

# Lighting in the third dimension: Laser scanning as an architectural survey and representation method

Myriam Rodrigue<sup>1</sup>, Claude MH. Demers<sup>1</sup>, Mojtaba Parsaee<sup>1,\*</sup>

<sup>1</sup> GRAP (Groupe de Recherche en Ambiances Physiques), École d'Architecture, Université Laval

\* Corresponding author: [mojtaba.parsaee.1@ulaval.ca](mailto:mojtaba.parsaee.1@ulaval.ca)

PhD candidate in Architecture

GRAP (Groupe de Recherche en Ambiances Physiques)

École d'Architecture, Université Laval

1 Côte de la Fabrique, Vieux Séminaire Québec, QC, Canada, G1R 3V6

Tele: (+1) 514 519 3058

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## **Abstract**

This paper proposes tridimensional (3D) laser scanning to architects and lighting designers as a lighting enquiry and visualization method for existing built environments. The method constitutes a complement to existing lighting methods by responding to limitations of photometric measurements, computer simulation and HDR imagery in surveying and visualizing light in actual buildings. The research explores advantages and limitations of 3D laser scanning in a case study addressing a vast, geometrically complex and fragmented naturally and artificially lit space. Lighting patterns and geometry of the case study are captured with a 3D laser scanner through a series of four scans. A single 3D model of the entire space is produced from the aligned and fused scans. Lighting distribution patterns are showcased in relation to the materiality, geometry and position of windows, walls, lighting fixtures and day lighting sources. Results are presented through images similar to architectural presentation drawings. More specifically, the lighting distribution patterns are illustrated in a floor plan, a reflected ceiling plan, an axonometry and a cross-section. The point cloud model of the case study is also generated into a video format representing the entire building as well as different viewpoints. The study shows that the proposed method provides powerful visualization results due to the unlimited number of images that can be generated from a point cloud and facilitates understanding of existing lighting conditions in spaces.

## **Keywords**

LiDAR

Lighting

Architecture

Visualization

Site evaluation

Post occupancy

## 1. Introduction

This research proposes tridimensional (3D) laser scanning for surveying and visualizing lighting in complex geometry spaces. Architects and lighting designers need to comprehend the characteristic of existing lighting in relation to the space configuration in order to design new lighting plans or installations whilst taking into account existing environment where they intervene. The limitations of existing lighting survey methods, as explained in the following section, hinder the visualization and understanding of the interaction between lighting sources and building configurations as well as implementing new metrics and design criteria that must be verified before and after building construction. A holistic spatial representation of lighting characteristics combined with building maps could effectively promote designers' perception of how light interacts in the space [1] and assist exploring optimal solutions and strategies to improve lighting performance. The emergence of 3D laser scanning has fostered new survey possibilities that respond to such needs of architects and lighting designers. The 3D laser scanning enables capturing vast complex-geometry spaces and its surface colors through aligning and fusing several scans to generate a 3D model of the space. The main objective of this paper is to develop the 3D laser scanning method to survey and represent lighting in the entire existing building independently of its dimension and spatial complexity. Thus far, the 3D laser scanning as a lighting survey method has not received sufficient attention of architects and designers. A few studies, such as Vaaja, et al. [2], have used 3D point clouds to survey and represent luminance data in an artificially lit exterior urban space. Their studied space, however, applies to a simple geometry as it could have been surveyed by other methods. This research has used 3D laser scanning to survey lighting in an interior fragmented artificially and naturally lit space. This allows discussing the potential of 3D laser scanning for improving the understanding of interactions between light sources and their context in non-intervisible, vast and geometrically complex spaces. The research discusses the underlying complexity of surveying and accurately representing environment exposed to varying lighting conditions. Outlines for future developments and transcending the limitations of the proposed method are also discussed.

## 2. Limitations of existing survey methods

Conventional survey and representation methods to monitor and describe lighting distribution patterns in real built environments include photometric measurements, computer lighting simulations and High Dynamic Range (HDR) imagery. Such methods have several potentials and shortcomings to survey the lighting of vast and geometrically complex spaces, as summarized in Table 1. Photometric measurements have mostly been performed by using illuminance meters [3, 4] which measure illuminance values at the height of work planes as prescribed by different standards and codes from the Illuminating engineering society (IES) [5], The International Commission on Illumination (CIE) [6] and the International Well Building Institute [7]. Lighting distribution can be represented in scatter plot graphics and architectural presentation documents such as plan views. Several authors criticize assessing the space lighting quality with illuminance values because it relates to measuring light falling on a horizontal surface instead of quantifying the amount of light reflected towards an observer [8-11]. Perceived brightness indeed depends on the luminance distribution from the viewpoint of an observer [12-14]. The photometric method is moreover limited in the number of viewpoints which can be recorded and visualized.

