field (DOF):* This is defined by the minimum and maximum scanning ranges. These are the shortest and largest distances from the laser source within which the scanner is able to acquire a point on a surface. DOF varies from scanner to scanner.
- *Field of View (FOV):* For mechanical reasons, the scanner has limited vertical and sometimes horizontal fields of value. Like DOF, FOV varies from scanner to scanner. But, typical modern laser scanners offer significant fields of view with 360^0 horizontally and up to 305^0 vertically (Figure 6).

When the above factors do not impact acquisition, the accuracy and precision of each measurement may then be impacted by many other internal and external factors. The most important ones include (some are illustrated in Figure 6).

- *View/Incidence Angle (α):* This is the angle between the vector normal to the scanned surface (at the location of the scanned point) and the scanning direction (i.e. from the scanner to that point) (Figure 6). Single point measurement precision typically reduces as the incidence angle increases [55].

- *Range (ρ): Single* point measurement precision reduces as the scanning range increases.
- *Surface Roughness:* Surface texture roughness results in some form of noise in the measurement. This reduces the single point measurement precision [56].
- *Reflectiveness:* Surface reflectiveness creates measurement uncertainty, and reduces single point precision in a similar way as surface roughness [17].
- *Edge effect:* Due to spatial discontinuities of a scanned object, sometimes data acquired at the edge of a surface is not robustly measured (the range is miscalculated) [57]. This can result in spurious points. Modern laser scanners nonetheless now implement robust filters to remove such points from outputted point clouds.

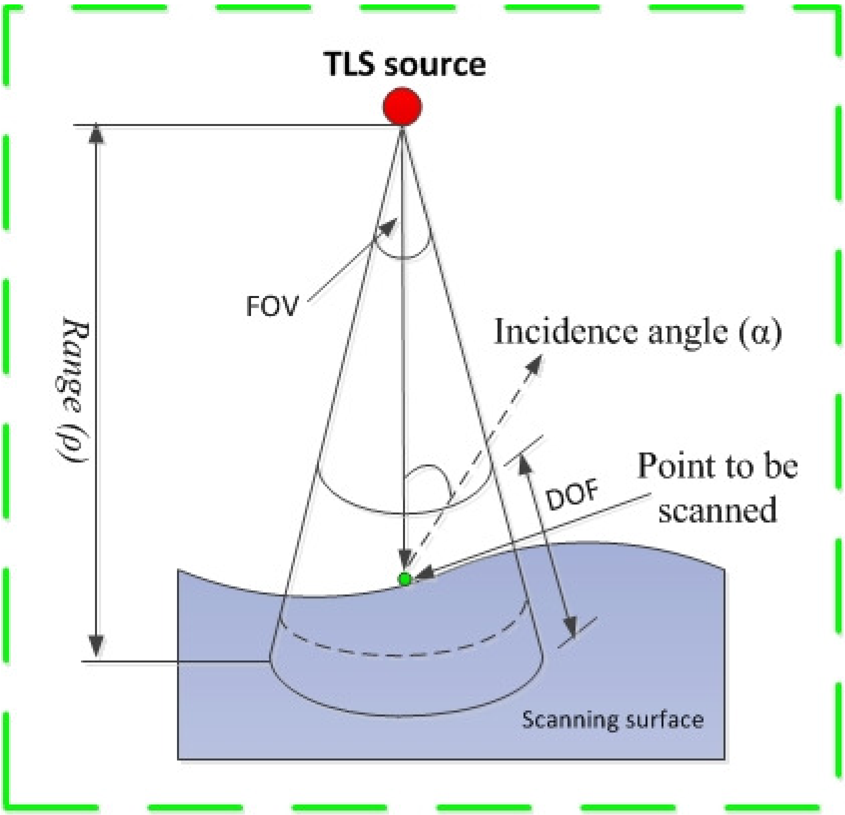


Figure 6. Some of the scanning factors impacting the quantity and quality of TLS data being acquired

Other secondary factors that impact scanning accuracy include environmental conditions (instrument variations, surface reflectivity), as well as surface colour and other surface properties.

As seen above, there are thus many factors that can impact the quantity and quality of TLS data. This shows that the positioning of the terrestrial laser scanner is an important consideration for scanning building sites and facilities [58]. Clearly, this requires that, for each scanning task, a *scanning plan* be devised that carefully defines the number and locations of scans necessary to achieve the desired data quality and completeness.

Table 2 maps the main scanning impact factors identified above to the point cloud specifications (LOA, LOD, and LOC) that they can directly impact. For instance, surface reflectiveness influences single point precision that is specified through the LOA criterion, but not LOD and LOC. The table suggests a clear distinction between the factors impacting LOC and those impacting LOA and LOD. The factors directly impacting LOC are those specifically related to the capability to physically acquire a point (line of sight, DOF and FOV) and therefore cover object surface. Naturally, if a point can be physically acquired but does not fulfil the LOA or LOD criteria, then it should be discarded and the covered surface will be reduced; this would suggest that all the factors impacting LOA and LOD actually also impact LOC. However, it is argued here that such impact is only indirect, and only the first three factors (line of sight, DOF and FOV) directly impact LOC. In fact, as the approach proposed in this dissertation shows, it is natural to check surface completeness (LOC) only after having rejected points that do not fulfil LOA and LOD criteria. This means that, by the time that LOC is checked, only the first three factors in Table 2 (line of sight, DOF and FOV) can still effectively impact the results.

Table 2. Summary of point cloud quality specifications

Scanning Impact Factors	LOA	LOD	LOC
Line of sight			X
DOF			X
FOV			X
Incidence angle	X	X	
Range	X	X	
Surface roughness	X		
Reflectiveness	X		
Edge effect	X	X	

Beyond identifying those factors that influence the three data quality criteria (i.e. the mapping in Table 2), quantitative relations between them must be established.

The data quality criteria LOD defines the minimum distance between neighbouring scanned points on the object surfaces (i.e. point density). The equation below is proposed by Song et al [5] to measure this surface sampling density:

$$S = \frac{\rho\Delta}{\cos\alpha} \qquad \text{(i)}$$

where S represents the surface sampling distance; ρ is the travelling range; Δ illustrates the angular resolution (horizontal or vertical) of the scanner and α represents the incidence angle.

For LOA and its single point precision criterion, establishing a formal or quantitative relationship is a challenging task and remains an area where information remains limited. However, some results have already been reported. For example, Figure 7 shows an example of diagram developed by researchers who aimed to establish a relationship between single point precision with incidence angle at a distance of 20m for a specific scanner. With this figure, it can be concluded that to ensure a precision of ±5mm at a maximum range of 20m, then the incidence angle should not exceed 70°, or in other words, points with incidence angle exceeding 70° should be discarded.

Note that incidence angle and range are two of the most important factors impacting single point accuracy. Therefore, a diagram like the one produced in Figure 7 can be used to estimate point precision.

For LOC, no data quality criterion has yet been suggested, and therefore its relation to the impacting factors has not been considered either. A first approach is proposed later in Chapter 4.

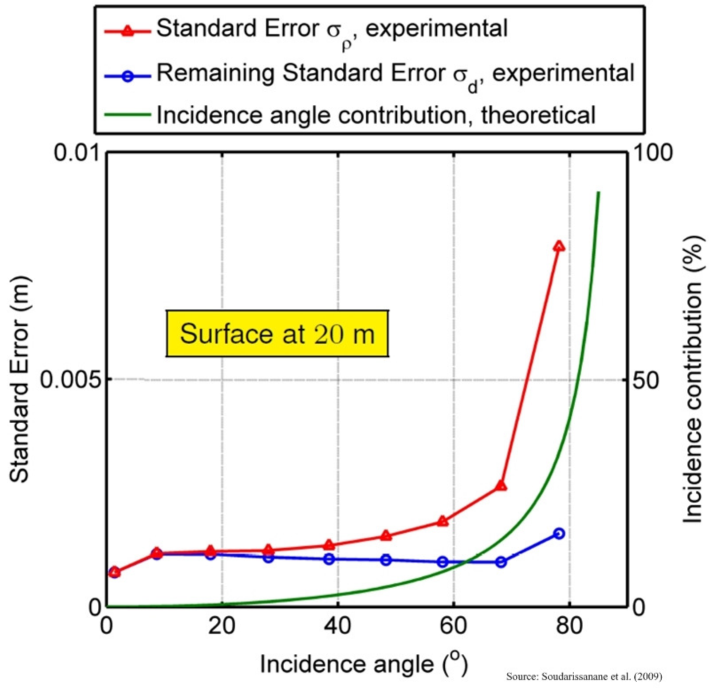


Figure 7. Single point precision (standard error) for various incidence angles for a surface located at 20m from the scanner [55]

2.3 Planning for Scanning

Effective Scan-to-BIM and Scan-vs-BIM applications, in particular dimensional quality control, require that the point clouds associated to the different objects under analysis be acquired with sufficient precision and cover the surface of those objects as completely as possible. As discussed in Section 2.2, there are numerous internal and external parameters that can impact the precision of scanning (e.g. like reflectance of the surface, and incidence angle). Without adequate planning for scanning, scanned point clouds can have insufficient precision and contain incomplete 3D geometric information. This can lead to discarding the acquired data and re-scanning, which is time consuming and constitutes a clear financial loss [59].

While such a need is only recently identified in the context of the construction industry, planning for scanning has already been investigated in the manufacturing sector [17, 60-62] although often for different types of 3D laser scanners. In [17, 60-62] methods are proposed for automatic process planning of laser scanning operations with the aim of reducing the cost and time for inspection. These methods employ the 3D CAD model of the object to be inspected to plan the scanning operations. By analogy, 3D BIM models could be used for the planning of 3D laser scanning operations in the construction industry. However, there is one significant difference between laser scanning in the manufacturing and AEC contexts: in manufacturing, scanners are of different kinds and are typically mounted on arms. The arm-mounting enables the scanner to be positioned in almost any necessary position (location and orientation) and, most importantly, makes the cost (in terms of time) of positioning the scanner in various positions very small. In addition, the scanners used in manufacturing are typically line profiling scanners that conduct scans rapidly. As a result, the problem of planning for scanning in manufacturing is about finding the set of optimal scanning locations for each point of interest on the surface of the part, and combines those in an effective path to be followed by the arm.

In contrast in the AEC sector, laser scanners cannot be mounted on precise automated robotic arms that can move all around the scene to be scanned. In addition, terrestrial laser scanners are much slower than the profile scanners used in manufacturing. Altogether this makes the cost (in terms of time) of moving the scanner to each new location and conduct any new scan very high, which deters from planning large numbers of scans to inspect a scene. As a result, the problem of planning for scanning in the AEC sector is much more focused on minimising the number of necessary scans than about finding the optimal scanning location for scanning each part of the scene. This means that the methods developed for manufacturing do not readily apply in the construction context. Nonetheless, they have likely inspired some previous work reviewed later in this section.

In the AEC sector, the traditional approach to planning for scanning is manually using a compass and draw circles in a regular grid on a 2D plan drawing so that the circles cover the entire ground surface with (minimum) overlap, as illustrated in Figure 1. The radius of the circle is set based on the scanner's characteristics (DOF) and the defined LOA and LOD specifications. These manual methods are very approximate and, as discussed earlier in Section 1.1.3, may lead to the acquisition of data that does not fulfil the LOA and LOD specifications, or they may lead to under-scanning (data missing for objects of interest) or over-scanning (wasted time and too much data to manage). As a result, authors like Akinci et al. [63] argue for the development of approaches for automatic and robust planning for scanning.

In the context of the construction industry, a few works have already been published on automated planning for scanning with TLS that use ideas suggested by works in the manufacturing context, adapting them to the specificities of the construction context. These prior works are reviewed in detail in the following sub-sections that group them according to their main specificity. This review particular considers the very recent works by Dr. Pingbo Tang and his colleagues [5, 19, 20] that can be considered as the current state of the art in the domain (Sections 2.3.2 and 2.3.3).

2.3.1 Planning for Scanning for Specific Case

Argüelles-Fraga et al. [4] investigated planning for scanning for the specific case of straight tunnels with cylindrical shapes with the aim of acquiring data enabling robust comparison of the as-built and as-designed conditions (Scan-vs-BIM). They propose an algorithm generating scanning locations by taking several factors into account, such as tunnel dimensions and incidence angle. The laser scanner's height and incremental distance between scanning stations are found to be the two most important parameters influencing scanning results. Point density and footprint are considered as LOD metrics, and incidence angle is considered as LOA metric. Using the naming in Figure 8, the coordinates (x_i, y_i, z_i) of each scanned point *i* are defined as:

$$(x_i, y_i, z_i) = (t + r_i \sin V_i \sin H_i\,, r_i \sin V_i \cos H_i\,, h + r_i \cos V_i) \qquad \text{(ii)}$$

where, h is the height of laser scanner, t is the orthogonal distance to the tunnel's centreline (i.e. cylinder's main axis), and (H_i, V_i, r_i) are the spherical coordinates of the point as measured by the scanner.

This leads to the formulation of the vector from the scanner to the scanned point as:

$$r_i = (x_i - t, y_i, z_i - h) \qquad \text{(iii)}$$

Therefore, given that the vector normal to the surface at the scanned point's location is $n_i = (-x_i, 0, -z_i)$, the incidence angle α (LOA) can be easily calculated from the formula:

$$\cos \alpha_i = \frac{-n_i \cdot r_i}{\|n_i\| \|r_i\|} \qquad \text{(iv)}$$

The size of the laser footprint at each point (LOD) has a roughly elliptical shape, and its major and minor axes have lengths that can be calculated using the formulas:

$$F_i = \frac{r_i \tan\frac{\varphi}{2}}{\cos\alpha_i} \tag{v}$$

$$f_i = r_i \tan\frac{\varphi}{2} \tag{vi}$$

where φ is the scanner's laser beam divergence angle (provided by the scanner's manufacturer).

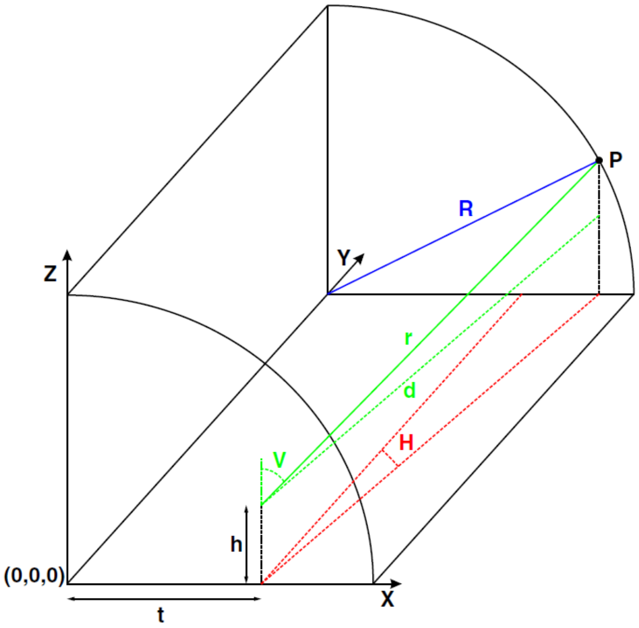


Figure 8: Diagram depicting measurement of a circular tunnel using TLS (reproduced from [4]).

Argüelles-Fraga et al. then define the planning for scanning problem as the problem of minimizing scanning time with three variables (the incremental distance D_R between consecutive scanning locations along the tunnel, and the two spherical angular resolution to be set for the scanning) and point density (LOD), footprint (LOD), and incidence angle (LOA) specifications. The total time required to perform a full scan of the tunnel is calculated as:

$$T_{total} = N_S T_S + (N_S - 1)\Delta T \tag{vii}$$

where, ΔT represents the time required to change position, T_S is the time needed for each scan and N_S is the number of scans calculated as:

$$N_S = ceil\left(\frac{L-pD_R}{(2-p)D_R}\right) \qquad \text{(viii)}$$

where, $ceil(x)$ returns the integer larger than x, L is the length of the tunnel, D_R is the incremental distance, and p is the user-defined overlap between scans.

Note that increasing the spherical angular resolution of scans (i.e. acquiring denser measurements) improves the distance from the scanner at which the point density LOD specification will be met, but increases the time required to conduct each scan. This shows that the optimal solution cannot be easily found manually. Unfortunately, Argüelles-Fraga et al. do not detail the method employed to solve the optimisation problem they define.

More generally, it is clear that their approach makes great use of the geometric specificity of the 'straight tunnel with cylindrical shape', which strictly limits the usability of their approach to such 'simple' cases. Their approach cannot be used in more general cases.

*2.3.2 **Planning for Scanning as Local Optimization of Preselected Locations***

A significant scientific work on planning for scanning in construction is that of Tang and Alaswad [19] who proposed a general sensor-based model to generate scanning plans using 3D (BIM) models of scenes of interest. The approach is the first designed to work in somewhat more general contexts, but it assumes an initial set of scanning locations provided by the surveyor and focuses on optimizing those scanning locations in terms of the angular resolution (for each scan) $\Delta = \Delta_\theta = \Delta_\varphi$ and distance, *d,* to key vertical surfaces to minimize data capture time while providing optimal data quality in terms of scan point density (LOD) and individual point precision (LOA).

The positioning error, *e*, of scanned points is considered for measuring LOA. *e* represents the difference of the coordinates of a scanned 3D point from its actual physical position. Using the definitions in Figure 9, the value of *e* is argued to mainly depend on the point range and incidence angle:

$$e = f_e(D, \alpha) \qquad \text{(ix)}$$

where, $\cos\alpha = \frac{d}{D}$. Note that this formulation only works for vertical or horizontal surfaces. Furthermore, the authors point that the function $f_e(\,)$ varies for each scanner, but do not provide even an example of such function; they simply assume it.

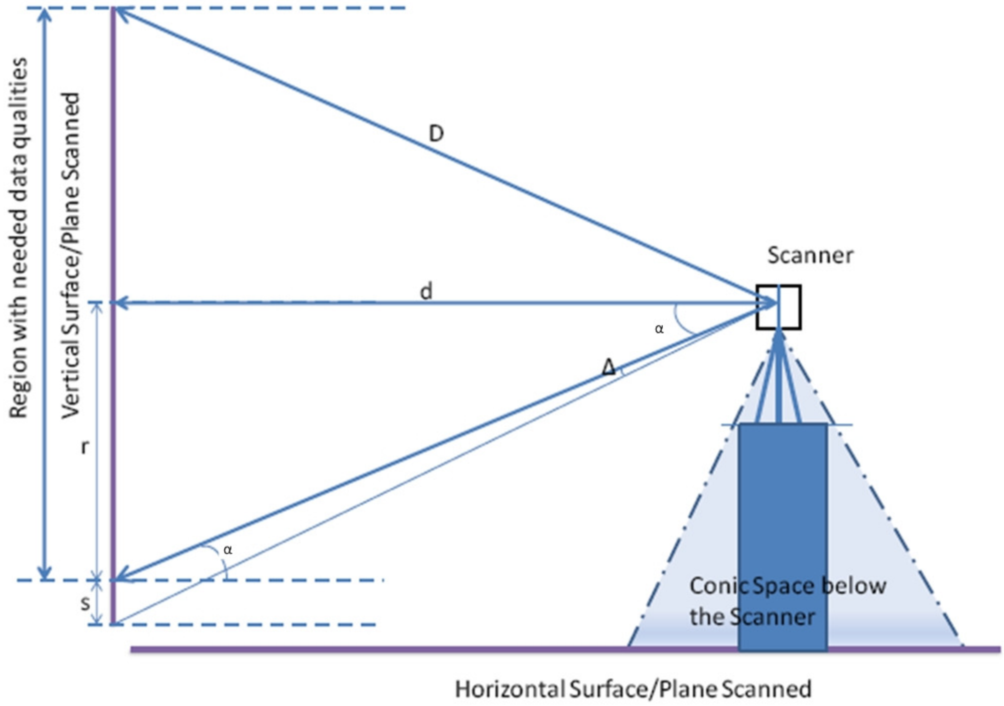


Figure 9. Geometric factors of horizontal and vertical planes (partially reproduced from [19])

Tang and Alaswad then consider two LOD metrics:

1. Surface sampling S (i.e. point density), that is the distance of a given point from its nearest neighbour (see Equation (*x*) below); and
2. Laser beam width on surface B_w' (i.e. footprint). The laser beam width depends on the point range and incidence angle, as well as the beam divergence angle (φ) and laser beam width calibration distance, D_0 (see Equation (*xi*) below).

Features smaller than S and B_w' may not be captured in the point cloud.

$$S = \frac{D\Delta}{\cos\alpha} = \frac{D\Delta}{\frac{d}{D}} = \frac{D^2\Delta}{d} \tag{x}$$

$$B_w' = \frac{B_w' + (D - D_0)\varphi}{\cos\alpha} \tag{xi}$$

Finally, the authors employ what can be seen as a LOC metric (although they themselves seem to mainly recognise it as an LOA metric) that is the vertical surface scanned, captured by the parameter r (see Figure 9) that relates to D and d with the formula:

$$r^2 = D^2 - d^2 \tag{xii}$$

Clearly, the larger r, the larger the scanned surface.

Equations (ix) to (xii) are set for each vertical planar surface of interest. Using those equations, the optimisation model is then formulated as a time minimisation model, where the overall scanning time is the time to acquire each of the surfaces of interest, and each of those times is calculated as:

$$t = \frac{\left(\frac{2\alpha}{\Delta}\right)^2}{C} = \frac{4\alpha^2}{C\Delta^2} = \frac{4\times\left(\cos^{-1}\frac{d}{D}\right)^2}{C\Delta^2} \tag{xiii}$$

where, $\left(\frac{2\alpha}{\Delta}\right)^2$ is the number of points within the surface of interest and C is the scanner's data collection rate.

The LOA, LOD and time constraints to this optimisation model are then:

$$\begin{cases} e \leq e_{limit} \\ S \leq S_{limit} \\ t \leq t_{limit} \end{cases}$$

Integrating equations *(ix)* to *(xiii)* in the optimisation model above, leads to the reformulation of the objective function for each of the surfaces of interest as the maximisation of:

$$P = \frac{\pi r^2}{t} = \frac{\frac{Sd}{\Delta}d^2}{\frac{4\times\left(\cos^{-1}\frac{d}{D}\right)^2}{C\Delta^2}} = \frac{\left(Sd\Delta - d^2\right)C\Delta}{4\times\left(\cos^{-1}\frac{d}{D}\right)^2} \tag{xiv}$$

It is noted that Tang and Alaswad do not explain how r is integrated in this model. It is assumed that r is likely considered as a fourth constraint of the form:

$$r = h$$

where, *h* is the height (above the scanner) up to which scanned points are expected to be acquired. Assuming the vertical surface is a wall, *h* could thus be defined as the height of the wall (minus the height of the scanner).

This approach of Tang and Alaswad uses the same LOA and two LOD metrics as Argüelles-Fraga et al. [4] (point precision, point density, and point footprint). It however aims to work in somewhat more general contexts, as the built environment indeed presents numerous vertical (and horizontal) surfaces. Furthermore, the approach appears to consider some LOC specification, although the authors themselves do not seem to recognize this. Nonetheless, despite these interesting advancements, the approach of Tang and Alaswad still presents two main limitations:

(1) It requires an initial set of scanning locations; it is thus a solution to a local optimisation problem, as opposed to the more general global optimization problem that would consider no initial scanning locations.

(2) The approach actually makes an important simplification (not stated by the authors) that all points at the same height on a vertical surface have the same incidence angle. In reality, the incidence angle increases with the horizontal distance between the scanned point and the orthogonal projection of the scanner on the vertical wall surface (the same logic applies to horizontal surfaces).

*2.3.3 **Planning for Scanning as Global Optimization***

Recently, Song et al. [5] introduced an algorithm that utilizes the concept of *sensor configuration spaces* to automatically generate scanning plans using 3D (BIM) models. The scanning locations are selected from a dense and regularly defined set of scanning locations on the ground (i.e. horizontal space discretisation), and a "*heat map*" technique is used where the temperature of each candidate scanning location increases with the number of geometric features it can acquire for the given LOD specification(s). The authors do not consider any LOA specification.

In contrast with the earlier work in [19], this approach aims to optimize the scanning of 'point' features (e.g. window corners) as opposed to planar surfaces. For each point feature on the given object surface, a *feasible space,* from within which that point can be scanned, is defined for the given LOD specifications. The approach considers the surface sampling S as LOD metric, calculated the same way as in their previous work in [19] (see Equation (ix)) and the authors find that the resulting LOD feasible space is a sphere that is tangent to the surface at the point location and has a radius of $\frac{S'}{2\Delta}$, where S' is the LOD specification and Δ is the scan resolution ($\Delta = \Delta_\theta = \Delta_\varphi$).

The heat map is then generated by projecting all those spheres on the floor (on which the scanner is to be located), and calculating the cumulative number of feasible spaces covered by each discrete scanning location. Note that the method described in [64] is employed to take into account occlusions of the point features by components in the 3D model.

The minimum set of scanning locations required to acquire all the point features with the required LOD specification, i.e. the optimal plan, is then searched using a progressive algorithm similar to Next Best View (NBV) approaches. In this approach, scanning location are incrementally added by selecting in the heat map the location with the highest temperature. The heat map is then updated by removing the feasible spaces of the features captured by that location, and the process repeated until all point features are captured by the selected set of scanning locations.

To reduce computational complexity (the survey job may have thousands of features), the authors introduce two principles to cluster features so that only one spherical feasible space needs to be generated for each cluster. These principles essentially aim to cluster point features that are close to each other and select the feasible space for the point feature with the most stringent LOD specification (its feasible space will be the smallest and will likely be contained within those of the other point features).

This method represents a significant improvement over prior works. Indeed, it simultaneously aims to achieve a global optimization and does it for any kind of feature points (only the local surface normal is required), which makes it usable in any construction context. The approach however still has two limitations:

- It does not consider LOA specifications. While the authors do not discuss this, it can nonetheless be assumed that their approach could be extended by calculating LOA feasible spaces and infer LOA+LOD feasible spaces for all point features by intersecting the LOA and LOD feasible spaces.

- It does not consider LOC specifications. In fact, because this approach focuses on point features as opposed to surfaces, this approach simply cannot accommodate any LOC-type specification.

Very recently, another planning for scanning method has been proposed by Zhang and Tang [20]. This approach is similar to that of Song et al. [5] in that it focuses on 'point' features, and employs the same feasible space approach with consideration for LOD specifications only (not LOA). It differs from that prior work in that it does not consider fixed values of the scanning resolutions for all scans, leaving those instead as variables in the optimisation model. This however significantly increases the size of the planning for scanning problem – that is already very large when fixed resolutions are considered. To address this challenge, they propose to employ a *divide-and-conquer* approach that clusters features into sub-areas and then finds an optimal set of locations for these sub-areas individually. The overall set of scanning locations is then simply the sum of all the sub-sets generated for all sub-areas. For clustering (*divide*) the feature points, a series of visibility confliction rules (i.e. whether points can be acquired in the same scan) are defined that consider the distance between the features and the difference between the orientations of the surface normals associated to those features. A graph is then built where each node is a feature point and edges are created between nodes if they cannot be scanned at the same time according to the rules above. The minimum set of clusters containing features without any visibility conflict can then be solved using Chromatic Number algorithms [65], a well-developed branch of Graph Theory. Figure 10 illustrates the clustering result for a chromatic number problem.

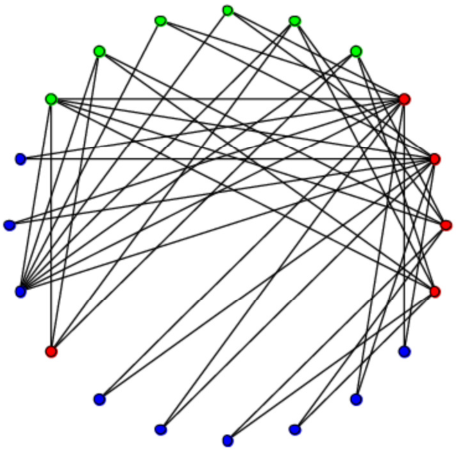


Figure 10. Clustering feature points using a Chromatic Number algorithm; each edge represent feature points with visibility conflict, and different colours show the clustering results [20]

The *conquer* stage processes each cluster separately. First, the lowest possible horizontal and vertical scanning resolutions are estimated that enable the acquisition of all the features with the required LOD. Given those resolutions, a similar 'heat map with progressive NBV' approach as in Song et al. [5] is used that produces a number of scans and consequently an overall estimated scanning time. Since the scanning depends on both the number of scans and the scan resolution, this step is then repeated for incrementally increased scan resolutions.

Another evolution from the 'heat map with progressive NBV' approach initially suggested in Song et al. [5] is also proposed, where the NBV algorithm is not run until all features are captured by the set of selected locations, but until all but 7% are captured. The 7% "garbage" point features from all clusters are then finally combined in one cluster and the same method is applied again. This approach can help prevent the selection of scanning locations for very small numbers of features, and can find better locations that capture more of these remaining features at once.

Overall, this approach of Zhang and Tang [20] is really just an extension of that of Song et al. [5], with more focus on improving the scalability of their planning for scanning approach to large problems. Otherwise, it suffers from the same limitations: its lack of consideration for both LOA and LOC specifications. Regarding LOC specifications, it is important to re-emphasize that those approaches focus on 'point' features, which means that they simply cannot accommodate any LOC-type specification.

2.4 Conclusions and Research Need Identification

Significant works, essentially all by Dr. Tang et al., have been published on the problem of planning for scanning in construction. Table 3 summarizes the strengths and limitations of the various works of Tang et al. reviewed above with respect to six performance criteria. The first three are the consideration for LOA, LOD and LOC specifications identified earlier. The other three are:

- **Occlusions**: whether the approach is able to take into account the occlusions of building components on others ones (for the given scanning locations) as well as self-occlusions.
- **Optimization**: whether the approach uses a local optimisation (of a manually pre-defined set of scanner locations) or a global optimisation (without any prior information).
- **Generalization**: whether the approach can be applied to any context (i.e. any 3D model) rather to specific ones.

Table 3. Comparison of existing planning for scanning methods

Criteria	Tang and Alaswad (2012) [19]	Song et al. (2014) [5]	Zhang and Tang (2015) [20]
LOA	*Yes*	*No*	*No*
LOD	*Yes*	*Yes*	*Yes*
LOC	*Partially*	*No*	*No*
Occlusions	*Yes*	*Yes*	*Yes*
Optimization	*Local*	*Global*	*Global*
Generalization	*Yes*	*Yes*	*Yes*

The analysis of Table 3 leads to the identification of a clear knowledge gap that there is currently no automated method for planning for scanning in construction (using 3D BIM models) that is ‘general’ for any context, that achieves a global optimisation, and that takes into account not just LOD but also LOA and LOC specifications. The lack of support for LOC specifications is particularly noted because the only two global approaches that have been published focus on ‘point’ features and so cannot accommodate at all LOC-type specifications.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Aim and Objectives

The literature review of Chapter 2 leads to the conclusion that there is a need for an effective, generalised method for planning for scanning in construction that automatically generates optimal laser scanning plans that satisfy not just point-based LOD and LOA specifications, but also surface-based specifications, like the proposed LOC.

This research aims to provide a solution that contributes to address this need.

To achieve this aim, three objectives are identified:

I. Review the key subjects related to the identified planning-for-scanning problem in the construction industry in particular BIM and TLS technologies, and explore how similar problems may have been investigated in other industries.
II. Design a mathematical model for optimizing the 3D scanning operations, i.e. establishing an optimal scanning plan given the design BIM model as well as LOA and LOC specifications for objects of interest.
III. Implement the developed solution in a prototype system and validate the performance of the proposed model experimentally.

3.2 Research Process

Figure 11 represents a typical research cyclical process, with different academic domains possibly designing different paths to reach the same destination. The methodology followed by any research has to be defined in light of the aim and objectives of the research.

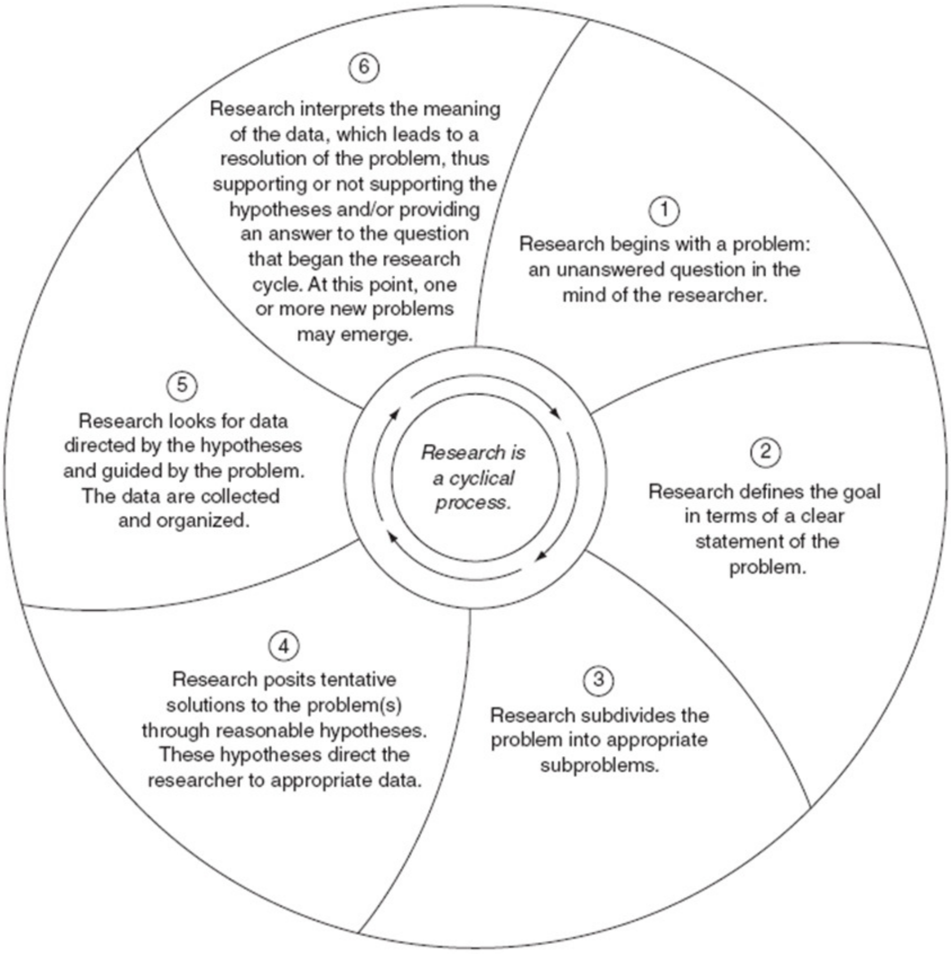
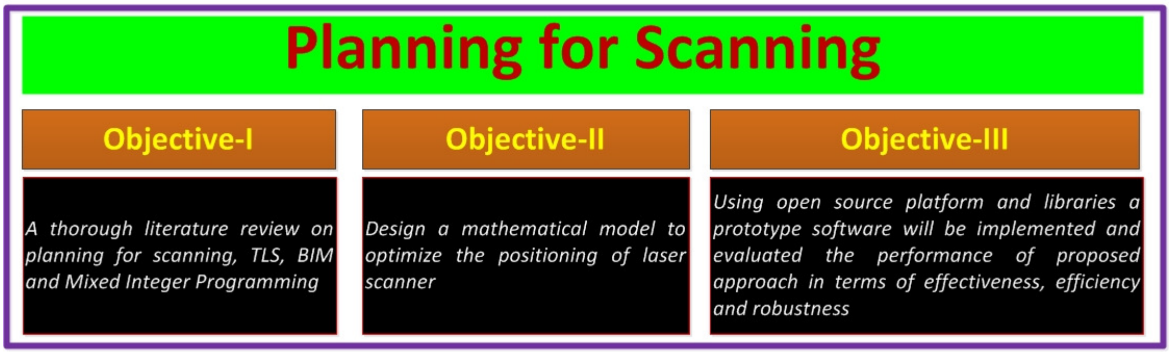


Figure 11. Research cyclical process [66]

The Steps 1 to 3 in Figure 11 have been covered in the literature review and identification of the aim and objectives above. In general terms, the literature review in this research has identified a mathematical problem, for which a model (hypothesis) must be developed to solve based on existing theory and new ideas. The model must finally be validated experimentally. This clearly classifies the proposed research as being deductive [67, 68].

The mathematical nature of the present research problem and the availability of data (3D BIM models) for its testing, suggest that *quantitative* research methods can be considered for the validation stage. In that regard, it has been shown that most quantitative research methods (for instance descriptive research, experimental design and statistical methods for analysing quantitative data) are appropriate for deductive research [69, 70].

The rest of this chapter develops the methodology designed to achieve the research objectives and aim above. Figure 12 summarizes these.



Planning for Scanning

Objective-I

A thorough literature review on planning for scanning, TLS, BIM and Mixed Integer Programming

Objective-II

Design a mathematical model to optimize the positioning of laser scanner

Objective-III

Using open source platform and libraries a prototype software will be implemented and evaluated the performance of proposed approach in terms of effectiveness, efficiency and robustness

Figure 12. Summary of research methodology

3.3 Objective I – Identifying Research Needs

Objective I is to review TLS and BIM technologies and identify the research gap and need in terms of automatic planning for scanning in the context of the AEC industry. This objective is also about investigating other industries to identify ideas that could be leveraged. Such objective is typically achieved by conducting a thorough review of literature from various databases of journal articles, e-books, and other library and Internet resources. The literature review is done to (1) assess existing research that directly relates to the identified problem; and (2) explore existing research that partially relates to the problem, e.g. from another industry, but remains of interest to the problem at hand.

This literature review has been reported in Chapter 2, and enabled a refinement of the research need. It was found that the idea of developing a scanning plan given an expected model of a scene or object has previously been considered for planning laser scanning operations in the AEC sector. But, limitations were identified, specifically the inexistence of methods that consider scanning quality requirements addressing surface completeness specifications, referred to as LOC specifications.

3.4 Objective II – Designing Mathematical Model

Objective II is to formulate the planning for scanning optimisation problem in a way that particularly enables to take into account scanning specifications relating to LOC. The mathematical formulation of the problem shall optimise the number and locations of laser scans given the input project's 3D BIM model, scanner characteristics, and scanning specifications.