Computer lighting simulation can also generate lighting distribution patterns of an actual built environment [15]. The lighting distribution patterns issued from computer lighting simulations are represented in different ways to enable an understanding of the space and its daylighting components. They are often illustrated in the plan, reflected ceiling plan, axonometric views and in section cuts. Plans views are used to illustrate lighting distribution patterns on horizontal work planes [16]. Sections are often used to discuss lighting distribution patterns of naturally lit spaces as they allow displaying the sun

elevation and skyline angle from different positions [17]. Plans and sections can illustrate the relation between lighting distribution patterns and the position and dimensions of transparent and opaque surfaces. They allow displaying lighting distribution patterns whether a space is continuous or fragmented, independently of its dimension and geometry [16]. For example, sections efficiently display phenomena such as borrowed daylight strategies referring to the reflected light coming from a sunlit space such as an atrium to its adjacent windowless rooms. Tridimensional axonometric views are also used for displaying lighting distribution patterns. However, computer daylighting simulations are more often used to describe lighting distribution patterns during the design process of a space rather than for describing existing environments. Generating computer lighting simulations of an existing built environment requires several technical skills such as knowing and surveying lighting fixture shape, rendering index, diffuse color, reflectance and specular roughness properties of surfaces, object position and geometry, [18]. Achieving such surveys can be time consuming when a designer needs to describe lighting distribution patterns of a vast and geometrically complex real environment.

HDR imagery is another method to capture the luminance information of a scene and present it in perspective viewpoints and 360 panoramas [19-21]. Generating HDR images in false color, with Isolux contour lines or gray level representations [22, 23] are the most common method for discussing illuminance and luminance in built environments. Existing environments offer the highest level of daylighting complexity. Recent developments in imaging technologies have provided highly relevant qualitative and quantitative results for discussing architectural ambience [20, 24, 25]. HDR fisheye images have been used to conduct visual comfort analysis with glare indices from human accessible viewpoints [26, 27]. Despite its widespread use, accuracy and reproducibility [19, 28], HDR imagery has several limitations [4]. For example, a limited number of viewpoints can be surveyed and analyzed. The estimation of the percentage of a space where users can be visually comfortable requires the designer to capture HDR images from every humanly accessible viewpoint. This process is highly challenging when the space is overly vast and complex and when users can adapt their position and orient themselves towards different directions for achieving different activities, such as reading, writing or meeting in a cafeteria, or library. Meanwhile, there is no normalized method for defining the number of HDR images, the location and direction of captures in existing environments. Designers, yet, need to select viewpoints to analyze the lighting conditions before understanding the overall interplay between lighting sources and surfaces of a studied field. Choosing survey points is a task which is subjected to considerations that cannot be totally resolved on-site. Understanding and representing the overall interplay between lighting sources and surfaces in a studied field hardens as the dimension and the geometry complexity increase. Designers, hence, rely on their professional experience and their brightness perception, when being on-site, for choosing the viewpoints to analyze post-survey. HDR imagery does not allow to fully understand interrelations between light sources and their physical context as well or their mutual influence. Visualizing a change of a lighting fixture or surface in an existing vast or geometrically complex built environment could also be a difficult task when every part of the space cannot be seen or captured in every HDR imagery. Designers must therefore try to assess the effect of people's change, movement and adaptation, corresponding to complex inhabitation patterns that influence the lighting distribution of elements that are not seen in HDR images. Therefore, when attempting to optimize an existing light plan, design decisions based on HDR imagery are highly speculative and problematic.



Table 1. Lighting survey methods' potentials and limitations

Method	Computer simulation	Photometric measurements	HDR imagery
Use	<ul style="list-style-type: none"> <li>It can be used to analyze and represent illuminance and luminance measurements or to define visual comfort risks.</li> </ul>	<ul style="list-style-type: none"> <li>A luxmeter takes one illuminance measurement at a time for determining the illuminance distribution of a space.</li> <li>It is often used to verify existing illuminance-based metrics.</li> </ul>	<ul style="list-style-type: none"> <li>It captures several luminance and illuminance measurements in each imagery.</li> <li>It represents lighting patterns in their context.</li> <li>It is used for achieving visual comfort studies or analyzing luminance and illuminance distribution in a space from one user's viewpoint. [26, 27].</li> </ul>
Method for choosing survey points	<ul style="list-style-type: none"> <li>Method for choosing survey points is not required for analyzing illuminance lighting distribution in one or several spaces as computer simulations can generate unlimited results.</li> <li>The method will depend on the matter of the analysis.</li> </ul>	<ul style="list-style-type: none"> <li>Measurements are normally achieved at work plane height at a fix distance on a grid [29, 30].</li> </ul>	<ul style="list-style-type: none"> <li>No normalized method exists for choosing viewpoints.</li> <li>The viewpoint selection is influenced by the surveyor brightness perception on-site and professional experience.</li> <li>The viewpoint visible in an imagery requires to be humanly accessible.</li> </ul>
Accuracy and reproducibility of results	<ul style="list-style-type: none"> <li>The accuracy and reproducibility of results depend on the accuracy and reproducibility of methods used to survey materials, lighting sources properties and the geometry of the space.</li> </ul>	<ul style="list-style-type: none"> <li>The accuracy and reproducibility is of <math>\pm 3\%</math> [31].</li> </ul>	<ul style="list-style-type: none"> <li>The accuracy and reproducibility is of 1.8–6.2% [28].</li> <li>Dynamic lighting conditions can influence the accuracy of results [20].</li> </ul>
Representation of lighting patterns.	<ul style="list-style-type: none"> <li>Unlimited possibilities (plan, section cuts, perspectives, false color images, isolux lines and gray level representations) [15]</li> </ul>	<ul style="list-style-type: none"> <li>Scatter plot graphics [19].</li> </ul>	<ul style="list-style-type: none"> <li>Perspectives, false color images, isolux lines and gray level representations [22, 23]</li> </ul>
Main limits	<ul style="list-style-type: none"> <li>It is rarely used in existing environments.</li> <li>Further research is required to define cost and time effective methods to survey all materials, lighting sources properties and the geometry of real existing spaces.</li> </ul>	<ul style="list-style-type: none"> <li>Luxmeter measures only one illuminance value at a time [19].</li> <li>Illuminance measured with a luxmeter cannot be represented in their context.</li> <li>Illuminance measurements are not representative of the human brightness perception [8-11].</li> <li>They cannot be used for visual comfort risks analysis.</li> </ul>	<ul style="list-style-type: none"> <li>The number and type of imageries is limited to the amount of on-site capture HDR images.</li> <li>No normalized method exists for choosing viewpoints. Relevance of viewpoint selection cannot be defined.</li> <li>High spatial cognition skills are required to understand the interaction between light sources and their context in vast and geometrically complex environments.</li> <li>Lighting distribution patterns cannot be visualized with spatial maps or in plan.</li> <li>Dynamic lighting conditions can influence the accuracy of the results [20].</li> </ul>

3D laser scanners offer the possibility to overcome the shortcomings of existing methods by representing lighting in colored 3D models of existing spaces independently of their dimensions and geometry. 3D laser scanning has recently been developed to identify materiality, reflectance [32, 33] and anisotropy properties [34] for every surface of a space from intensity values of laser scanners [32, 35]. Such potentials of laser scanning devices could provide several data, facilitating the application of new lighting and architectural norms and criteria on existing spaces. This research, therefore, aims to explore 3D laser scanning for the visualization and understanding of the lighting in a vast and geometrically complex space. The research hypothesizes that lighting designers can benefit in intersecting results from existing 3D laser scanning methods and HDR images for surveying and visualizing lighting plans of existing built environments. The paper argues that existing HDR imagery luminance mapping calculations and 3D laser scanning methods should be complementary tools for field surveying of lighting patterns in geometrically complex spaces for designing and post occupancy evaluation purposes. The paper will be interesting for architects, lighting architects and designers who study field lighting surveys and visualization. Through a case study, the paper addresses the following questions:

- How could the data and image from a 3D point cloud model be used by architects for analyzing existing environments?
- How could such images be used by architects during the design and renovation processes?

### 3. Methodology

A field survey of an interior space was completed with the 3D laser scanning method in the Kruger Pavilion of Laval University, Quebec, Canada, (Lat. 46°46'49.1"N and Long.71°16'46.0"W), which is called the cafeteria. HDR images were also captured separately with another device to discuss the potential of 3D laser scanning. Figure 1 shows the survey process and post processing with (A) laser scanning and (B) HDR imagery devices. Point cloud models can be acquired from the field laser scanning survey. The International Organization for Standardization [36] defines a point cloud as “A collection of data points in 3D space. The distance between points is generally non-uniform and hence all three coordinates (Cartesian or spherical) for each point must be specifically encoded.” The point clouds are fused to generate new imaging types suitable to describe lighting patterns in vast and geometrically complex environments. The number and location of required 3D laser scans were defined according to the dimension and geometry of the particular space, as discussed in the survey context section.

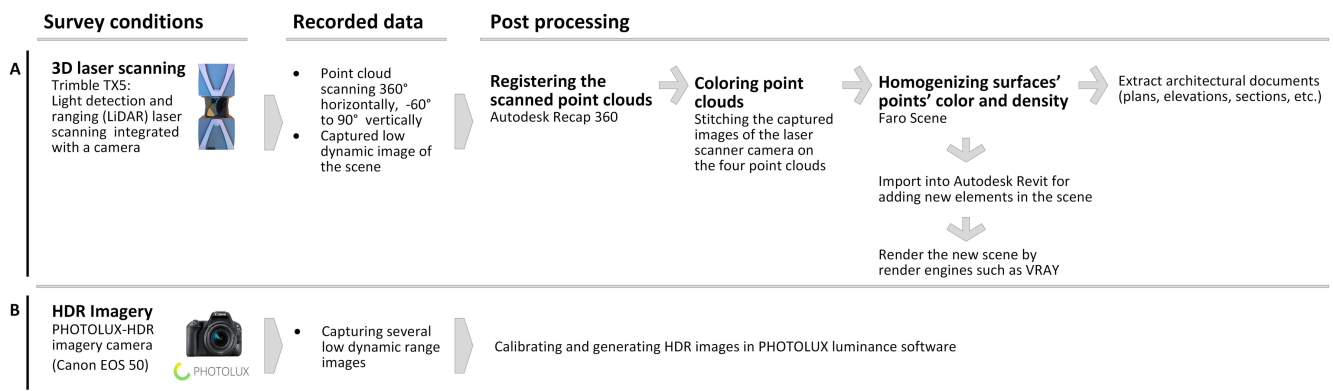


Figure 1. (A) 3D laser scanning process and post processing, (B) HDR imagery.