This objective is achieved by analysing both the problem at hand and prior work in the field (discovered and analysed as part of Objective I) and derive from those a mathematical formulation that solves the optimisation problem.

3.5 Objective III – Performance Evaluation

To validate and assess the performance of the proposed optimisation model, experiments must be conducted. For this, it is proposed to implement a software prototype, and assess its performance through experiments conducted using both simulated and real case studies [11, 71]. The analysis of these experimental results can then be conducted using quantitative and/or qualitative methods [72]. Although quantitative methods are preferred to assess the performance of mathematical models, qualitative methods can also be considered. It is worth noting that one but one of the state-of-the-art works on automatic planning for scanning have assessed performance of their approach beyond a basic qualitative assessment of their effectiveness to find a solution. Criteria commonly considered to assess the performance of algorithms typically cover [50, 73]:

- *Effectiveness:* the model's capability to produce a good solution to the problem;
- *Efficiency:* the model's capability to use as little resources as possible. In the case of computer algorithms, memory footprint and processing speed are commonly considered; and
- *Sensitivity:* the model's stability to changes to its internal parameters. A model that produces very different solutions when its manually-defined internal parameters change even a little can be considered unstable, and difficult to use in practice. More stable models are preferable.

It is proposed to validate the model proposed in this research for automated planning for scanning by considering performance metrics covering all three areas above:

- ***Effectiveness:*** The approach is compared qualitatively against the previously published ones (in particular those of Tang et al.), but is assessed qualitatively and quantitatively against current practice. For this, an expert surveyor is invited to propose their own scanning plan given a BIM model and set of scanning requirements. A qualitative analysis is done to give an overall observation of the similarity of the two solutions (including whether the one provided by the proposed approach makes sense). But, a more accurate, quantitative assessment of performance is also conducted. In this research, this is done by comparing the system-generated and professional-generated plans in terms of the number of scanning locations required in the plans and the covered surface areas achieved through those locations.

- ***Efficiency:*** A quantitative analysis of the efficiency of the proposed system (i.e. how fast the plan is generated) is conducted by analysing its computational time for 3D BIM models with varying levels of complexity. This enables an assessment of the *scalability* of the proposed method. It is also proposed to use the experiment above with the professional to compare the efficiency of the proposed approach against that of current practice.
- ***Sensitivity:*** Finally, it is proposed to assess the sensitivity of the model to small variations in its manually-defined key input parameters.

3.6 Conclusion

This chapter detailed the research methodology set to achieve the three objectives, and ultimately the aim of the proposed research. To achieve Objective I, a thorough literature review was conducted in Chapter 2 focusing on TLS, BIM and identifying the research gap within the most recent works conducted in the field of planning for scanning in construction. Objective II is to be achieved by designing a new optimisation method, or mathematical model, that minimises the scanning locations to achieve the scanning specifications. This new method shall take into account the newly identified LOC specification. Objective III is to evaluate the performance of the proposed approach through adequately designed experiments. Chapter 4 next presents the proposed new mathematical optimisation model (Objective II).

CHAPTER 4: PLANNING FOR SCANNING APPROACH

In this chapter the proposed approach for planning for scanning in construction (hereafter also referred to as P4S) is presented. The approach aims to generate a scanning plan given an as-planned 3D BIM model, the scanner characteristics and the scanning specifications. The approach uniquely considers the Level of Surface Completeness (LOC) as a new, yet relevant scanning specification.

4.1 Overview of Proposed Approach

An overview of the proposed P4S approach is presented in Figure 13. The *inputs* are the as-planned 3D BIM model, the scanner characteristics (i.e. field of view, and scanning resolution) and the scanning specifications (i.e. LOA and LOC), the latter two really acting as *constraints* to the problem. The *output* of the approach is an optimal set of scanning locations, i.e. the minimal set of locations that fulfil the scanning requirements. Single point precision is used as the LOA specification. The object surface covered by the scans to be conducted from the selected locations is used as LOC metric. Note that this study does not consider LOD specification, but the proposed model does not prevent its use and it could be integrated in future research (see discussion in Chapter 6).

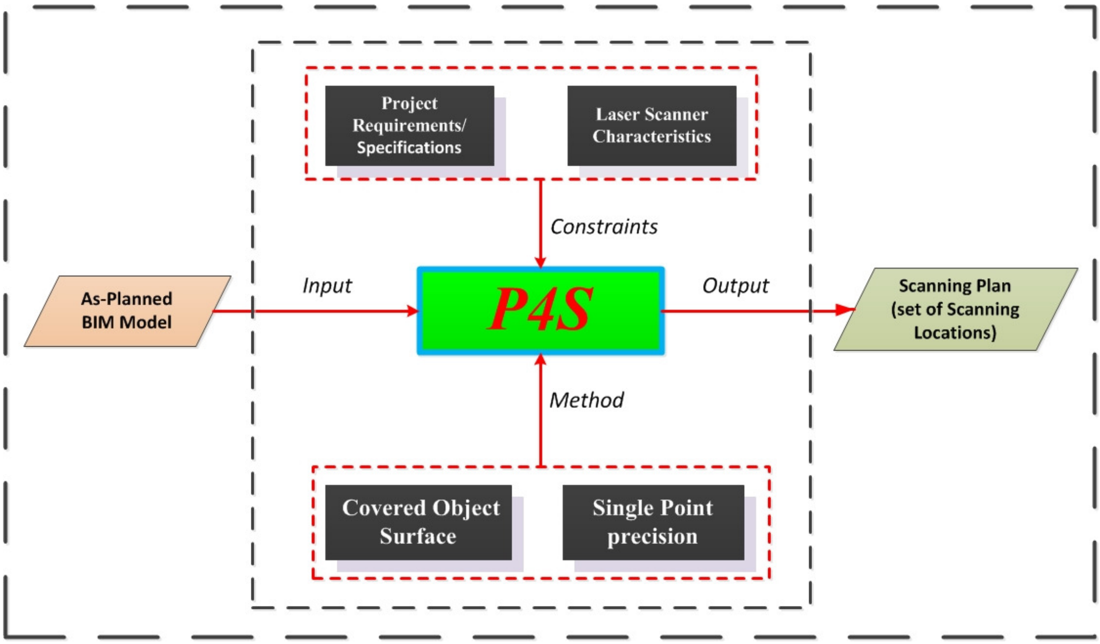


Figure 13. Overview of the proposed Planning for scanning (P4S) approach

The proposed P4S algorithm can be decomposed into five main steps, summarised in Figure 14:

1. **Generate Potential Scanning Locations:** The input as-planned 3D BIM model is composed of numerous objects that should include floors. The user is thus first asked to select from the list of all floors automatically extracted from the BIM model the floor on which the scanner is expected to be positioned. Then, a square grid is automatically generated on the selected floor, where each grid intersection is considered as a potential scanning location.
2. **Calculate Virtual Scans:** Virtual scans are calculated from each potential scanning location using the 3D BIM model as the virtually scanned world, and the scanner characteristics (specifically it's FOV, DOF and angular resolutions).
3. **Filter Point According to LOA Specifications:** Each virtually scanned point is tested against the defined LOA specification (single point precision). The points that fail this test are discarded.
4. **Calculate Covered Surface Areas:** The covered/scanned surface areas for the BIM objects of interest are calculated from the set of remaining points for all potential scanning locations.
5. **Finding Optimal Scanning Plan:** The optimal scanning plan is calculated automatically as the minimum set of scanning locations needed to satisfy the LOC specification (i.e. minimum scanned surface areas) for the objects of interest. This is achieved by formulating the problem as a binary integer programming problem.

All five steps of the P4S algorithm are detailed in the following corresponding sections. To visually support the explanations, the example of a simple concrete structure is considered. Figure 15 shows the 3D BIM model of the structure that includes one floor and twelve columns.

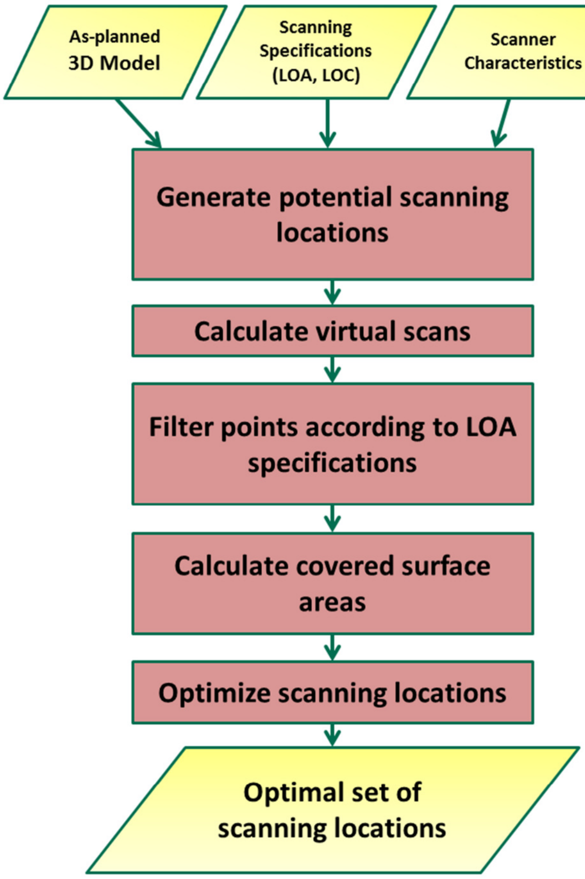


Figure 14. Flowchart of the proposed planning for scanning (P4S) algorithm

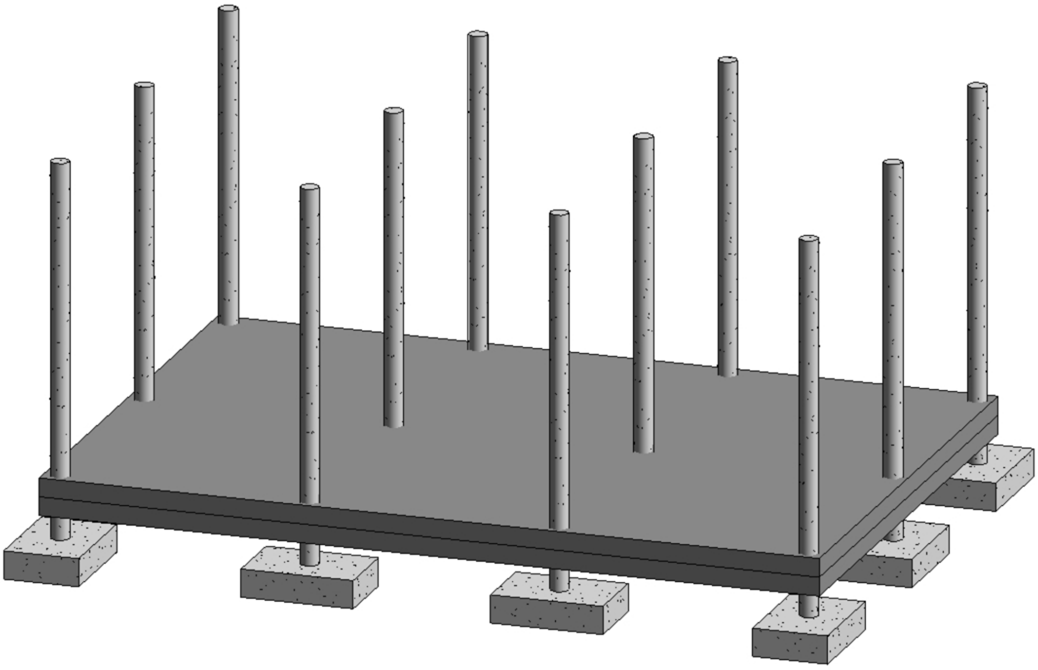


Figure 15. 3D BIM model of a simple concrete structure

4.2 Generating Potential Locations

Given the input 3D BIM model of the facility (Figure 15) in IFC format, the system automatically parses the file and retrieves the list of objects of standard type *IfcSlab*. The system presents that list to the user who is asked to select the floor on which the potential scanner locations are to be considered. A square-grid is then defined on the top face of the selected floor object and each grid intersection is considered as a potential scanning location. The grid orientation is defined along the global X and Y axes, and the extents of the grid sides are set by the dimensions of the floor's axis-aligned bounding box. The grid density is defined with a parameter β (metres) that can be selected by the user. Figure 16 shows the set of potential scanning locations defined with this approach for the example project, and with β=2m. Note that, a second parameter *h* also defines the height at which the scanner's measurement unit is located (typically mounted on a tripod). While different values of *h* could be considered, in this study *h* is set to 2m, a value representative of typical practice.

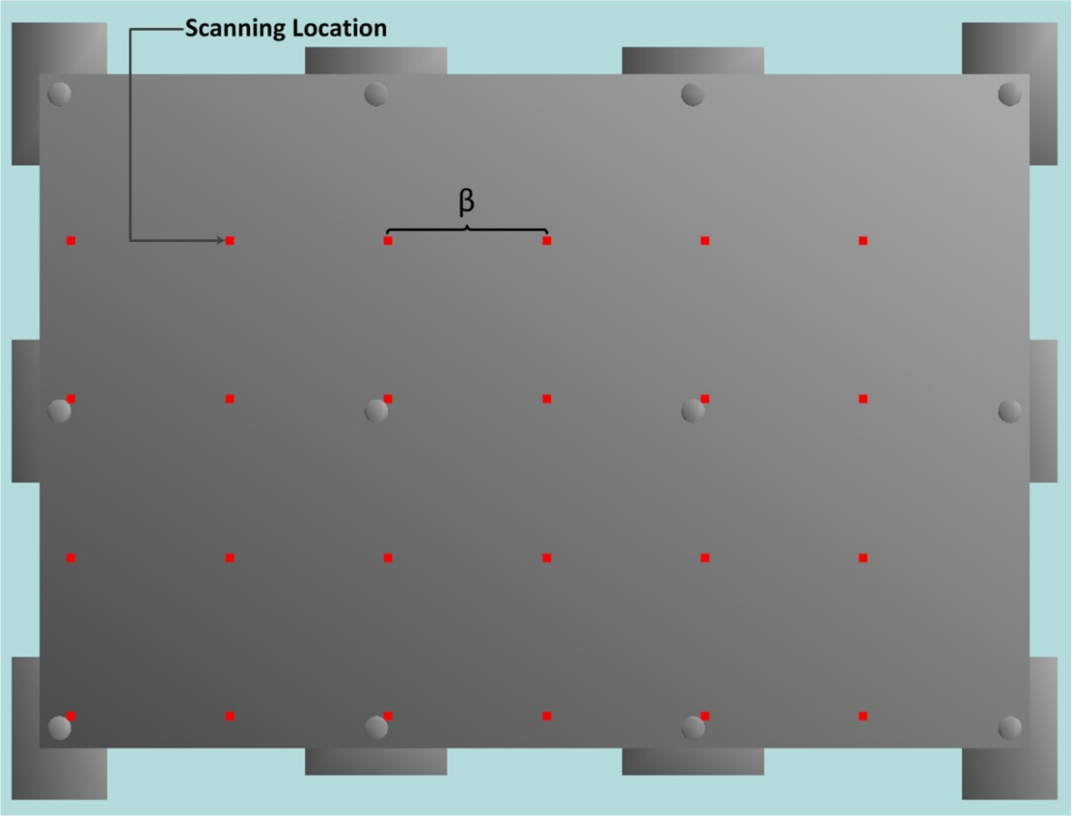


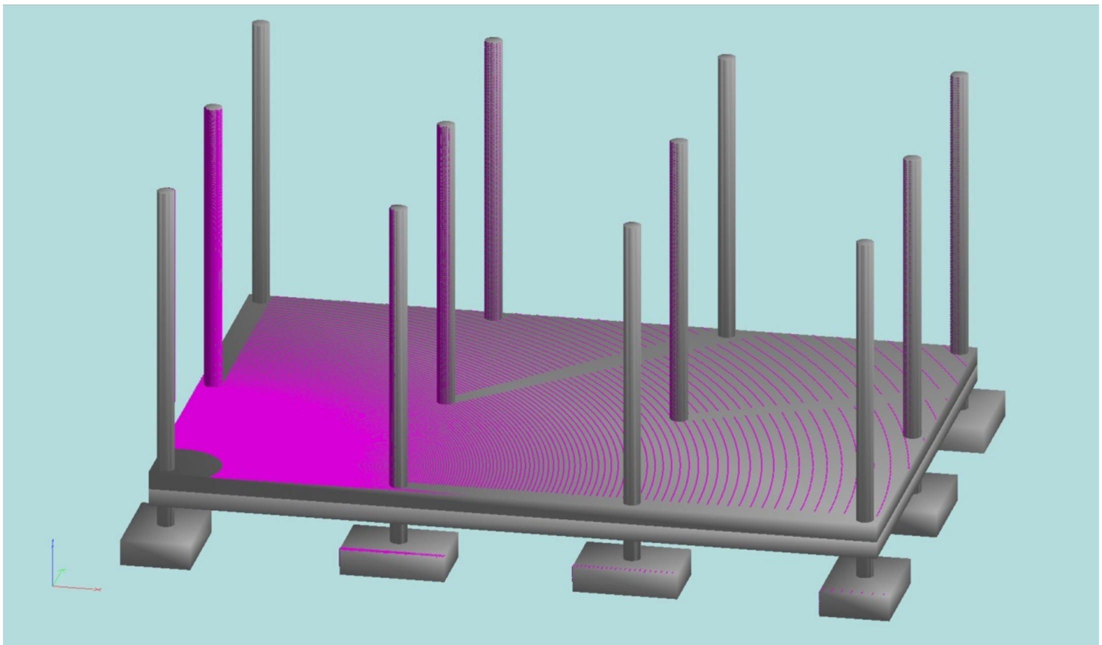
Figure 16. 24 potential scanning locations are generated for the example of the simple structure of Figure 15, using β=2m

The smaller β is, the more scanning locations are generated. This increases the chances of finding not only a solution, but the best solution to the P4S problem. However, this also proportionally increases computational demand.

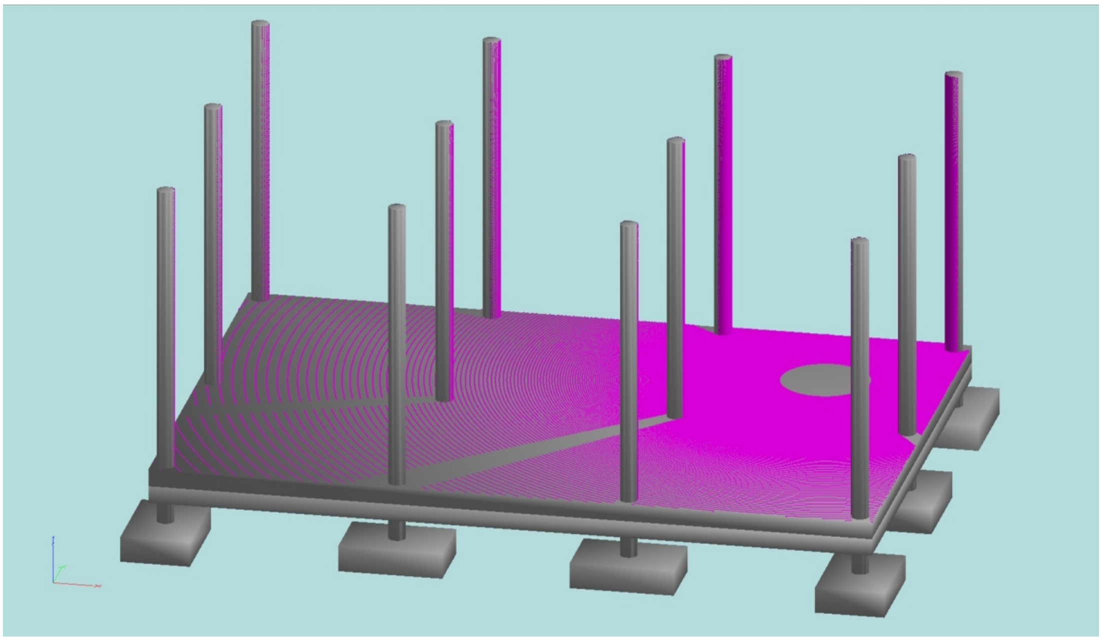
4.3 Calculating Virtual Scans

For each potential scanning location, a virtual scan is conducted given the facility's 3D BIM model, taking into account the scanner's characteristics (sensor model), more specifically its FOV and angular resolution.