### 3.1. Material and settings

Two types of data were separately captured on-site with two different devices: 3D laser scans and HDR images. The 3D laser scans were generated with a Trimble TX5 tridimensional laser scanner, shown in Figure 1. The device consists of a light detection and ranging (LiDAR) laser scanning system integrated with a camera. The device scanned 360° horizontally and from -60° to 90° vertically. The device integrated camera also simultaneously captured Low Dynamic Range (LDR) pictures. Therefore, the laser scanner has captured the XYZ georeferenced positions, the XYZ normal vectors to the surfaces, the RGB values and the intensity values of the returning laser beam of each of the scanned points. All 3D laser scans were captured with the settings presented in Table 2. The resolution, quality and laser range were chosen to ensure the alignment of the scans after the survey while preventing ocular injuries to occupants of the cafeteria's upper level. The survey therefore respected the chosen nominal ocular hazard distance (NOHD) between the occupants and the laser scanner while completing the scans.

Table 2. Trimble TX5 - Tridimensional laser scanner settings

Resolution		Quality	Repetition rate (Hz)	Pulse duration (μs)	NOHD (m)	
Mio. Pts (full scan)					Axial	Radial
1.8	1/20	8x	15	22.686	10.60	3.30

The laser scans survey positions affect the quality of the rendered images as well as the quantitative data that could potentially be extracted. Laser scanning a simple space such as a rectangular space could only require one scan to capture all data and produce a 3D image. However, in complex spaces, multiple 3D laser scans are required to ensure that all relevant surfaces are “seen” by the laser scanner. In terms of effectiveness, capturing a minimum set of points should be aimed to prevent potential errors related to the alignment of the 3D laser scans.

Generating the 3D architectural model is the most challenging and technical aspect of the process. In order to generate an architectural 3D model from the different laser scans, the point clouds have to be registered and colored. Registering scans consists of aligning different point clouds together to form a single 3D model, a point cloud. A 3D point cloud models differ from a conventional architectural 3D model made of edges and surfaces. 3D point cloud models are made of points instead of planes and edges. Interstices separate each point from one another. Those interstices are named occlusions. Points were presented only on surfaces scanned by the laser scanner during the scans. As presented in the case study described in the next subsection, reference positions are considered to be seen by at least two scans to ensure the registration of the scans after the survey (see Figure 2). The scans were registered in the software Autodesk Recap 360 [37]. To color point clouds, the pictures of the laser scanner integrated camera have been stitched on the four point clouds with the method used by Busayarat et al. [38] and by Jones and White [39]. The point cloud has been fused in Faro Scene [40] to homogenize the colors and the density of points on the same surfaces [41].

As depicted in Figure 1, HDR images were also generated using a photo luminance meter system consisting of a calibrated Canon EOS 50D camera and the PHOTOLUX software [42]. Multiple LDR images with low to high Exposure Values ( $\pm 2$  EV) were captured and merged to generate HDR images based on the procedure published by Inanici [43], Inanici [44].

Table 3. PHOTOLUX – HDR imagery camera settings

Feature	Setting	Feature	Setting
White balance	Auto	Image size	3456 x 2304 pixels
Sensitivity	400 ISO	Color space	sRGB
Picture style	Neutral	Auto-bracketing	Off
Lens	Sigma 50mm		

Surveying the cafeteria with the laser scanning and the HDR imagery methods required 56 minutes, 35 minutes for achieving 4 scans and 21 minutes for capturing HDR images. Planning the survey necessitated approximately 3 hours and processing the scans and generating the HDR images lasted about 6-8 hours of work. An ophthalmic exam and a three-hour safety and security training for using laser scans of categories 1M, 2M, 3A/3R, 3B and 4 was also completed at Laval University prior to the survey.

### 3.2. Survey context

The artificially and naturally lit cafeteria and its adjacent corridor were surveyed by the 3D laser scanner. The space was selected to clearly demonstrate the higher potential of the 3D laser scanning method than the HDR imagery method to describe lighting distribution patterns in complex spaces. The spatial complexity is hereby expressed from its dimension, its geometry, its numerous artificial and natural lighting sources. The space complexity can be discussed in the architectural plan and section. In the plan view (Figure 2-a), the small kitchenette separates the cafeteria from its adjacent corridor without actual doors. A large portion of the cafeteria lighting is shared with its adjacent spaces, such as a mezzanine and its bordering corridors, as illustrated in Figure 2-b. Natural lighting penetrates deeply into the cafeteria through a south-southeast oriented window-wall. The north-eastern adjacent corridor of the cafeteria, which is two-level high, is double sided glazed and naturally lit. In opposition, a non-daylit north-western corridor is illuminated by artificial lighting fixtures during the on-site 3D laser scanning and HDR imagery survey. The architectural longitudinal section in Figure 2-b cuts shows this particular space condition through the mezzanine floor openings. The longitudinal cross-section showcases the climate sky conditions during each of the four the laser scans, as well as the time of data collection. As illustrated in Figure 2-c, the sky condition was overcast at the beginning of the survey. However, due to climate variations during the day as the survey progressed, nearly all clouds dispersed and clear skies prevailed. This inherent condition of a space surveyed under real skies is illustrated in Figure 2-c) to identify timely experiences and pattern distributions through time. The transversal section (Figure 2-d) assesses the geometrical complexity of the space, and typically uncovers the potential of a laser scanner for surveying daylighting conditions in relation to sky views and sun lighting penetration. It shows the cafeteria (lower left space), its adjacent corridor and the spatial connection between the ground floor and its upper level achieved through the three floor hoppers. The spatial volume is therefore much more complex than a rectangular prism, resulting from the juxtaposition of several architectural components and daylighting strategies such as borrowed and indirect light. Achieving the 3D survey of the space required a series of steps due to its dimension and geometrical complexity.

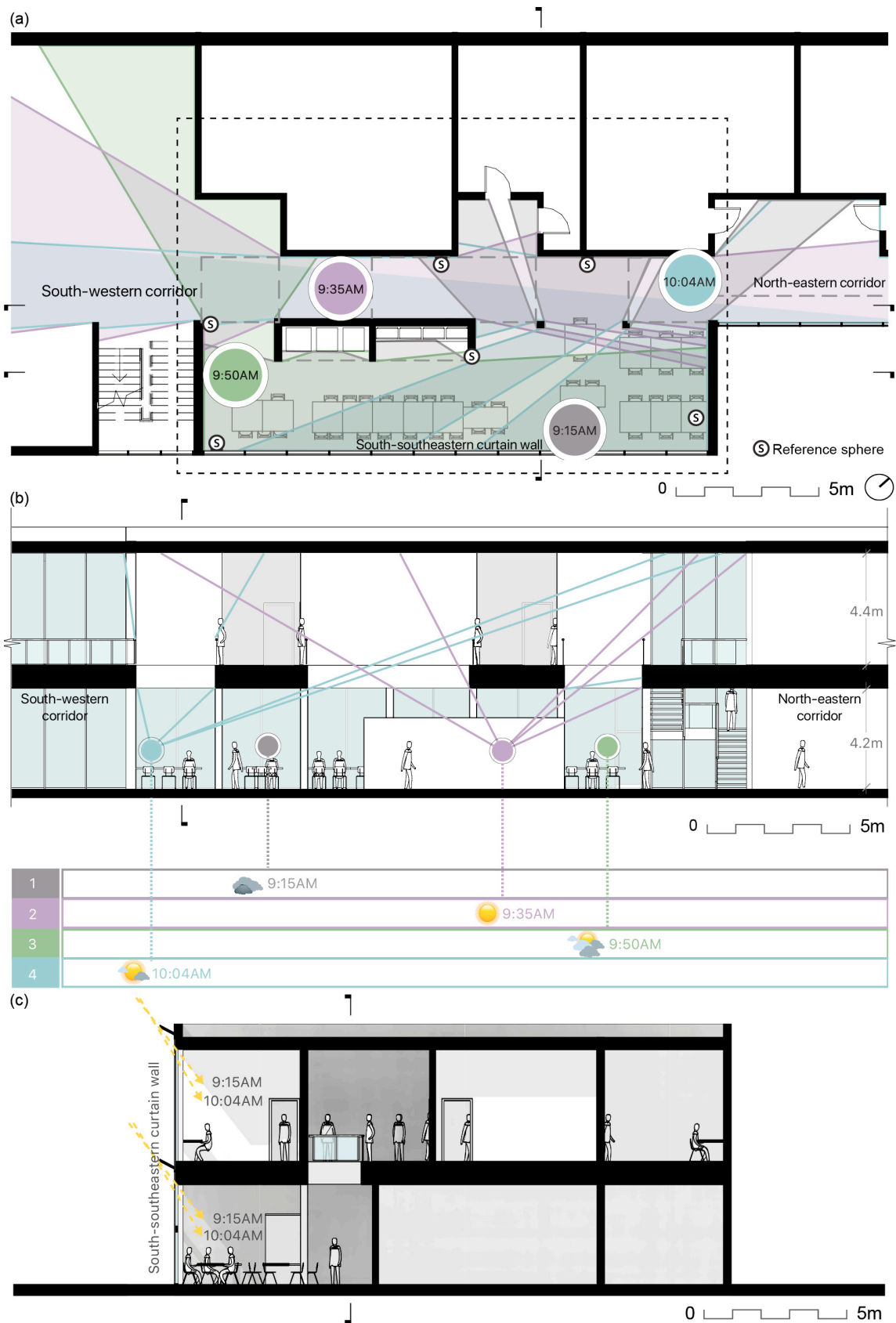


Figure 2. Dimensions of the cafeteria and the laser scan survey points location and their time of capture in (a) the plan view, (b) section, (3) the climate sky conditions during each of the four the laser scans, and (c) transversal section of June 8 from 9:15AM to 10:04AM (Sun elevation  $51.8^\circ$  to  $58.8^\circ$ , azimuth  $115.6^\circ$  to  $131.2^\circ$ ).

The preliminary experimental stage consisted of establishing the 3D laser scan survey points and reference sphere positions. The four laser scans locations with the respective time when they were generated are illustrated as colored circles in Figure 2. Four point clouds captured on June 8, 2016, between 9:15 AM and 10:04 AM. HDR images were also captured at the same location as the four laser scans (Figure 2) in order to compare the fused point cloud and the HDR images in the results section. The challenges for representing lighting distribution patterns in the studied space relate to the presence of the kitchenette and columns which occluded parts of the space for occupants in the dining area observing towards the corridor; and for the ones located in the corridor and observing the dining area. The adjacent corridors share their lighting with the studied space through the 3 floor hoppers as illustrated in Figure 2-b. Therefore, the 3D laser scanner survey locations were chosen to capture surfaces of the three upper floor hoppers, all four sides of the cafeteria central kitchenette and tabletops as well as the two wooden columns. The laser device range was set to avoid scanning the upper floor walls and the ceiling through the floor hoppers as there would have been a risk of causing ocular injury to people circulating on the upper floor. The non-scanned surfaces consist of the cafeteria adjacent spaces, upper floor ceiling and walls, and floor surfaces situated under tabletops. The laser range settings also ensure that adjacent spaces to the cafeteria were only partially scanned. The curtain glass wall surfaces were neither scanned because of their high reflectivity.