The method in [74] is used here that performs virtual scans by faithfully replicating the process of a real laser scanner. It is just summarised here. The virtually-scanned points are calculated by virtually casting rays from the scanner in all incremental directions defined by the scanner's angular resolution and within the scanner's FOV. For each ray, the point is defined as the first intersection of the ray with a face of the 3D model objects' meshes. This process enables the calculation of the point's Euclidean coordinates and therefore its *range*. Furthermore, knowing which mesh face is intersected enables the calculation of the point's *incidence angle*. Naturally, it is also known from which object each virtually scanned point is obtained. Figure 17 shows the virtual scans obtained for the scanning locations 1 and 24 for the example project. For these scans, the scanner's horizontal and vertical resolutions are both set to 0.003rad (= 0.17° = 300mm @ 100m), and the horizontal and vertical FOV are set to 360° and 152° respectively.



(a) Virtual scan for scanning location 1



(b) Virtual scan for scanning location 24

Figure 17. As planned scans from scanning locations 1(a) and 24(b) for the example of the simple structure

4.4 Filtering Points According to LOA Specification

As discussed in [5, 19, 20, 55, 57] individual point precision is a function of many factors, but in particular range and incidence angle. This means that for a given specified LOA precision level, corresponding maximum range (ρ_{max}) and maximum incidence angle (σ_{max}) can be identified that points should not exceed. In [55], Soudarissanane et al. provide a graph, reproduced earlier in Figure 7, establishing the relations between precision, range and incidence angle for a given scanner. In that figure, it is shown that to obtain with the given scanner a precision of ±5mm at a maximum range of ρ_{max}=20m, then the incidence angle should not exceed σ_{max}=70°. Similarly, to obtain a single point precision of ±2mm at a maximum range of 20m, the incidence angle should not exceed 60°. In other words, range and incidence angle can be used (to a certain extent) as proxy metrics for assessing point precision.

As explained in Section 4.3, the range and incidence angle of each virtually scanned point are readily available (see Figure 18). So, using relationships such as the one established in Figure 7 as generic rules for estimating the expected precision, it can be reasonably assumed that, for example, all points with range not exceeding 20m and incidence angle not exceeding 60° should have a precision of ±2mm. In other words, all points whose range exceeds 20m or incidence angle exceeds 60° must be filtered out and discarded from further processing to fulfil a LOA precision level of ±2mm.

It should be reminded that tables like the one in Figure 7 are difficult to produce and are normally valid only for the scanner considered and for one type of surface material. Having access to such table remains the main hurdle to the practical application of the proposed P4S method, but this is also the case for all previously proposed methods that considered LOA. Nonetheless, only the maximum range and maximum incidence angle need to be defined here, and these could possibly still be set in an ad-hoc manner by experienced practitioners. In this research, the relationships established in the graph of Figure 7 are assumed adequate and representative, and are thus used in the rest of this dissertation, in particular in the experimental studies (Chapter 5).

4.5 Calculating Covered Surface Areas

At this stage, all remaining virtually scanned points are those that fulfil the LOA specification. Then, for each object of interest, the surface covered by those points that were scanned on it is calculated. This can be achieved using the approach described in [10, 75] and summarised below.

The surface area, $\bar{s}_{k,j,i}$ of each mesh's triangular face, *i*, of each object, *j*, covered by each virtual scan, *k*, is calculated as the sum of the surfaces covered by the *n* points virtually scanned on that face that passed the LOA filtering stage:

$$\bar{s}_{k,j,i} = \sum_{p=1}^{n} s_p$$

where, the surface covered by the p^{th} scanned point, s_p , is calculated using the formula [41]:

$$s_p = \frac{\tan(\varphi_{res})\tan(\theta_{res})}{\cos(\varphi_{\alpha p})\cos(\theta_{\alpha p})}\rho_p^2$$

where, ρ_p is the scanning range of point *p*, ($\varphi_{\alpha p}$; $\theta_{\alpha p}$) are the spherical components (i.e. horizontal and vertical) of the point's incidence angle (see Figure 18), and (φ_{res}; θ_{res}) are the spherical angular resolutions of the scan.

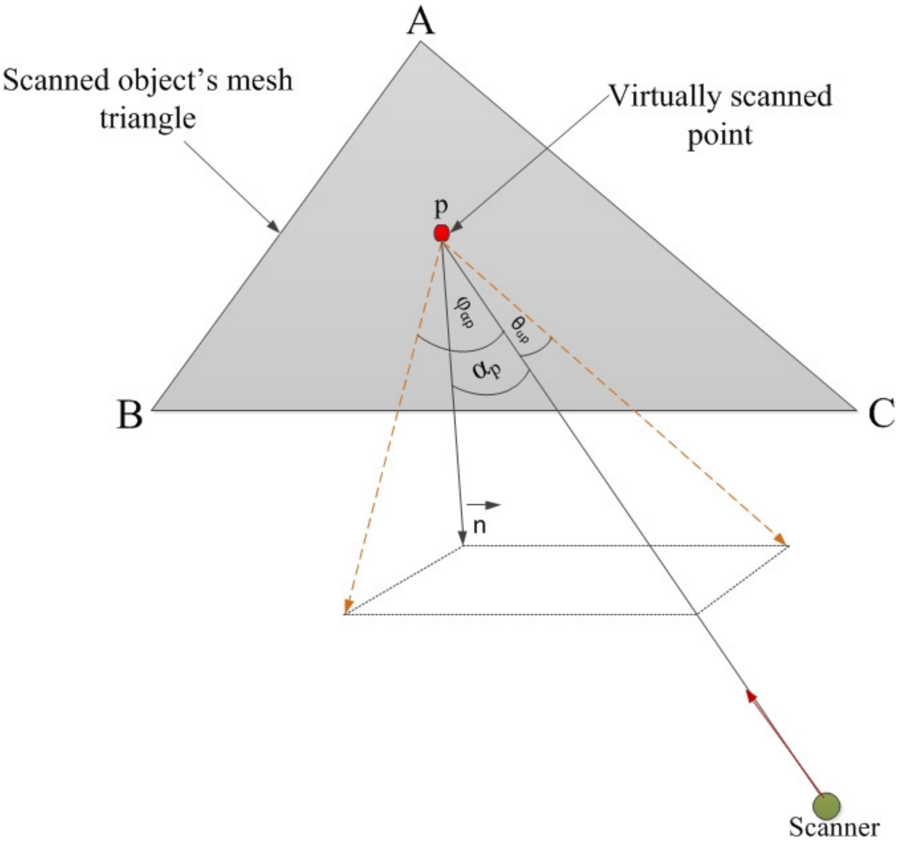


Figure 18. Spherical decomposition ($\varphi_{\alpha p}$; $\theta_{\alpha p}$) of the incidence angle α_p of a scanning point *p*. ABC is the object's mesh face on which the point is scanned, and $\vec{n}$ is the normal vector of that face

The scanning covered surface for each triangle $\bar{s}_{k,j,i}$ can then be compared with the actual surface of the mesh triangular face $s_{j,i}$ that is simply calculated as:

$$s_{j,i} = \frac{1}{2} \left\| \overrightarrow{AB} \times \overrightarrow{AC} \right\|$$

where, $\overrightarrow{AB}$ *and* $\overrightarrow{AC}$ are the vectors of two sides of the triangular face (see Figure 18).

After calculating the covered surface for all the triangular faces of a mesh, these can be added up to obtain the covered surface for that BIM model object, *j,* for each scanning location, *k*, as follows:

$$\bar{s}_{k,j} = \sum_{i=1}^{f_j} \bar{s}_{k,j,i}$$

where, f_j is the number of faces in the mesh of object *j.*

The actual surface of the object (i.e. surface of the mesh) s_j can be similarly calculated by summing up the actual surfaces of all its triangular faces:

$$s_j = \sum_{i=1}^{f_j} s_{j,i}$$

All necessary information is now available to conduct the final step of the process that is finding the optimal scanning plan.

4.6 Finding Optimal Scanning Plan

The P4S optimisation can now be formulated as a Binary Integer Programming (BIP) problem, also called Binary Integer Linear Programming (BILP) problem. For this, $x = [\delta_1 \quad \delta_2 \quad \dots \quad \delta_l]^T$ is defined as the vector of l binary decision variables corresponding to the l potential scanning locations. In x, $\delta_k = 1$ if the scanning location *k* is selected in the final plan; $\delta_k = 0$ otherwise. The matrix *A* is also defined that gathers the covered surfaces calculated in the previous step for all scanning objects from all potential scanning locations.

$$A = \begin{bmatrix} \bar{s}_{11} & \cdots & \bar{s}_{1l} \\ \vdots & \ddots & \vdots \\ \bar{s}_{l1} & \cdots & \bar{s}_{lo} \end{bmatrix}$$

where, *o* is the number of objects of interest, i.e. the objects that the surveyors wishes to scan.

The P4S optimization model is then formulated as follows:

$$\text{Minimize: } c^T x$$
$$\text{Subject to: } x^T A \geq b$$

where, *c* is the coefficient vector of the objective function and contains only 1's; as a result $c^T x = \sum_{k=1}^{k=1} \delta_k$ is the sum of selected scanning locations, i.e. the objective function to be minimized. $x^T A$ calculates the vector of covered surface areas for all objects of interest given the selected scanning locations, and *b* is the vector of specified minimum covered surfaces, i.e. the LOC specification for each object. Exploding the optimisation constraint gives:

$$\begin{bmatrix} \sum_{k=1}^{l} \delta_k \bar{s}_{k1} \\ \vdots \\ \sum_{k=1}^{l} \delta_k \bar{s}_{ko} \end{bmatrix} \geq \begin{bmatrix} s_1^{min} \\ \vdots \\ s_o^{min} \end{bmatrix}$$

Note that, in practice, the minimum covered surfaces defined for the LOC specification would likely be set according to each object's overall surface. For example, for object j one may define the minimum covered surface s_j^{min} as a percentage ω_j^{min} of its overall surface s_j. Using this approach, the optimisation constraint becomes:

$$\begin{bmatrix} \sum_{k=1}^{l} \delta_k \bar{s}_{k1} \\ \vdots \\ \sum_{k=1}^{l} \delta_k \bar{s}_{ko} \end{bmatrix} \geq \begin{bmatrix} \omega_1^{min} s_1 \\ \vdots \\ \omega_o^{min} s_o \end{bmatrix}$$

*4.6.1 **Solving the BIP Methods:***

The proposed approach for automatic planning for scanning is formulated as a BIP problem, which is a special case of Mixed Integer Programming (MIP) problem. This section reviews various techniques that can be used to solve BIP problems [76].

Branch-and-Bound algorithms are typically used for solving MIP problems [77]. In these algorithms, an optimal solution is initially found to a linear relaxation of the given MIP problem (i.e. without taking into account the integer constraints). If the decision variables in the solution have integer values, then no further work is needed. But if any variable does not have integer value, then the Branch and Bound algorithm selects it and creates two branches for generating two new sub-problems where the value of that variable is tightly constrained to the surrounding integer values (in the case of BIP, 0 or 1). These sub-problems are solved similarly and the process iterated if necessary until an optimal solution is found for which all integer variables have integer (binary) values.

For BIP problems, a specialized Branch-and-Bound algorithm can be used that is known as *Balas Additive Algorithm* [78]. This method is only usable if the objective function is set for minimization and its coefficients are all nonnegative. The algorithm starts with the solution containing only zeros (since it would minimise the objective function) and tests it. If it does not solve the problem, it tests changing the 0 to 1 for the term with the smallest coefficient (since this would lead to the smallest minimisation possible of the objective function). This process is iterated with a depth-first node selection strategy until a solution is found (or no solution exists).

Beside Branch-and-Bound algorithms, another type of methods that can be used to solve MIP problems are *Cutting Plane* methods. These algorithms aim to iteratively refine the region of feasible solutions for the linear relaxation of the given MIP problem. These methods can be very fast, but they are also known to be unreliable. There is a group of methods for solving MIP problems that integrate Branch-and-Bound and Cutting Planes methods, called *Branch-and-Cut* [77]. Like Branch-and-Bound algorithms, these algorithms solve a series of relaxations of the initial MIP problem following a divide-and-conquer approach. But they additionally integrate Cutting Planes methods to improve the relaxation to more closely approximate the initial MIP problem.

In addition, since MIP problems are a sub-set of *non-linear programming problems*, all methods available for solving the latter can be used to solve the former. A set of methods commonly employed for solving non-linear programming problems are *evolutionary algorithms* that aim to mimic processes observed in nature. The most well-known one is *genetic algorithm* that uses input variables expressed as a single vector/string of binary variables ('chromosome'). This iterative method identifies at each iteration which individuals is the most promising to solve the problem and should thus survive and reproduce, and discards the other ones. Various genetic operations can occur during the reproduction stage that mimics evolution processes observed in nature, such as inheritance, mutation, selection and crossover. The algorithm typically stops after a pre-defined number of iterations or when no further improvement is observed in a number of iterations [79, 80].

The above mentioned BIP solving techniques are commonly implemented in various commercial and non-commercial solvers. As noted above, the Branch-and-Bound method and its variants are the most commonly used and recognized methods for solving MIP algorithms [81]. The methods are commonly implemented in software/libraries used in research, such as:

- **CPLEX:** The IBM ILOG CPLEX Optimizer can efficiently solve mixed integer programming, linear programming, and quadratic programming problems. For MIP problems, a distributed parallel algorithm is available that can leverage multiple computer threads, or even multiple computers, to solve difficult problems.
- **GUROBI:** This is a modern commercial solver for mixed integer linear and other non-linear optimization problems. This optimizer is developed using the C programming language and is available on all computing platforms [82].
- **Coin-OR Branch-and-Cut (CBC):** This is an open-source mixed integer programming (including BIP) solver created within the Coin-OR project, written in C++. The main goal of the Coin-OR project is to create open source software for the community conducting operations research. CBC is a widely recognised library within the research community and this library is built on top of the COIN-OR CLP library [82-84].

In this research, the COIN-OR Branch-and-Cut (CBC) algorithm is selected because it has been shown to be good and efficient but also for practical reasons. In particular, CBC provides a plug-in for Excel in which the covered surface tables could be easily copied from the software prototype. Using the plug-in enabled testing the proposed approach without having to spend a lot of time trying to integrate the CBC library with the current P4S software prototype. Nonetheless, it must be noted that the P4S software prototype implemented for this research is written in C++, so such integration is definitely possible to deliver a full-featured solution.

4.7 Conclusion

In this chapter, the planning for scanning approach proposed to achieve Objective II has been presented. The approach finds the minimum set of scanning locations that enable the acquisition of data from a pre-defined set of objects and pre-defined LOA and LOC scanning specifications. Using the facility's 3D BIM model, the approach first generates a set of potential scanning locations on the (selected) floor of the facility and conducts virtual scans for each of them using the characteristics of the selected scanner. All scanned points are then checked against the expected precision (LOA specification). Precision is assessed using the scanning range and incidence angle as proxy metrics. The surface areas of the objects covered from all potential scanning locations are then calculated and employed in a BIP optimisation model that is used to identify a solution to the planning for scanning problem. Objective III is addressed through a set of experiments that reported the next chapter.

Table 4 replicates Table 3 with an additional column for the newly proposed approach, thereby highlighting the key differences between it and the previous state-of-the-art methods. Like the two most recent publications identified in the literature review as the state-of-the-art [5, 20], the proposed approach aims to be general (i.e. it does not make any assumption regarding the context in which it is to be applied) and achieve a global optimisation (i.e. it does not assume any manually pre-defined set of scanning locations). But, the proposed approach differs from any prior work by its unique consideration for LOC specifications. Furthermore, it is worth noting that it is the first global approach that considers not just one but two of the LOA, LOC and LOD specifications. In fact, it is explained in the conclusion of this thesis how it could easily also integrate the third specification LOD.

Table 4. Comparing proposed approach with existing methods

Criteria	**Tang and Alaswad (2012) [19]**	**Song et al. (2014) [5]**	**Zhang and Tang (2015) [20]**	**Proposed Approach**
LOA	*Yes*	*No*	*No*	*Yes*
LOD	*Yes*	*Yes*	*Yes*	*No*
LOC	*Partially*	*No*	*No*	*Yes*
Occlusions	*Yes*	*Yes*	*Yes*	*Yes*
Optimization	*Local*	*Global*	*Global*	*Global*
Generalization	*Yes*	*Yes*	*Yes*	*Yes*

The proposed approach assumes as input a 3D BIM model of the facility to be scanned. In contrast with a 3D CAD model, the 3D BIM model provides knowledge of the type of objects contained in the scene. In the proposed approach, this information enables the automated retrieval of the floors (in Step 1). It also enables the automated retrieval of the objects of interest; for example, if the user aims to plan to scan all structural components, s/he would only need to tell the system to focus on “structural components” and the system could automatically identify them in the BIM model and focus the analysis on them when finding the optimal set of scans (Steps 3 to 5). Furthermore, the type of material of each object, which can be automatically obtained from the BIM model, could be used to get a more robust estimation of the precision expected for each scan point (LOA) – assuming that graphs like the one shown in Figure 7 are available for various materials.

Nonetheless, the core of the P4S algorithm proposed here only requires the knowledge of the 3D geometry of each object. This means that the proposed approach could be employed with 3D CAD models as opposed to 3D BIM models. The only different would be that the user would have to manually select (e.g. through a 3D interface): which objects are ‘floor’ objects upon which the scanner would be positioned; which objects are planned to be scanned; and possibly what their material is.

As presented in Section 2.1, the AEC sector is rapidly embracing BIM processes and the use of BIM models, so that BIM models are rapidly replacing 2D/3D CAD models. For this reason, this research focuses on the case where the input model is a 3D BIM model.