#### **4. Results**

This section presents architectural imagery issued from the generated 3D laser scan model and analyzes the lighting distribution patterns of the cases study. Internal surfaces of the space captured during each 3D laser scan are layered under the cafeteria plan view in Figure 3-a. Each of the four illustrations presents a different scan in the plan view. Figure 3-b presents a plan view of the cafeteria after the alignment of the four point clouds in Autodesk Recap 360. Figure 3-c presents a plan view of the fusion of the four point-clouds. The resulting image combines all scanned patterns into a synthesized daylight space. The point cloud model is also represented in a video presentation format which can be found in the supplementary materials.



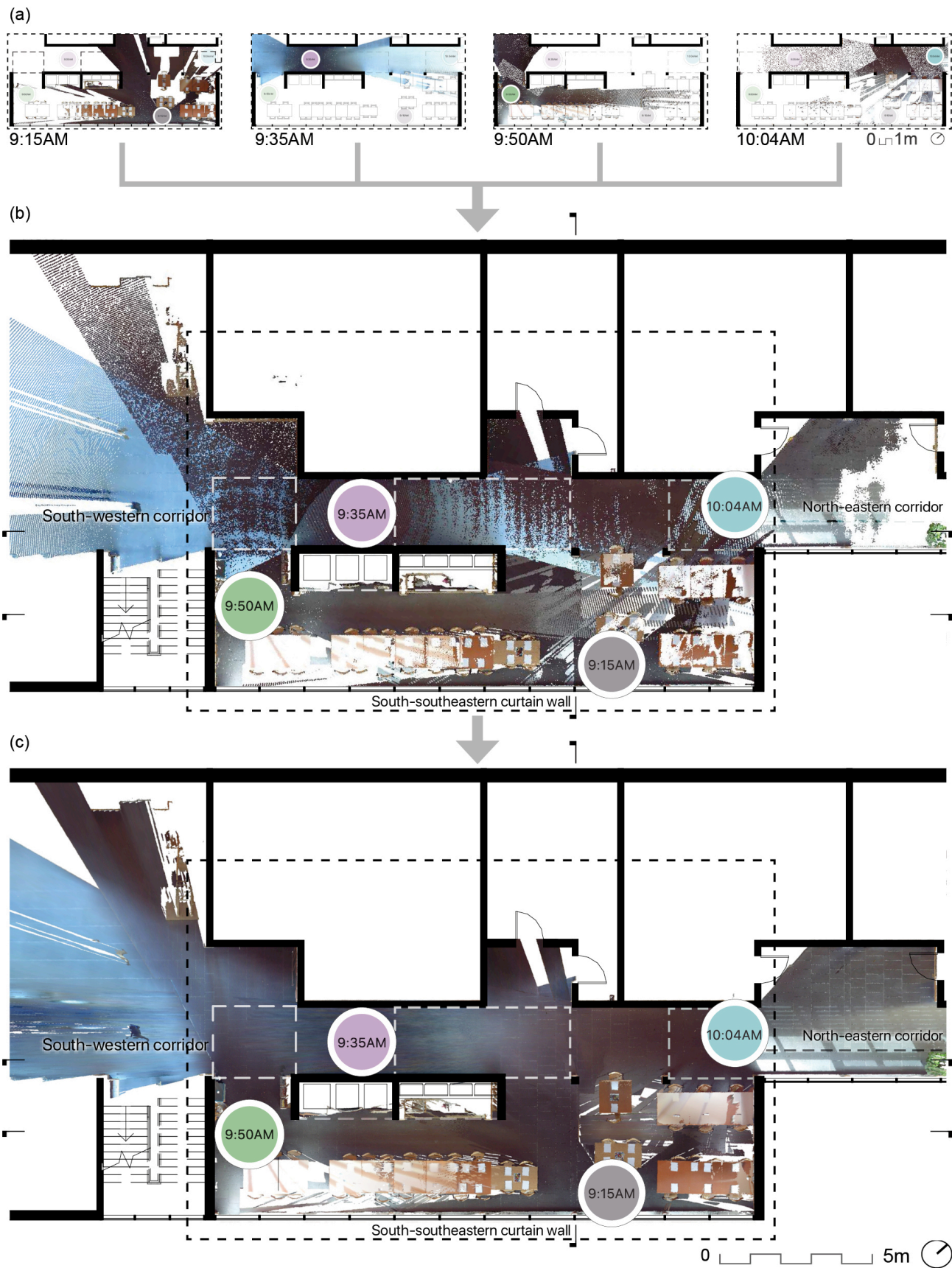


Figure 3. (a) Individual scans. (b) Plan view of the cafeteria after the alignment of the four-point clouds in Autodesk Recap 360. (c) Plan view of the cafeteria 3D point cloud model after the fusion of the scans in Faro Scene.