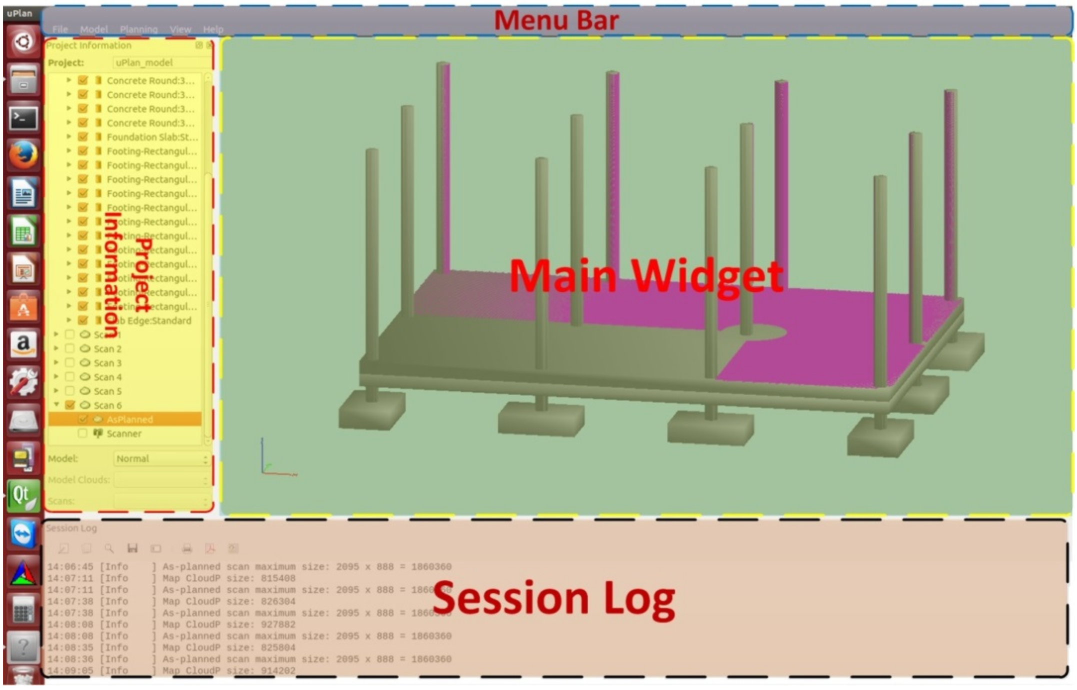
CHAPTER 5: EXPERIMENTAL RESULTS AND ANALYSIS

This chapter presents the prototype implemented to validate the proposed approach, and then reports the experimental results and their analysis. Experiments are conducted to assess the performance of the proposed system in terms of effectiveness, efficiency and sensitivity (to internal parameter selection). Altogether, this chapter focuses on the work conducted towards Objective III.

5.1 Software Prototype

This section presents the P4S software prototype designed to conduct the experiments aimed at validating the research Objective III. To design this prototype, open source C++ libraries and software are used. More specifically, the prototype is built using an existing Point Cloud and BIM software platform [41] employing: the IfcOpenShell library to manage BIM model data in IFC format [85]; the libe57 library to manage point cloud data in e57 format [86]; and the Qt library to develop the software in particular its Graphical User Interface (GUI) [87].

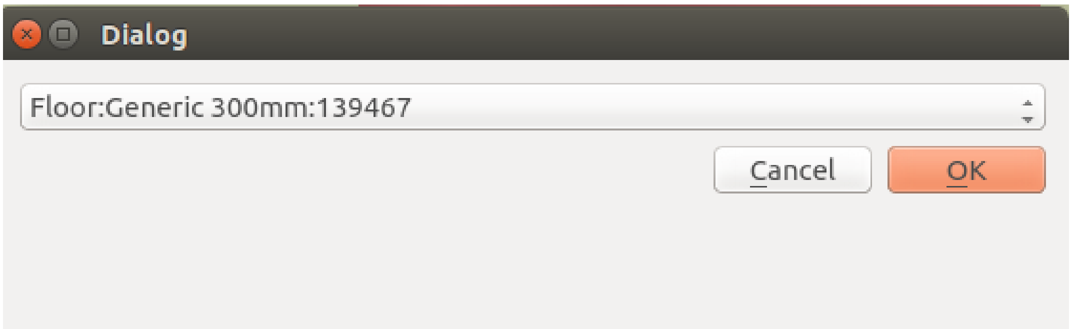
The software prototype has a user-friendly GUI. Using this GUI, the user is able to import 3D BIM models, specify the LOA and LOC requirements, and enter the scanner characteristics. Figure 19 illustrates the P4S software GUI that is composed of four parts:



```
14:06:45 [Info     ] As-planned scan maximum size: 2095 x 888 = 1860360
14:07:11 [Info     ] Map CloudP size: 815408
14:07:11 [Info     ] As-planned scan maximum size: 2095 x 888 = 1860
14:07:38 [Info     ] Map CloudP size: 826304
14:07:38 [Info     ] As-planned scan maximum size: 2095 x 888 = 1860
14:08:08 [Info     ] Map CloudP size: 927882
14:08:08 [Info     ] As-planned scan maximum size: 2095 x 888 = 1860360
14:08:35 [Info     ] Map CloudP size: 825804
14:08:36 [Info     ] As-planned scan maximum size: 2095 x 888 = 1860360
14:09:05 [Info     ] Map CloudP size: 914202
```

Figure 19. Planning for Scanning GUI

- Menu Bar: The menu bar has five menus: File, Model, Planning, View and Help. The most important ones are the menu 'Model' to import the 3D BIM model and the menu 'Planning' to launch the P4S process. When starting the P4S process, the system extracts all the floors from the BIM model and asks the user to select the one to use for the current process. Figure 20 shows the window that pops to ask the user for the floor object to be used.



Floor:Generic 300mm:139467

Figure 20. Automatically system identified objects (Floor)

- **Main Widget:** The main widget is a 3D (OpenGL) widget that is used to display the 3D BIM model and the P4S results. The user can orbit and translate the 3D data, select individual objects, etc. The potential scanning locations generated by the system as well as the virtual scans generated for all those locations can also be visualized in the 3D environment.

  Once the covered surface areas have been calculated for all objects and all potential scanning locations, a Binary Integer Programming (BIP) algorithm is employed to solve the optimization problem for finding the minimum set of scanning locations delivering the specified minimum covered surface for each of the given objects. This is currently achieved by exporting the system-generated covered surface areas for all potentials scanning locations in CSV format (spreadsheet). The OpenSolver plug-in to Excel is then employed to apply the open-source branch-and-cut (CBC) BIP solver [88]; this plug-in employs the CBC implementation from the widely-used and robust Computational Infrastructure for Operations Research (COIN-OR) library [89].

  Note that the COIN-OR library is also available as a C++ library, and so this step could be embedded within the P4S software package to achieve a completely automated process. However, during this research, maintaining this stage of the process separate from the main software package did actually provide some valuable flexibility.

- **Project Information Panel:** The project information panel lists all the objects contained in the scene: the 3D BIM model objects and later on all the virtual scans. Selecting an object in this list highlights it in the 3D environment, which eases visualisation and data navigation.

- **Session Log Panel:** The session log panel presents logging information while the system is in execution. This provides detailed information about progress but also at which stage potential errors/bugs have occurred.

5.2 Experimental Data

In addition to the Simple Structural Model already used as example in Chapter 4, two other models are considered for the experimental work:

- *Structural Model*: A typical structural 3D BIM model of a building storey that is made up of columns and a floor.

- *Structural+MEP Model*: A section of the structural model above extended with Mechanical, Electrical and Plumbing (MEP) components.

While the first model is considered for the planning of the scanning of structural works, the second model is used to more specifically consider the planning for scanning of MEP components. Table 5 summarises the number of objects in each model.

Table 5. List of experimental as-planned 3D BIM models

As-planned 3D BIM Models	Plan size	Number of Objects
Simple Structural Model	12m x 8m	25
Structural Model	66m x 54m	64
Structural+MEP Model	33m x 6m	118

5.2.1 *Simple Structural Model*

The Simple Structural Model can be considered as simulated data because it was designed by the author. This model was mainly used to check that the proposed P4S method is working as expected and identify any necessary correction prior to testing at larger scales. As shown in Figure 21, this model is made up of one floor, twelve columns and footings. However, footing foundations are not considered within the optimisation as they would be backfilled at the time one would need to scan the floor and columns. Experimental results obtained with this model are provided in Section 5.3 to further illustrate the working of the proposed system.

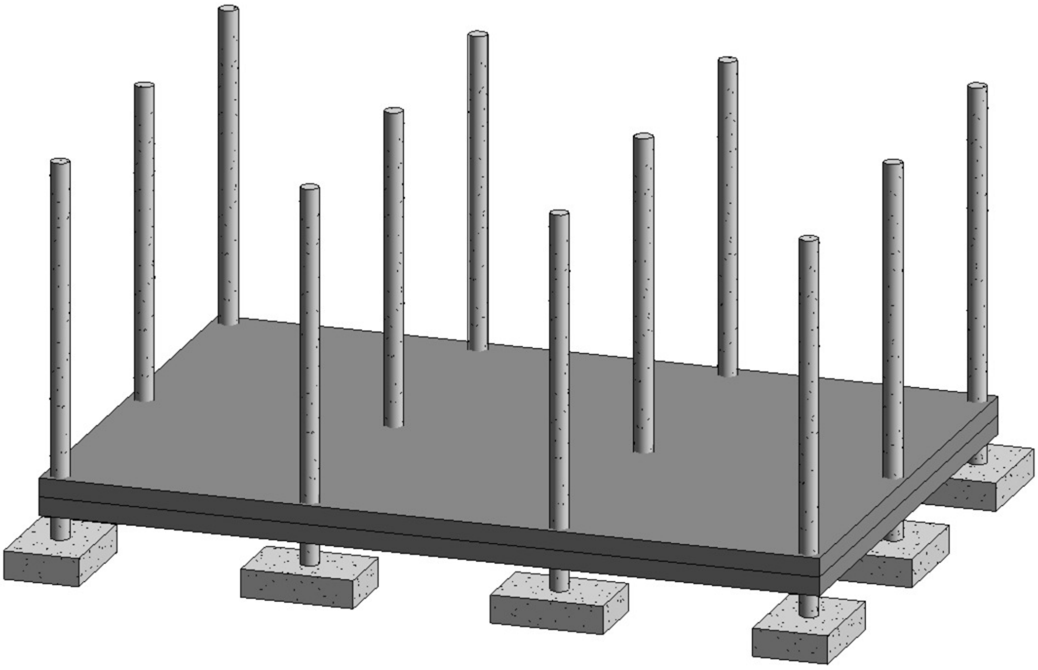


Figure 21. 3D view of the Simple Structural Model

5.2.2 *Structural Model*

The Structural Model, shown in Figure 22, is the ground storey of a sample Structural 3D BIM model provided by Autodesk. The Structural Model (of the ground storey) is composed of 63 cylindrical concrete columns and one large floor slab.

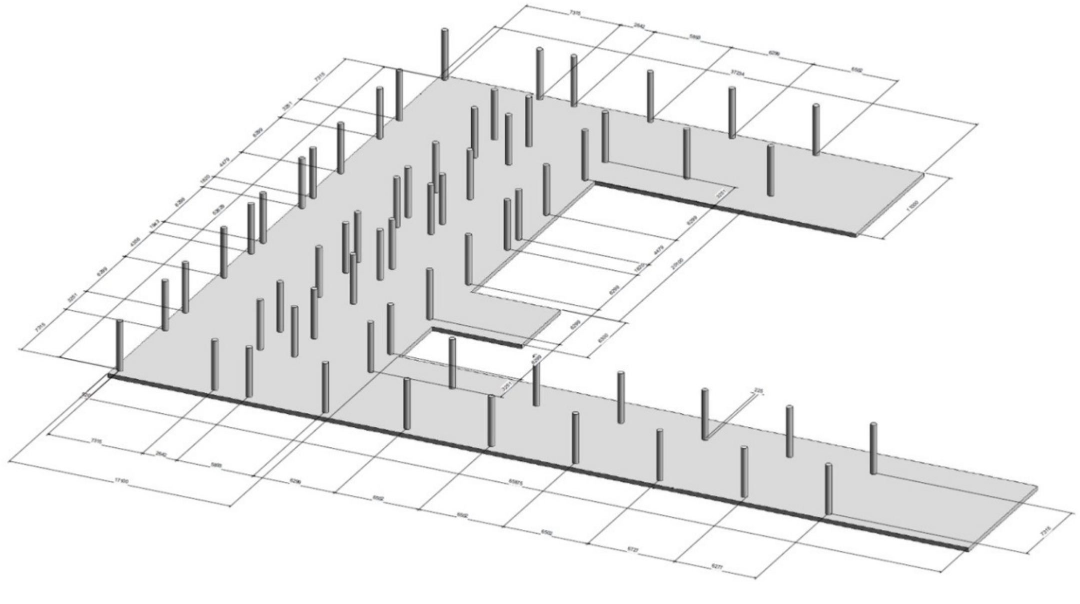


Figure 22. 3D view of the Structural Model

5.2.3 ***Structural + MEP Model***

A section of the Structural Model above is also considered extended with Mechanical, Electrical and plumbing (MEP) components (also provided by Autodesk). This model, shown in Figure 23, is composed of 118 objects: 10 structural columns, one floor and 107 MEP objects (including rectangular duct, duct elbow, pipes, etc.). This model is used to assess the value of the proposed P4S method for planning the scanning of MEP systems, as opposed to structural ones. The structural components in it are there because the occlusions they would create in practice need to be also considered during planning.

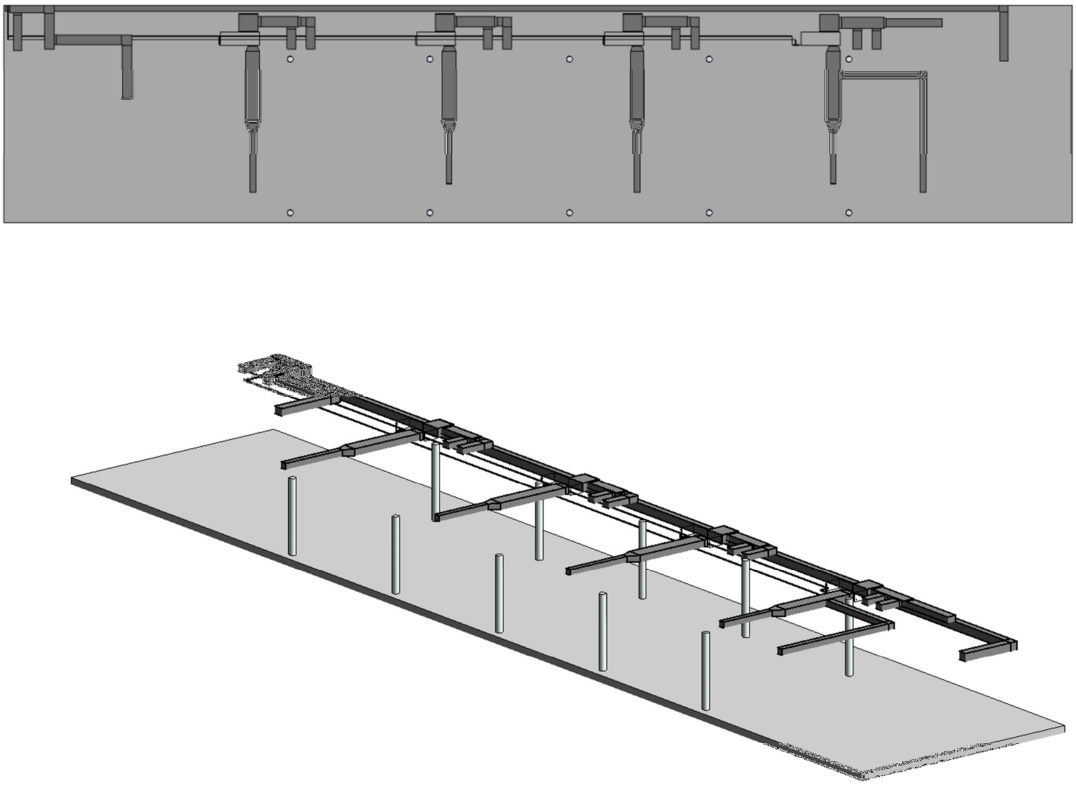


Figure 23. Top view and 3D view of the Structural+MEP Model

5.3 Experiments and Evaluation of System Performance

This section presents the experiments that have been conducted using the models above to validate the proposed P4S system. The performance of the system is evaluated in terms of effectiveness, efficiency and sensitivity (to internal parameter value selection). Note that in this research effectiveness refers to “doing the right thing” whereas efficiency refers to “doing it with few resources, particularly time”.

But first, illustrative results obtained with the proposed system are presented in the next section using the Simple Structural Model.

5.3.1 Illustrative Experiment

The working of the proposed P4S system is illustrated using the Simple Structural Model. For the experiment, the necessary input parameters are set as summarised in Table 6.

Table 6. Scanner characteristics, scanning specifications and other parameters set for the illustrative experiment

Parameter	Value
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height (h)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	50% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	4m

The defined grid density leads to the generation of 24 potential scanning locations as shown earlier in Figure 16. Table 7 then summarizes the covered surface areas calculated by the system for all 13 objects and for all of the 24 potential scanning locations – i.e. the matrix A. The optimisation stage is successful and finds a solution summarised in Table 8. The results indicate that the minimum set of scanning locations necessary to fulfil the LOC (and LOA) specifications for all 13 objects contains four locations. The set reported by the system includes the scanning locations SL6, SL8, SL13 and SL14 (see Figure 24), but other sets of 4 scanning locations may solve the problem. However, there is no solution that contains 3 or fewer locations.

Table 7. Covered surface areas (in m^2) calculated for all objects in the illustrative example. "Col.0" to "Col. 11" refers to the 12 columns in the model, and "SL1" to "SL24" refer to the 24 potential scanning locations.

SLs	**Col. 0**	**Col. 1**	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Col. 8**	**Col. 9**	**Col. 10**	**Col. 11**	**Floor**
SL1	1.51	1.58	0.03	1.61	1.59	1.58	0.00	1.60	0.00	1.55	1.25	0.00	8.62
SL2	1.60	1.34	1.51	1.53	1.60	1.56	1.41	1.58	1.48	0.00	1.50	1.52	14.39
SL3	1.52	0.03	0.00	1.60	1.68	1.55	1.39	0.00	1.62	1.25	0.00	1.62	14.07
SL4	1.68	1.51	0.00	1.60	1.61	1.60	1.47	1.58	1.62	1.50	1.52	0.74	14.08
SL5	1.51	1.56	1.52	1.72	1.59	1.34	1.61	1.53	0.00	1.26	1.48	0.00	14.39
SL6	1.60	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.64	1.72	1.65	1.48	25.40
SL7	1.24	1.52	1.64	1.58	1.34	1.59	1.59	0.00	1.56	1.48	0.00	1.59	25.22
SL8	0.99	1.63	1.57	1.56	1.66	1.72	1.64	1.47	0.65	1.65	1.48	1.73	24.50
SL9	1.60	1.55	0.00	0.00	1.58	0.03	1.61	1.59	1.58	0.00	1.60	0.00	14.07
SL10	1.64	1.59	1.57	0.00	1.34	1.52	1.53	1.60	1.56	1.33	1.58	1.58	25.22
SL11	1.65	0.00	0.00	1.68	0.03	0.00	1.60	1.68	1.55	1.60	0.00	1.59	19.52
SL12	0.60	1.57	1.48	1.34	1.51	0.00	1.60	1.61	1.60	1.58	1.58	1.65	24.46
SL13	1.59	1.60	0.00	1.58	1.56	1.51	1.72	1.59	1.34	1.62	1.53	0.00	14.54
SL14	1.63	1.72	1.55	1.47	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.47	25.69
SL15	1.66	0.00	1.64	1.61	1.52	1.57	1.58	1.34	1.59	1.53	0.00	1.57	25.44
SL16	1.66	1.55	0.00	1.66	1.63	1.55	1.56	1.66	1.72	1.60	1.47	0.67	24.79
SL17	1.64	1.41	0.00	1.59	1.55	0.00	0.00	1.58	0.03	1.60	0.71	1.68	14.07
SL18	1.60	1.49	1.53	1.57	1.59	1.64	0.00	1.34	1.52	1.67	1.60	1.61	25.23
SL19	1.55	0.00	0.00	1.59	0.00	0.00	1.68	0.03	0.00	1.59	1.68	1.59	19.52
SL20	1.56	1.53	1.61	1.50	1.57	1.64	1.34	1.51	0.00	1.60	1.61	1.71	24.46
SL21	1.60	1.52	0.00	1.65	1.60	0.00	1.58	1.56	1.51	0.19	1.59	1.34	13.89
SL22	0.68	1.54	1.55	0.67	1.72	1.57	1.47	1.66	1.63	1.50	0.71	1.66	23.16
SL23	1.25	0.00	1.60	1.71	0.00	1.48	1.61	1.52	1.57	1.59	1.34	0.00	23.97
SL24	1.67	1.55	1.53	1.55	1.55	0.00	1.66	1.63	1.55	1.59	1.66	1.55	23.58

Table 8. Covered surface areas for the optimal solution of four scanning locations found by the system

SLs	**Col. 0**	**Col. 1**	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**	**Col. 7**	**Col. 8**	**Col. 9**	**Col. 10**	**Col. 11**	**Floor**
SL6	1.60	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.64	1.72	1.65	1.48	25.40
SL8	0.99	1.63	1.57	1.56	1.66	1.72	1.64	1.47	0.65	1.65	1.48	1.73	24.50
SL13	1.59	1.60	0.00	1.58	1.56	1.51	1.72	1.59	1.34	1.62	1.53	0.00	14.54
SL14	1.63	1.72	1.55	1.47	1.66	1.63	1.58	1.59	1.66	0.00	1.60	1.47	25.69
Covered Surface	5.81	6.60	4.75	6.19	6.48	6.51	4.94	6.25	5.29	4.98	6.26	4.68	90.14
Total Surface	9	9	9	9	9	9	9	9	9	9	9	9	106
LOC specification	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	53

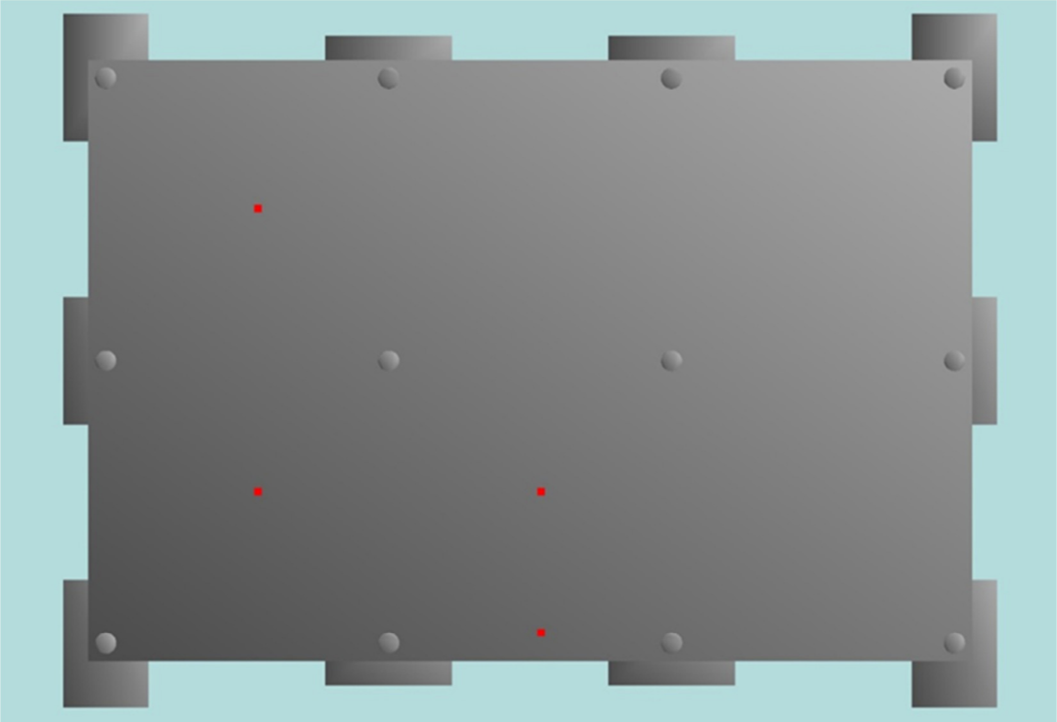


Figure 24. Top view of the Simple Structural Model showing the optimal set of scanning locations (four locations) obtained for the illustrative example

5.3.2 ***Evaluating Effectiveness***

In order to assess the effectiveness of the proposed approach, a professional surveyor with experience conducting TLS surveys was invited to propose her own scanning plan for the Structural Model (Figure 22) given pre-defined scanning requirements and specifications. A top view of a 2D drawing of the model was provided to the professional as standard practice is to use such drawing for generating scanning plans manually with a pen and a compass.

The professional was provided with instructions that included the same information as that used by the system including: scanner characteristics, and LOA and LOC scanning specifications. These are summarised in Table 9. Figure 25 shows the professional's solution with triangle icons showing the 8 scanning locations she defined.

In contrast, the solution obtained automatically by the P4S software prototype, shown in Figure 26, contains 7 scanning locations selected from 154 potential scanning locations.

Both solutions are not perfectly equivalent, but do resemble each other. Most interestingly is the fact that they suggest a very similar number of scanning locations to solve the problem. However, it can be noted that, while the scanning locations automatically generated by the proposed system are somewhat spread around the floor, some locations appear very close to one another (a similar observation could be made for the Illustrative Experiment earlier). This is actually due to a weakness of the proposed P4S approach that will be discussed in more detail later in this chapter.

Table 9. Scanner characteristics, scanning specifications and other parameters set for the effectiveness experiment with the Structural Model

Parameter	Value
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height (h)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	50% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	5m

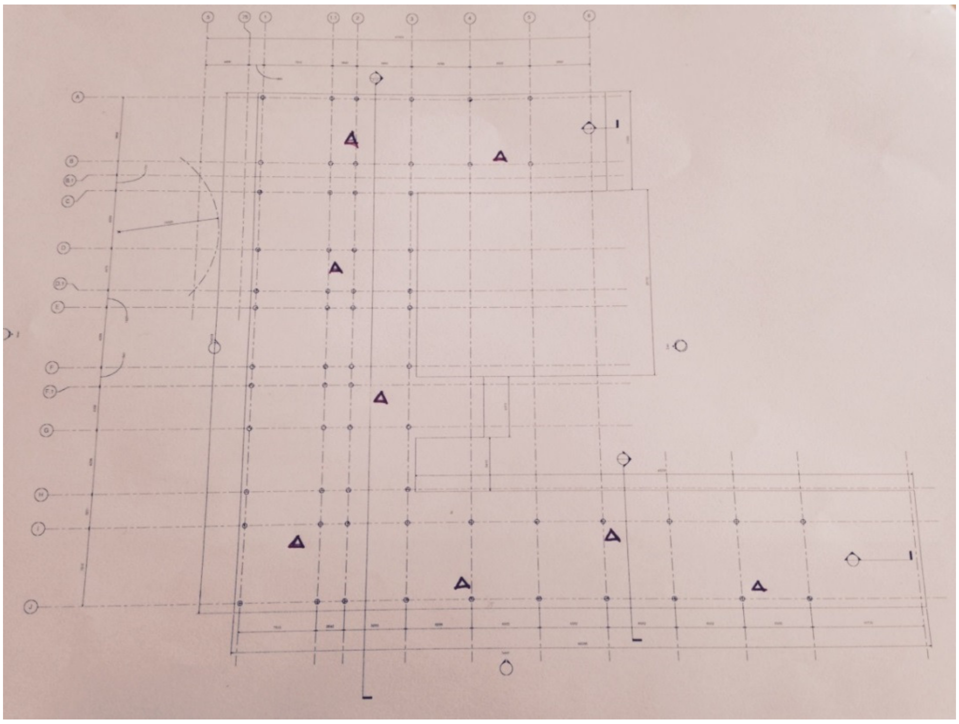


Figure 25. Scanning plan generated by the professional for the Structural Model

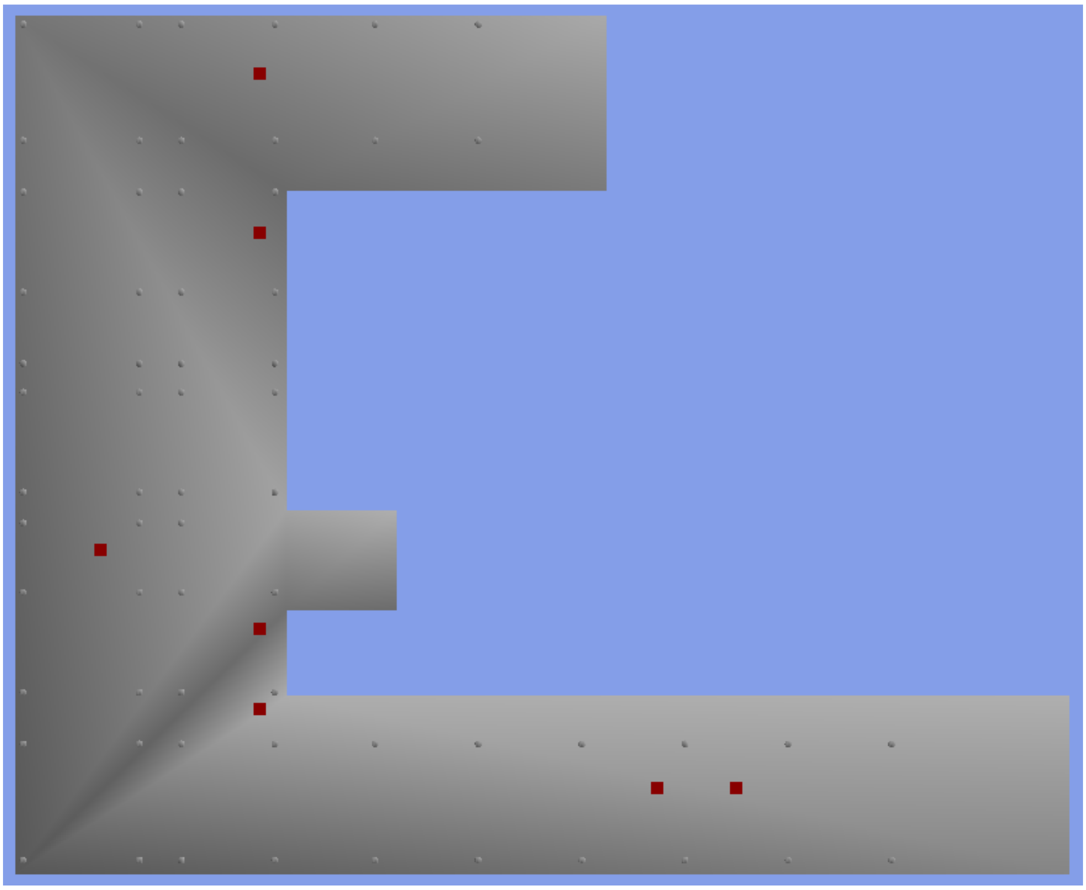


Figure 26. Scanning plan generated by the proposed system for the Structural Model

To conduct a more quantitative comparison of the solutions obtained automatically by the proposed system and manually by the professional, the scanning locations defined by the professional were 'inputted' inside the developed software prototype to assess whether that solution indeed fulfils the specifications or not. The virtual scans were calculated for those eight locations (see Figure 27), the points not fulfilling the LOA specification discarded, and finally the covered surfaces for all objects calculated. As summarised in Table 10, the LOC specification is met for all but seven objects (C0, C5, C9, C11, C14, C16 and C59), although for most of those the covered surfaces are not significantly off the LOC specification. In contrast, the automatically generated solution fulfils the LOC specifications for all objects.

The conclusion from this result is first that professional surveyors have significant expertise to generate scanning plans. Indeed, although the LOC specification is not completely fulfilled for all objects, the solution provided by the professional appears very good, demonstrating great skills. Nonetheless, it must be noted that the case study considered here was rather simple, with columns homogenously spread over a floor. Many other scanning scenarios can however be significantly more complex, in which case ad-hoc knowledge and rules may not suffice to generate effective plan.

Table 10. Covered surface areas for 8 optimal locations suggested by the professional

S. Locations	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31	C32	C33	C34	C35	C36	C37	C38	C39	C40	C41	C42	C43	C44	C45	C46	C47	C48	C49	C50	C51	C52	C53	C54	C55	C56	C57	C58	C59	C60	C61	C62
SL13	0	0	0	0	0	1.9	1.6	1.6	1.7	1.9	2	0	0	0	0	0	0	1.9	0	0	1.7	1.6	0	0	0	0	0	0	0	0	0	1.8	2.1	0	0	0	1.6	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.6	1.7	1.7	1.8	1.5	0	1.7
SL30	0	1.8	1.6	1.7	1.6	0.4	0	0	0	0	0	1.7	0	0	0	1.4	0	0	0	0	0	0	1.7	1.8	1.8	1.9	1.7	1.7	1.7	1.7	0	0	0	1.9	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	1.8	1.8	1.8	1.8	1.7	1.7	0	0	0	1.6	1.7	0
SL33	1.7	1.7	1.7	1.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	1.9	1.8	1.7	0	0	0	0	0	0	1.9	1.7	1.8	0	0	1.9	1.4	0	0	0	0	0	0	0	0	0	0	1.8	1.7	1.8	1.9	0	0	0	0	0	0	0	1.8	0
SL38	0	0	0	0	1.7	0.2	1.6	1.1	1.4	0	1.6	0.5	0	0	0	1.9	1.6	1.7	1.7	1.7	1.8	1.8	1.7	0	0	0	1.1	1.7	1.8	1.8	1.7	1	1.5	0.5	0	0	1.7	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	1.2	1.7	1.7	1.7	1.7	1.8	0	1.8	1.7	1
SL45	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0	0	1.9	1.8	1.7	0	0	0	0	0	0	0	0	1.7	1.7	1.8	1.8	0	0	0	1.8	1.8	0	0	1.7	1.6	1.6	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	1.5	0.3	0	0	1.4
SL65	0	0	0	0	0	0	0	0	0	0	0	0	1.9	1.6	1.9	1.9	0	0	0	0	0	0	1.6	1.7	1.7	1.8	2	1.6	0	0	0	0	0	1.8	1.9	1.7	0	0	1.9	1.7	0	0	0	0	0	0	0	0	0	0	1.9	0.6	1.7	2	0	0	0	0	0	0	0	0	0
SL79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9	1.9	1.9	0	0	0	1.8	1.9	0	0	1.8	1.8	1.9	1.8	1.8	1.8	1.8	1.7	1.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SL111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	0.9	1.9	1.6	1.7	1.7	1.7	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0
Covered Surf.	**1.7**	**3.5**	**3.3**	**3.6**	**3.3**	**2.5**	**3.2**	**2.8**	**3.2**	**2.4**	**3.5**	**2.2**	**3.8**	**3.3**	**1.9**	**5.2**	**1.6**	**3.6**	**3.7**	**3.5**	**5.2**	**3.4**	**5**	**5.3**	**5.4**	**5.5**	**6.5**	**5**	**3.5**	**5.2**	**5.4**	**6.4**	**7.3**	**6.1**	**3.6**	**5.1**	**6.8**	**5.3**	**3.8**	**3.2**	**4.9**	**3.4**	**5.2**	**3.4**	**3.7**	**3.4**	**3.5**	**3.5**	**3.3**	**1.7**	**5.4**	**4.1**	**5.2**	**6.8**	**3.5**	**4.4**	**5.1**	**5**	**5.1**	**2**	**4.8**	**5.2**	**4.2**
LOC	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8

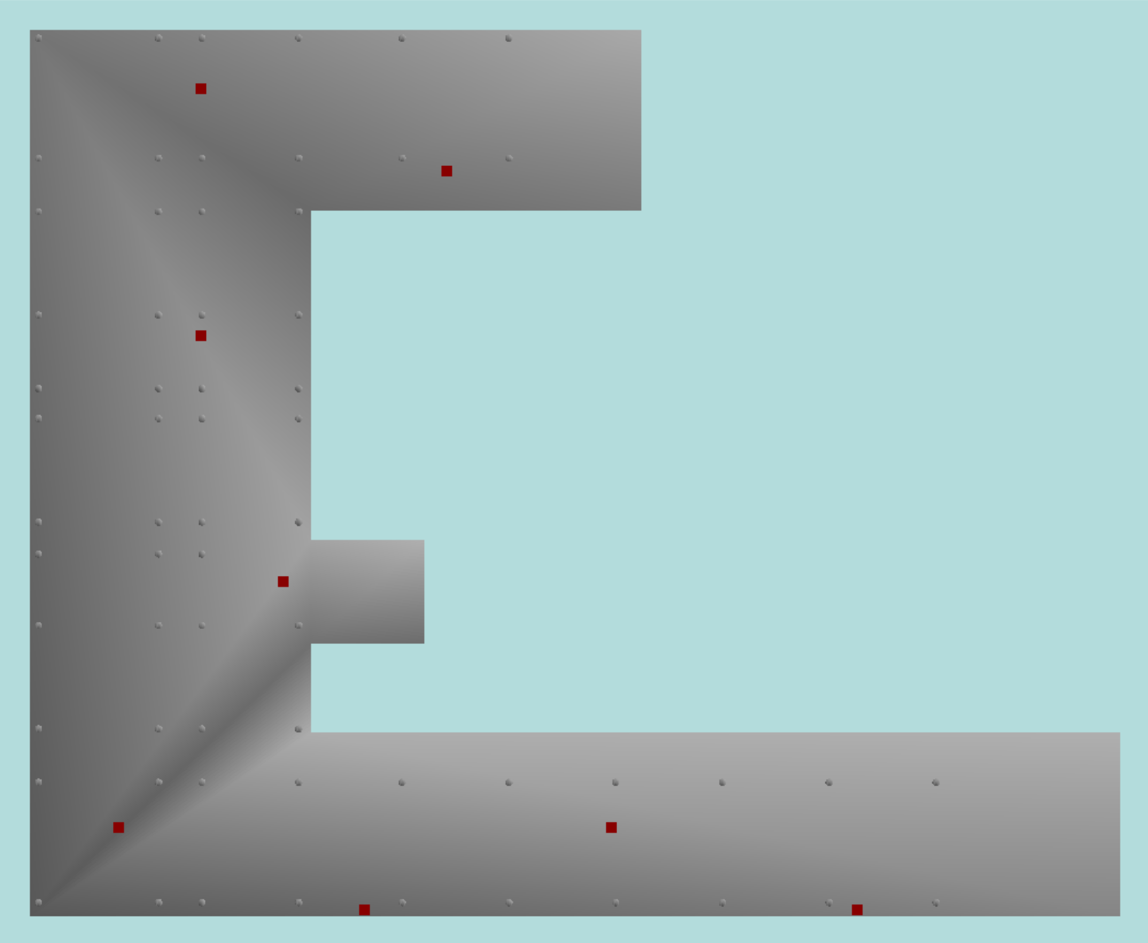


Figure 27. Professional suggested 8 scanning locations

To further test the system's effectiveness, an experiment is also conducted with the MEP+Structural Model, that is composed of concrete structural objects (floor and columns) and numerous MEP objects with various shapes and orientation. This experiment is conducted by assuming that the scanning plan needs only be provided for the MEP element; the structural elements are only considered as part of the scene (they can result in occlusions that should not be overlooked during planning). The values of all the parameters used for this experiment are summarized in Table 11. In particular, the selected grid density led to the generation of 231 potential scanning locations shown in Figure 28.