The captured daylit surfaces of the entire case study is illustrated in an axonometric view in Figure 4. The cafeteria geometry is situated at the center of the axonometric view, represented as the rectangular prism extruded towards the south-east end. The cafeteria is illustrated without its external curtain wall mullions to show its interior space. At this scale, physical parameters that could affect lighting distribution patterns within the space are visible. They include the materiality, the colors, the location of glazed and opaque surfaces, the space geometry, and the artificial lighting fixtures within the space and the adjacent spaces. The absence of non-scanned surfaces is responsible for the presence of white areas in the axonometric view.

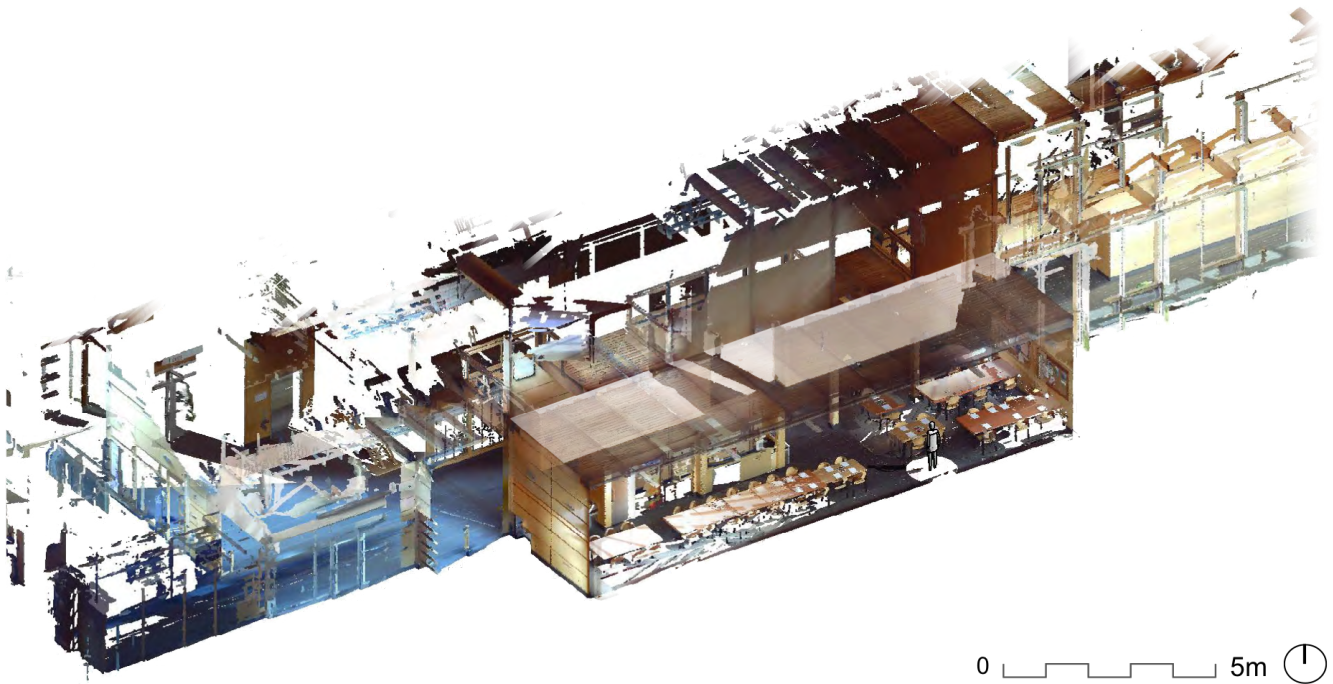


Figure 4. Axonometric view of the cafeteria 3D point cloud model.

Figure 5-a shows the fused point cloud made of four different scans in a colored plan view. The figure presents the relationship between the lighting patterns of the cafeteria, the hallway and the adjacent rooms. The colored plan view illustrates the lighting distribution in relation to the walls and the window locations. This plan view includes the lighting distribution patterns of the cafeteria representing light from its natural and artificial sources in adjacent corridors. It also allows representing the brightness distribution on all the tables. This view allows evaluating the relationships between the lighting distribution patterns and the positions of the glazed and opaque surfaces, the space geometry and materials of the cafeteria. The presented axonometric and the plan views, inter alia, allow the visualization of the cafeteria space, the northwestern corridor, two adjacent two-level corridors and the lighting shared between the spaces. The kitchenette casts shadows on the portion of the northwest corridor wall and floor situated at the northwestern side. The gray shaded plan in Figure 5-b illustrates the lighting distribution within the studied space. The whitest zones correspond to surfaces with the highest image brightness values whereas the lowest image brightness is illustrated with darkest shades of gray. The relative lighting distribution on horizontal planes, such as the floor and tables, is also defined. Figure 5-c shows a reflected ceiling plan. It presents the surface finishes, the three hoppers, the lighting sources and fixtures position(s). The 3D laser scanning surveys the position of surfaces and of lighting fixtures in the space with colored points. It also showcases the lighting distribution patterns on the bottom surface of the ceiling. The higher image brightness of the ceiling surface in the circle in Figure



5-c can be explained by the presence of two lighting fixtures lighting upward in the circled zone. Their location is also indicated in the figure.