Table 11. Scanner characteristics, scanning specifications and other parameters set for the effectiveness experiment with the Structural+MEP Model

Parameter	**Value**
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height (*h*)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	40% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	1.5m

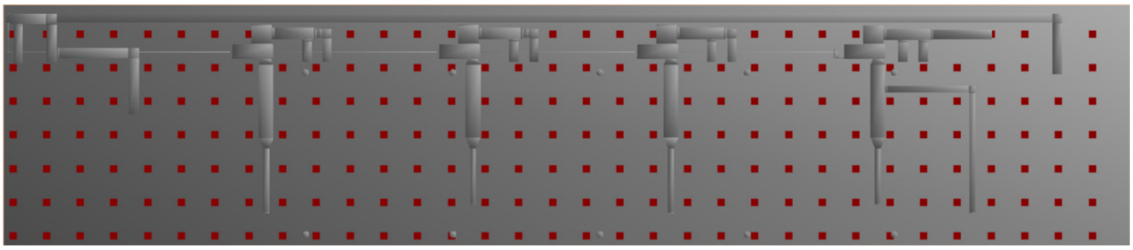


Figure 28. Potential scanning locations generated by the proposed approach for the Structural+MEP model for β=1.5m

The proposed approach is unable to find any feasible solution (optimal scanning locations) when the LOC specification is set to 50% of the MEP objects' total external surface areas, even when the relatively high grid density (β=1.5m) considered. A solution is only found for that grid density when reducing the level of surface completeness to 40% of the objects' surface areas. Figure 29 shows the system-generated solution that contains 59 scanning locations. The first reaction to this result is the large number of scans required to obtain the necessary data (i.e. fulfil the LOA and LOC specifications). For such a small scene, conducting such a number of scans seems unrealistic. There are several reasons for this arguably disappointing result:

1. At least 25% of the surface of most MEP components faces the ceiling and so could not be scanned from any location. This made fulfilling the LOC specification much harder than with the concrete columns earlier.
2. The incidence angle LOA constraint results in the rejection of many virtually scanned points. This interestingly suggests that scanning such objects without

large incidence angles is very difficult and so very high point precision levels cannot be easily achieved. However, it can also be argued that many of the scanning locations are actually fairly close to MEP objects (<5m) and at those distances the maximum allowable incidence angle to achieve a ±2mm precision would likely be larger than the 60° value required here. Unfortunately, the author could not get access to any table like Figure 7 for other distances than 20m and so couldn't exactly confirm this theory.

3. The scanner's height was set to 2m, which was about 1.5m below the height of the MEP equipment. This height may possibly be both too low to optimise the chances of acquiring points on the side faces of the MEP objects with sufficient precision, but also too high to optimise the chances of acquiring points on the bottom faces of the MEP objects with sufficient precision. For the case of planning for scanning MEP objects, it may thus be more appropriate to combine potential scanning locations at two different heights: one height similar to that of the objects (e.g. 3.5m here), and a second much closer to the floor; e.g. 1m here. Unfortunately, this experiment was not conducted due to the developed system crashing during compilation (unfortunately, the issue could not be solved during the time of the study).

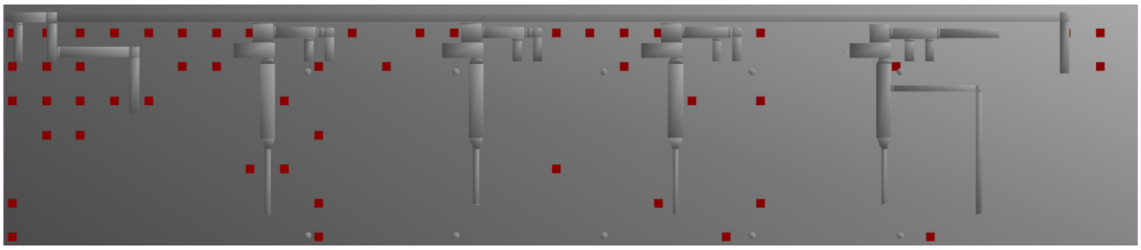


Figure 29. Optimal scanning locations (59) for the MEP+Structural model

5.3.3 *Evaluating Efficiency*

The efficiency of the proposed approach is measured using the time necessary to calculate all virtual scans and covered surfaces (Steps 1 to 4), i.e. the time required to generate the matrix *A*. The optimisation stage (the fifth stage) has been found to be comparatively very fast, so that the time taken by the first four steps (that all occur within the developed software system) is very much representative of the overall computational time. Experiments are conducted using the Structural Model and Structural+MEP Model to show the impact of varying numbers of objects, and grid sizes. Finally, the efficiency of the automated system is compared with the time spent by the professional for the first experiment. The scanning parameters employed for all cases are summarized in Table 12.

Table 12. Scanner characteristics, scanning specifications and other parameters set for the efficiency experiment with the Structural Model and Structural+MEP Model

Parameter	**Value**
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height(h)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	50% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	1.5m and 5m

Table 13 summaries the results. It shows that, as expected, the overall computational time increases linearly with the number of scans and the number of objects (more precisely, the number of mesh faces) in the 3D models. Regarding the comparison with the professional for the first experiment, she was clearly significantly faster than the prototype of the proposed approach. Nonetheless, one must remember that that case study, although common, can be considered rather simple. Furthermore, the assessment of the solution provided by the professional showed that it did not quite meet the scanning specifications.

Table 13. Computational times using the Structural and Structural+MEP models, for various grid sizes, and also time spent by the professional surveyor. Note that the 3rd column is the "number of potential locations" as opposed to the number of locations in the solution. Therefore, this column does not apply in the case of the solution devised by the professional.

Overall Computational Time			
Model	**Grid Size (Meter)**	**No. Potential Scans**	**Total Time**
Structural Model	1.5	1584	17:39:40
	5	154	1:30:31
Structural + MEP Model	1.5	231	3:24:03
Structural Model (Professional)	1.5	N/A	0:15:00

5.3.4 **Evaluating Sensitivity**

The sensitivity of the proposed system should be assessed with regard to the values of internal parameters it uses. The proposed method employs a few such parameters that could be varied and therefore impact the results outputted by the system:

- $(\varphi_{res}, \theta_{res})$, the horizontal and vertical angular resolutions of the scanner;
- h, the height of the scanner; and
- β, the size (density) of the grid of potential scanning locations;

The first parameters, $(\varphi_{res}, \theta_{res})$, have actually hardly any impact on the plans delivered by the proposed approach. Indeed, the covered surface of each scanned point takes into account the scanning resolution, so that the covered surface of a point cloud acquired with a given resolution is essentially the same as the covered surface of a point cloud of the same scene acquired with any other resolution. Scanning resolution actually only impacts the specification LOD, which is not taken into account in the method presented here.

The scanner's height, h, could have an impact on the result, but that impact is considered comparatively small, particular in the case of the structural model. The default height $h=2m$ is set as half the ceiling height and is very representative of typical scanner heights set in such environment. Conducting a sensitivity analysis on this parameter would thus unlikely yield any interesting information.

In contrast, the last parameter, β, can significantly impact the result. If the grid is set too sparse, a solution may even not be found at all by the system. If it is set very dense, the optimal solution is increasingly likely to be found, but at the cost of significant computational time. Conducting a sensitivity analysis on that parameter would enable identify if its value could indeed significantly impact the quality of the results obtained or not. Experiments have thus been conducted with the Structural Model using grid sizes of 1.5m, 3m, 5m, 7m, and 10m. These and all other experimental parameters employed for this experiment are summarised in Table 14.

Table 14. Scanner characteristics, scanning specifications and other parameters set for the robustness experiment with the Structural Model

Parameter	**Value**
Scanner Characteristics	
Angular Resolution	0.17° x 0.17°
Scanner Height (*h*)	2m
Field of View	360° x 152°
Scanning Specifications	
LOA	±2mm
LOC	50% of the object's overall surface (same for all objects)
Other Parameters	
Grid density (β)	1.5m, 3m, 5m, 7m, and 10m

The potential scanning locations generated for the different grid sizes are shown in Figure 30. Table 15 then summarises the results obtained, and Figure 31 shows the optimal sets of scanning locations for the different grid sizes. The smaller the grid size β, the more likely a solution can be found and the better this solution should be. The results obtained here show that for β=10m, the system is actually unable to find a solution. Then, for β=5m and below, the system finds a solution that systematically includes 19 scans, and for β=7m the solution only includes one additional scan. This first means that the solution is not very sensitive to the parameter β in this context of building structures. As shown earlier the process is 10 times faster for β=5m than for β=1.5m. Therefore, in such context, selecting β=5m may be sufficient to obtain good results (see appendix A) in reasonable computational times.

Table 15. System sensitivity and optimal scanning locations

Grid Size (β)	**No. of Potential Scanning Locations**	**Optimal Set of Scanning Locations**
1.5m	799	19
3m	197	19
5m	82	19
7m	42	20
10m	25	nil

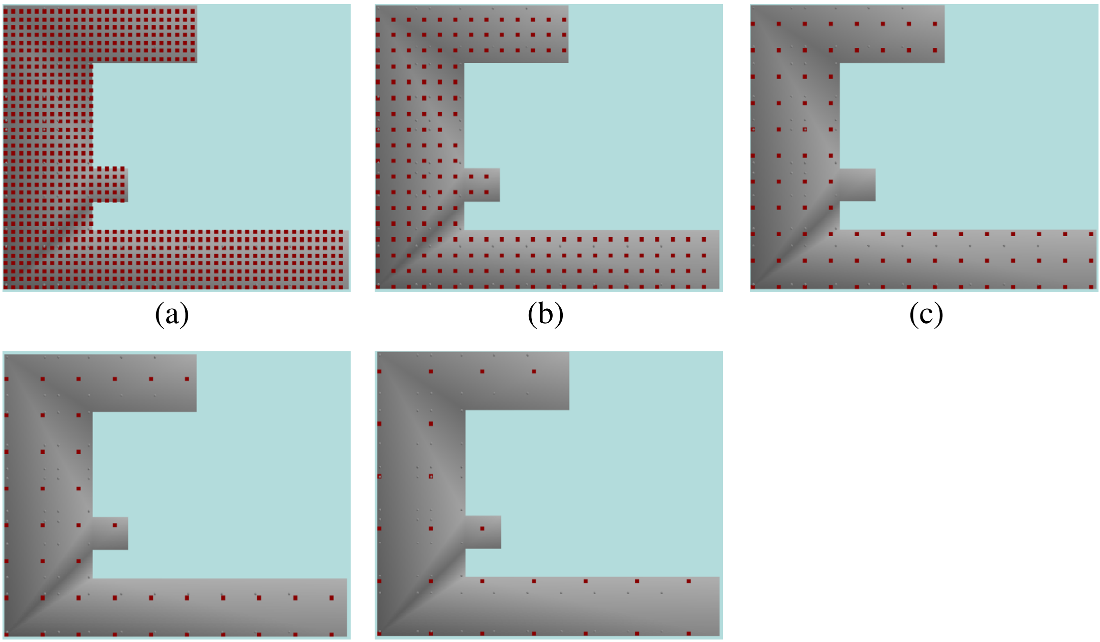
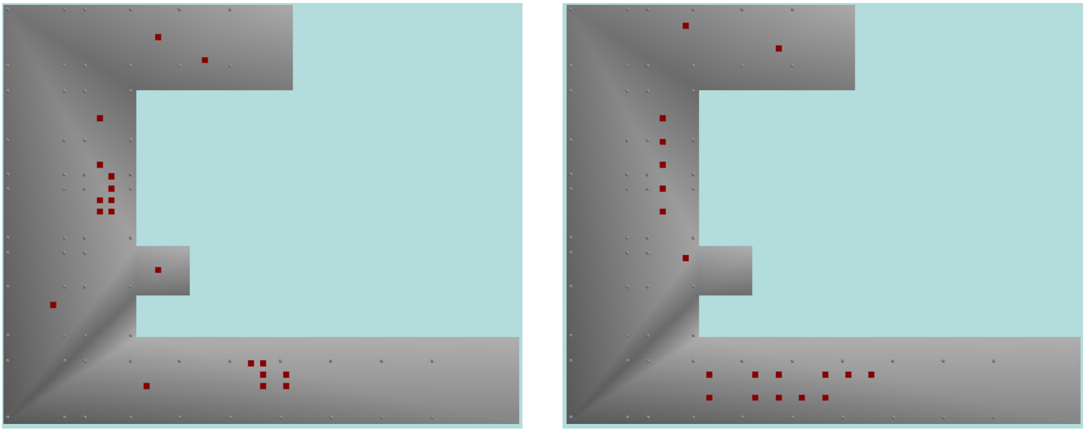
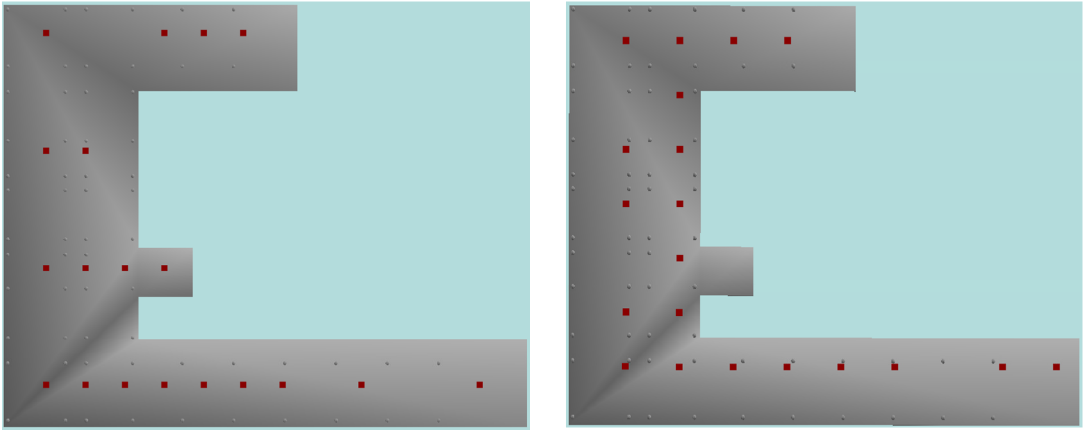


Figure 30. Potential scanning locations generated for different grid densities (β) with the Structural Model; (a) as plan scans for β=1.5m; (b) as plan scans for β=3m; (c) as plan scans for β=5m; (d) as plan scans for β=7m; (e) as plan scans for β=10m



(a) 19 optimal locations for β=1.5m (b) 19 optimal locations for β=3m



(c) 19 optimal locations for β=5m (d) 20 optimal locations for β=7m

Figure 31. System-generated optimal sets of scanning locations for different grid densities (β) for the Structural Model

One can also note that the pattern of optimal scanning locations for β=1.5m and β=3m are quite different from those obtained for β=5m and β=7m; the latter looking more like what would be expected (evenly spread pattern similar to the one produced by the professional). The odd patterns obtained for β=1.5m and β=3m actually result from an important weakness of the proposed approach that has been already noticed earlier and is discussed in the following section.

5.4 Discussion on the main limitation of the proposed method

The evaluation of the proposed system has shown some level of effectiveness and efficiency. But, some of the generated scanning plans were surprising, with the selection of locations very close to one another. This actually brought to light a significant weakness of the currently proposed approach, which can impact its effectiveness. That weakness is that the current approach does not take into account the overlapping of covered surface areas from different locations. And, as a result, the generated results may actually not comply with the LOC specification.

Figure 32 illustrates the scenario of overlapping of covered surfaces from two different scanning locations. In that figure, A1 and A2 are the surface areas covered from two different scanning locations SL1 and SL2, and A12 represents the surface overlapping area from scanning locations SL1 and SL2. In the current approach A12 is actually counted twice. This is arguably an important issue that needs to be addressed through further research, so that the system actually generates effective planning for scanning solutions that completely and systematically satisfy LOC scanning specifications.

Addressing this limitation is actually not straight forward because taking into account overlapping of covered surfaces within the optimisation model would require; (i) developing a method that is able to quantify these overlaps in m^2 , and (ii) adding non-linear constraints to the optimization model. The latter would lead to the need to employ different optimisation techniques, which could significantly increase computational times.

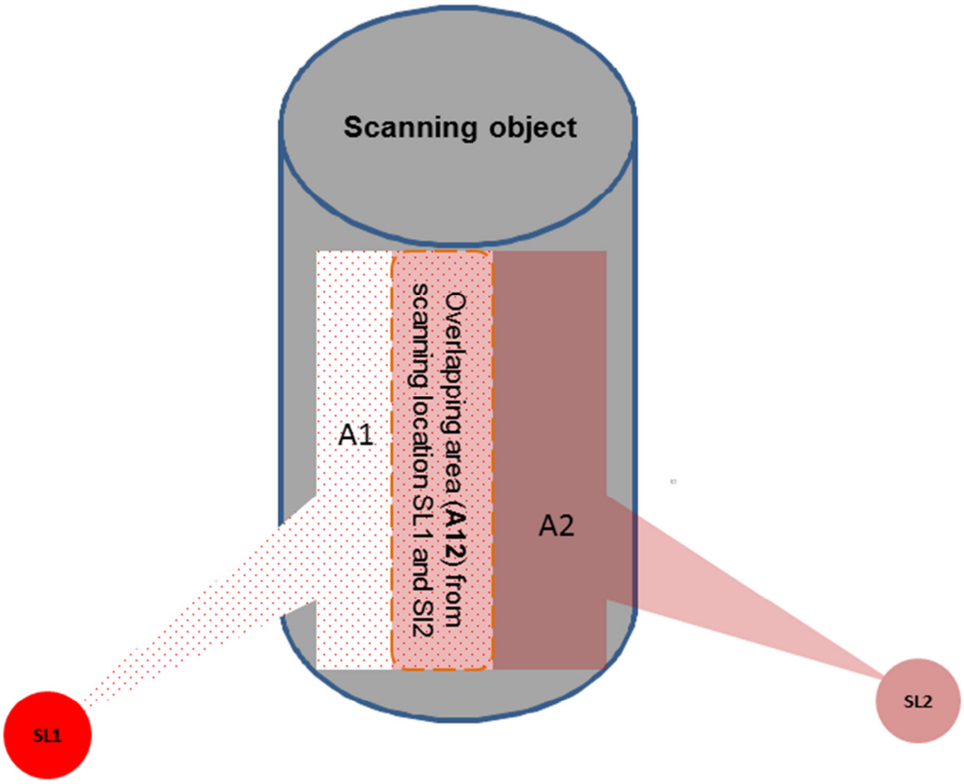


Figure 32. Surface overlapping of scanning object from SL1 and SL2

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This conclusion chapter consists of two parts. The first part reviews the main research contributions. The second part highlights the limitations of the work conducted and provides recommendations for future research to further develop and enhance this research work.

6.1 Research Contributions

This research introduced a novel approach for automatic planning for scanning in the context of the AEC industry, aimed at optimizing 3D laser scanning operations. This approach automatically generates an optimal laser scanning plan (the minimum set of necessary scans) given LOA and LOC scanning specifications and a 3D BIM model of the facility where the scanning is to be conducted. The approach is not developed for use in a specific type of environment but is developed using a general framework enabling its application in various kinds of construction contexts. Furthermore, the approach provides a global optimisation, meaning that the approach does not need to be provided with a manually predefined set of initial scanning locations.

With regard to scanning quality, the approach takes into account a new type of specification that the author identified was lacking from current practice. The author proposes to call it Level of Surface Completeness (LOC) specification. The LOC specification considers the object surface that can be expected to be scanned. It thus focuses on surface-related performance, thereby complementing existing LOA and LOD specifications that are focused solely on local point-related performance.

In order to achieve the main aim of this research, the following objectives were defined:

I. Review the key subjects related to the identified planning-for-scanning problem in the construction industry in particular BIM and TLS technologies, and explore how similar problems may have been investigated in other industries.
II. Design a mathematical model for optimizing the 3D scanning operations, i.e. establishing an optimal scanning plan given the design BIM model as well as LOA and LOC specifications for objects of interest.
III. Implement the developed solution in a prototype system and validate the performance of the proposed model experimentally.

Objective I is addressed through a comprehensive review of subjects related to the research topic (Chapter 2). The chapter first reviews TLS, showing that it has gained significant popularity as a 3D surveying technology. The main applications of TLS, its 3D data capturing principles and the factors impacting its measurements are reviewed. The literature review also covers BIM that is similarly identified as a rapidly growing procedural and technological development in the AEC&FM industry. While BIM focuses on both process and data, this research particularly considers it from the point of view of data and presents the BIM model as a digital representation of a building that gathers all life-cycle data and information about it. The information contained in BIM models that is of particular interest to this research is the types of objects and their 3D geometry (and potentially their constitutive materials). Finally, the literature review makes the case for effective and efficient methods for planning for scanning and reviews current practice and recent research on the subject. The literature review concludes with the identification of a specific need for planning for scanning algorithms that take into account not only point-based quality criteria for assessing the performance of a scanning plan (i.e. LOA and LOD), but also surface-related ones, in particular the amount of surface scanned for each object of interest (the proposed LOC).

For Objective II, an algorithm for Planning for Scanning (P4S) in the context of the construction industry is developed that takes as input a 3D BIM model of the facility to be scanned, and generates an optimal scanning plan that satisfies constraints related to the characteristics of the scanner, and LOA and LOC scanning specifications. The P4S algorithm follows five steps:

Step1: Semi-automatically select the floor in the given input 3D BIM model on which the scanner shall be located, and then automatically generate a grid on the top face of the floor. Each grid intersection is then considered as a potential scanning location.

Step2: Given the scanner characteristics, automatically calculate virtual laser scans from all potential scanning locations.

Step3: Filter each virtually scanned 3D point according to the LOA specification. This is achieved indirectly by filtering points according to specified maximum range (ρ_{max}) and maximum incidence angle (σ_{max}) that should altogether ensure fulfilment of the LOA specification.

Step4: Automatically calculate the covered surface areas for each object of interest for each potential scanning location.

Step5: Automatically calculate the optimal set of scanning locations (i.e. minimum set of scanning locations) that satisfy the LOC specification expressed in terms of minimum covered surface for each object of interest. This is achieved by formulating the optimization problem as a BIP problem and solving it using a Branch-and-Cut algorithm.

To achieve Objective III, a prototype system has been developed that implements the above approach. The system also provides a user-friendly Graphical User interface (GUI) that enables easy data input and visualisation of the results. Then, three different 3D BIM models have been used to conduct illustrative and performance assessment experiments. A simulated simple structural model was first used to demonstrate the working of the approach. Then, a real (medium-size) Structural Model and a portion of it augmented with MEP components were used to evaluate the performance of the proposed approach in terms of effectiveness, efficiency, and sensitivity to the selected grid size.

To evaluate the effectiveness, a professional surveyor was invited to suggest a scanning plan for the Structural Model. This led to two conclusions: first, professional surveyors do have valuable expertise and ad-hoc approaches enabling them to propose reasonably good scanning plans, at least for simple examples like simple building structures composed of evenly spread columns and slabs. Second, the proposed approach also works reasonably well in such context. The effectiveness of the proposed approach was then tested in the more challenging case of scanning MEP components with complex shapes and self-occlusions. The results particular suggested that to achieve high surface coverage with very high data precision in such context could actually require more scans than current practice currently suggests. So, it is likely that in practice LOA specifications (particularly in terms of incidence angle) have to be reduced for such scanning works. Nonetheless, the results also suggested that, in such context, it may be more critical to consider different scanner heights during the planning stage, as opposed to the ‘default’ height (2m) considered here.

The current implementation of the proposed system is not very efficient. For the Structural Model, the professional was significantly faster – although her solution did not quite fulfil the LOC specification for all objects. Furthermore, the computational time increases essentially linearly with the number of scanning locations (i.e. the square of the grid size), and linearly with the number of objects in the 3D model (to be more exact, the number of mesh faces). Considering various scanner heights (i.e. considering potential scanning locations in 3D as opposed to only 2D plan) would further impact computational times. While the process can easily benefit from parallel processing, experiments are also showing that selecting an overly small grid size (i.e. augmenting the number of potential scanning location) does not necessarily lead to better solutions. For structural works, for example, it would seem that a 5m grid size is likely to provide reasonable solutions for the sort of LOA and LOC specifications considered here.

Overall, this study first uniquely identified the need for a new kind of scanning specification that considers the amount of surface scanned, as opposed to the current LOA and LOD specifications that focus on local point specifications. The proposed LOC specification is of particular value to support activities such Scan-to-BIM modelling. Then, the study proposed a first approach that aims to demonstrate that it is possible to develop automated systems for generating scanning plans using 3D BIM models (e.g. for application in construction quality control) that consider both point-related scanning specifications such as LOA and surface-related specifications such as LOC. As a result, the overall aim of the research has been at least partially achieved. However, the approach developed in this research still presents an important weakness (the lack of consideration for scanning surface overlap), that leads the current approach does not fully achieves the initial research aim, and that further research remains necessary to completely achieve it. In contexts where the objects are similar and evenly spread around the scene (like in the Structural Model case presented in this dissertation), the lack of consideration for scanning surface overlap does not seem to affect the results significantly. However, it is clear that in more general cases, this limitation seriously impacts the results. This leads to the conclusion that, although the approach is fully designed to be usable in any context (*generalizable*), in practice it currently does not achieve that objective.

The section below reviews all the limitations that can be identified in the work reported here, and suggests approaches to address them through further research.

6.2 Limitations and Future Research

Though the proposed approach has demonstrated promising results, some limitations of the proposed method can be identified that require further research:

- The implemented prototype does not currently take into account multiple floors at a time in order to generate the grid and potential laser scanning locations. It can only process one floor at a time. It should nonetheless be straightforward to enhance the system so that it can take into account multiple “floors” where the scanner can be located. Indeed, it was shown how floors can be automatically extracted from the BIM model (in IFC format). Therefore, instead of selecting one floor, the system could easily consider all of them, find those that are of potential value to the scanning of the objects of interest, and generate potential scanning locations on all those floors, using the exact same approach as presented in this dissertation.
- The proposed system does not currently consider the level of detail (LOD) specification used in prior research and in practice. The author however does not foresee any problem in integrating LOD into the current framework. It is anticipated that points could be filtered out based on the LOD specification at the same stage of the process as when they are filtered out based on the LOA specification. But this remains to be developed and validated.
- Like all previous works that have considered the LOA criterion, this method theoretically requires performance information (tables or graphs) that detail the expected point precision for different ranges and incidence angles (i.e. like Figure 7). In fact, such information should also be generated for various materials, since the type of material is another parameter that can notably impact point precision. Getting this information requires conducting laboratory experiments that would be best conducted by laser scanner manufacturers because they already own the necessary expensive testing rigs.
- An important parameter of the proposed method is the density of scanning locations, β. In the work presented here the value of β is specified manually by the user. It may however be possible to define an automated approach to define an appropriate value of β. For example, β could possibly be defined according to the size of the objects to be scanned, or more generally their geometry.

- Due to time constraints, the comparison of the performance of the proposed approach against current practice has only been measured against the plan provided by one professional. Arguably, such comparison should be conducted with plans provided by more professionals. Nonetheless, the author's opinion is that the result obtained by the one professional who took part in this study are as expected, and most likely representative of what other professionals would have produced (the compass-based approach to set the scanning plan and the pattern of selected locations in the plan are both typical). While some differences would naturally be observed with other professionals, those would be minor. For example, it is expected that other professionals would have provided plans with the same or almost the same number of scanning locations, even though the actual locations may be different.
- Most importantly, the proposed P4S optimization model does not take into account the overlapping of the surfaces covered from different scanning locations. As a result, when the system currently reports that sufficient object surfaces are covered by the selected scanning locations, in reality the covered surfaces may significantly overlap and thus the true overall covered surface may remain insufficient. This limitation appeared clearly in some of the reported results when the system sometimes selected several neighbouring scanning locations within the optimal scanning plan instead of locations better spread around the scene.

  This limitation is certainly significant and requires further research. Although the first four steps of the process presented in this thesis could possibly remain unchanged, taking surface overlaps into account would essentially make the optimisation non-linear and thus an entirely different optimisation approach would have to be considered to solve this problem. Two approaches could be considered to address this issue:

  - The first approach would consist in comparing point clouds generated from each pair of potential scanning locations and identify whether each point in one point cloud is very close to a point in the other one. This method, that is commonly used to reduce the size of point clouds resulting from multiple scans (called *point cloud dissemination*; e.g. see [90-92]), would here be used to identify 'overlapping points' between each pair of selected scans. This information could then be used in the optimisation stage to discard overlapping points if the two scanning locations they refer to are selected by the algorithm.

- A second approach would consist in uniformly sampling the surface of each object, e.g. into points. The uniform sampling leads to a corresponding constant surface covered by each of those points. Then, for each potential scanning location, it only suffices to check whether each point is scannable with the necessary LOA (and LOD) specification. And, during the optimisation process, if one more scanning locations are selected that can all scan that surface sample point then that point (and its covered surface) is counted only once.

As noted above, both these approaches introduce non-linear constraints in the optimisation model, which would require a different type of optimisation method, such as genetic algorithm.

In addition to the areas of further development suggested above, further experiments should also be conducted using other types of contexts and even more complex scenarios. This could help better assess the value of any newly proposed planning for scanning method, particularly in comparison with current manual approaches.

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Appendix 1: System Generated-Covered Surface Areas for the 19 scanning locations constituting the optimal solution for the Structural 3D Model with density β =5m and height of scanner *h*=2m.

Appendix 1 represents the system-generated covered surface areas for all objects from the optimal solution of 19 scanning locations obtained for the Structural 3D Model with density β =5m and height of scanner *h*=2m. The 19 scanning locations are shown in Figure 31.

S.Locations	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31	C32	C33	C34	C35	C36	C37	C38	C39	C40	C41	C42	C43	C44	C45	C46	C47	C48	C49	C50	C51	C52	C53	C54	C55	C56	C57	C58	C59	C60	C61	Floor	C63
SL13	0	0	0	1.95	1.63	1.72	1.74	1.62	1.79	1.18	1.74	1.73	0	0	0	1.89	1.82	0	1.79	1.66	1.81	1.74	1.73	0	0	0	0	1.82	0	1.66	1.75	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.85	1.65	1.8	1.75	1.6	1.91	1.59	1.67	1.61	46.84	0
SL16	1.41	1.77	2.01	1.68	1.7	1.61	1.7	0	0	0	1.75	1.75	1.42	1.81	1.7	1.79	1.78	0.2	1.8	0	0	1.65	1.72	0	1.61	1.82	2.07	1.81	0	0	0	0	0	1.92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.68	1.64	1.71	1.78	1.7	1.86	1.72	0	0	0	1.36	1.81	46.42	0
SL19	0	0	0	0	0	0	1.67	1.71	1.75	1.61	1.89	0	0	0	0	0	0	0	0	0	1.78	0	0	0	0	0	0	0	1.9	1.89	1.88	1.8	1.72	0	0	0	1.9	1.78	0	0	1.75	1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	1.9	1.78	1.82	1.79	1.89	0	47.34	1.8
SL22	0	0	0	1.85	1.73	1.89	2.05	1.45	1.66	0	1.78	1.92	0	0	0	0	0	0	1.78	0	0	1.74	0	0	0	0	1.57	1.72	1.81	1.8	1.73	1.91	0	1.78	0	0	1.58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.84	1.83	1.76	1.75	1.76	1.68	1.49	1.8	1.8	46.32	0
SL24	0	1.7	1.66	0	0	1.73	1.71	0	0	0	1.77	1.77	0	0	0	0	0	1.74	0	0	0	0	1.73	0	1.56	2.04	1.71	1.78	1.61	2.05	1.57	0	0	1.79	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.68	1.69	1.71	1.71	1.79	1.75	1.85	0	0	1.86	1.72	47.48	0
SL27	0	1.79	1.62	1.74	1.65	0.4	0	0	0	0	0	1.67	0	0	0	1.38	0	0	0	0	0	0	1.71	1.78	1.84	1.89	1.75	1.69	1.74	1.73	0	0	0	1.94	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.73	1.83	1.81	1.79	1.79	1.74	1.74	0	0	0	1.59	1.74	46.63	0
SL30	0	0	0	0	0	0	0.53	1.27	1.69	1.74	0	0	0	0	0	0	0	1.93	1.64	1.83	1.71	1.97	0	0	0	0	0	0	1.4	1.67	1.72	1.83	1.72	0	0	0	1.86	1.7	0	0	1.73	1.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.73	1.67	1.75	1.81	1.58	0	47.22	1.83
SL35	0	0	0	0	1.67	0.24	1.59	1.12	1.45	0	1.56	0.53	0	0	0	1.95	1.63	1.72	1.71	1.65	1.8	1.76	1.73	0	0	0	1.08	1.74	1.81	1.79	1.69	0.95	1.54	0.51	0	0	1.66	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	1.16	1.68	1.67	1.73	1.75	1.8	0	1.77	1.66	49.34	1.04
SL38	1.94	1.84	1.61	1.95	0	0	0	0	0	0	0	1.59	1.95	1.81	1.69	1.76	1.63	0	0	0	0	0	1.74	1.8	1.44	1.75	1.63	0.48	0	0	0	0	0	1.55	0	1.65	0	0	0	1.71	0	0	0	0	0	0	0	0	0	0	1.81	1.07	1.72	1.71	1.89	0	0	0	0	0	0	0	42.67	0
SL46	0	0	0	0	0	0	0	0	1.85	0	0	0	0	0	0	0	0	0	1.76	1.56	1.76	1.96	0	0	0	0	0	0	1.79	2.06	1.81	1.71	1.83	0	0	0	1.56	1.77	0	0	1.73	1.74	1.73	1.81	0	0	0	0	0	0	0	0	0	0	0	0	2.01	1.71	1.74	1.8	0	0	48.32	1.6
SL49	0	0	0	0	0	0	1.59	0	0	0	1.94	0	0	0	0	2.35	1.45	1.69	1.9	1.83	1.75	1.77	1.59	0	0	0	1.44	1.58	1.76	1.82	1.71	1.77	2	1.62	0	0	1.97	1.49	0	0	1.68	0	1.48	0	0	0	0	0	0	0	0	0	0	0	1.67	1.61	1.74	0.28	2	0	1.48	0	49.72	0
SL55	1.36	0	0	0	0	0	0	0	0	0	0	0	1.86	1.75	1.67	1.57	0	0	0	0	0	0	0	1.72	1.74	1.74	1.67	0	0	0	0	0	0	1.82	1.76	1.8	0	0	1.8	1.7	0	0	0	0	0	0	0	0	0	0	2.06	1.82	1.81	0	0	0	0	0	0	0	0	0	46.26	0
SL57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.88	1.76	1.62	0	0	0	0	0	0	0	0	1.58	1.75	1.63	1.78	0	0	0	1.78	1.7	0	0	1.67	1.75	1.95	1.67	1.91	1.64	0	0	0	0	0	0	0	0	0	0	0	1.43	1.65	2.18	0	0	49.3	1.62
SL66	0	0	0	0	0	0	0	0	0	0	0	0	1.88	1.93	1.38	0	0	0	0	0	0	0	0	1.82	1.76	1.73	0	0	0	0	0	0	0	0	1.83	1.69	0	0	1.84	1.79	0	0	0	0	0	0	0	0	0	0	1.7	1.65	1.44	0	0	0	0	0	0	0	0	0	47.39	0
SL68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.53	0	0	0	0	0	0	0	0	1.71	1.87	1.76	1.54	0	0	0	1.82	1.69	0	0	1.82	1.72	1.78	1.68	1.8	2	1.79	1.76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49.53	0
SL77	0	0	0	0	0	0	0	0	0	0	0	0	0.87	0	0	0	0	0	0	0	0	0	0	1.79	1.53	0	2.04	0	0	0	0	0	0	0	1.86	1.83	0	0	1.75	1.76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48.14	0
SL79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.94	1.86	1.92	0	0	0	1.77	1.85	0	0	1.78	1.81	1.85	1.82	1.81	1.76	1.85	1.74	1.61	0	0	0	0	0	0	0	0	0	0	0	0	0	49.2	0
SL101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.84	1.93	1.78	1.58	1.72	1.85	1.79	1.76	1.81	1.77	0	0	0	0	0	0	0	0	0	0	0	0	46.25	0
SL134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.72	2.3	1.83	1.69	1.75	1.65	0	0	0	0	0	0	0	0	0	0	0	0	46.26	0
Covered Surf.	**4.71**	**7.09**	**6.9**	**9.16**	**8.37**	**7.59**	**12.6**	**7.18**	**10.2**	**4.53**	**12.4**	**11**	**7.98**	**7.29**	**6.43**	**12.7**	**8.31**	**7.28**	**14.3**	**10.3**	**13.8**	**12.6**	**11.9**	**8.9**	**11.5**	**11**	**15**	**12.6**	**13.8**	**19.8**	**19.4**	**15.2**	**14**	**14.3**	**5.46**	**10.7**	**15.9**	**12**	**5.39**	**6.96**	**15.4**	**12.2**	**10.6**	**8.55**	**8.95**	**9.55**	**7.26**	**6.95**	**5.17**	**3.42**	**8.98**	**9.69**	**10.2**	**11.8**	**13.9**	**13.5**	**17.8**	**13.8**	**14.4**	**10.7**	**15**	**10.3**	**900.6**	**7.89**
Total Surface	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	5.67	1785	5.67
LOC	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.84	892.4	2.84