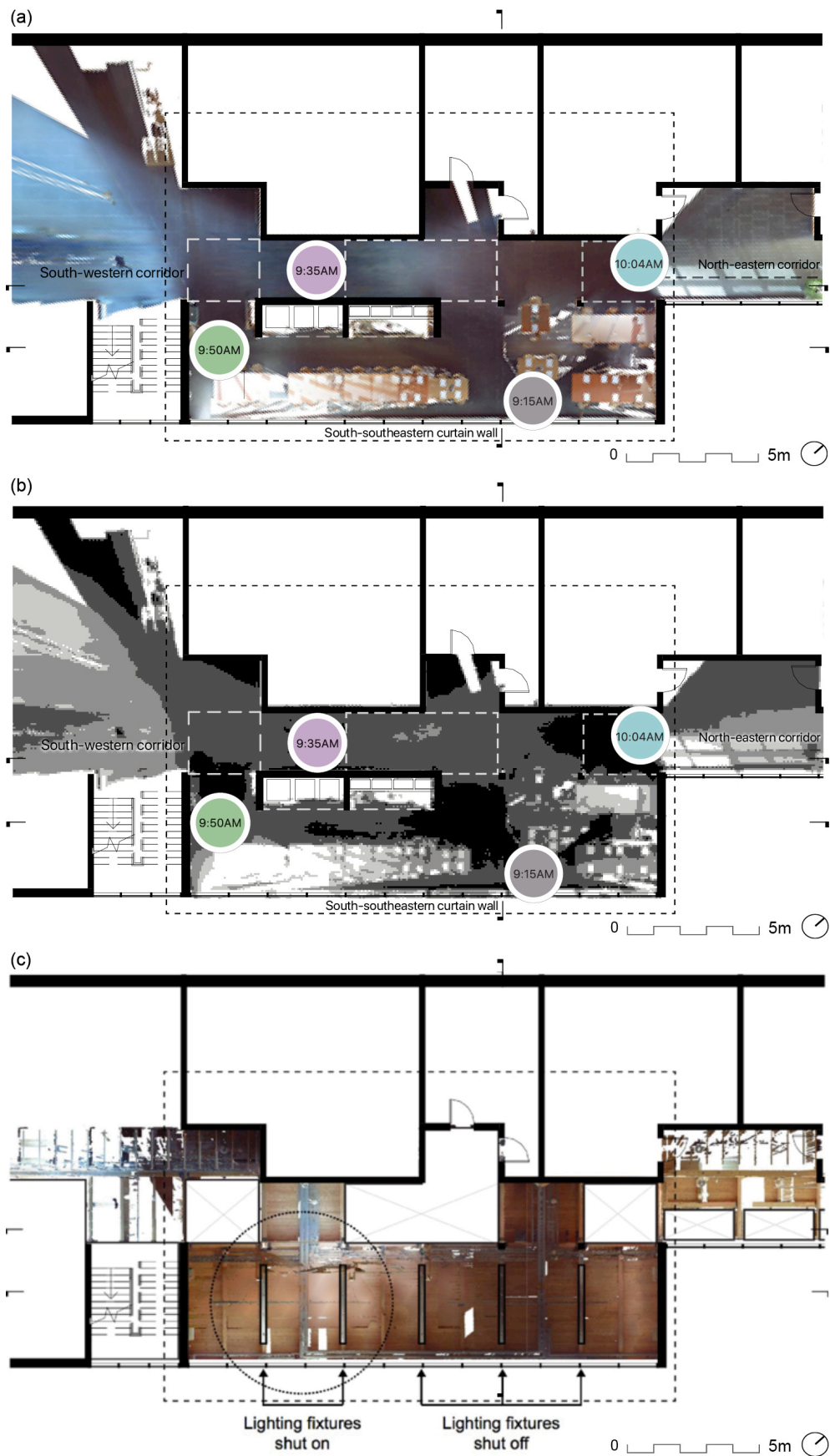


Figure 5. (a) Plan view issued from the 3D point cloud model, (b) Plan view in 5 shades of gray issued from the 3D point cloud model, (c) Reflected ceiling plan view from the 3D point cloud model.

Observation points located at the eye level are commonly used in perspective representations and HDR imageries. The central kitchenette was always occluding parts of the studied cafeteria or adjacent spaces when capturing HDR images. However, even HDR images captured from the upper level of the cafeteria (Figure 6) did not allow representing light in relation between the cafeteria and the adjacent spaces.



Figure 6. HDR images captured from the upper level of the cafeteria.

Through the 3D laser scanning method, a perspective cross-section can be generated as of Figure 7 which shows the relation between the curtain wall and apertures in the visual field. This cross-section allows the observation of the scenery fronting the curtain wall from different viewpoints in a single image. The view field of occupants sitting at each extremity of the space (Figure 7) may have exceeded the scene visible in this cross-section. For example, an occupant sat on the right side of this cross section must have seen the building located far away situated on the eastern side of the cafeteria.



Figure 7. Perspective cross-section view issued from the fused point cloud.

Several perspectives can be extracted from the 3D point cloud model. Figure 8 presents an example of a viewpoint located in the adjacent corridor leading to the cafeteria. The figure presents surfaces, colors, lighting sources and fixtures seen from an observer at a chosen viewpoint during the survey. Figure 8 also shows an HDR image captured on-site at a homologous viewpoint from images generated from the 3D point cloud model. These images were captured at the scanned survey points. The mean image brightness and standard deviation of each of the point cloud and the HDR image are compared in histograms shown in Figure 8. Varying lighting conditions seem to induce chromatic errors in the point cloud as illustrated in histograms in Figure 8.

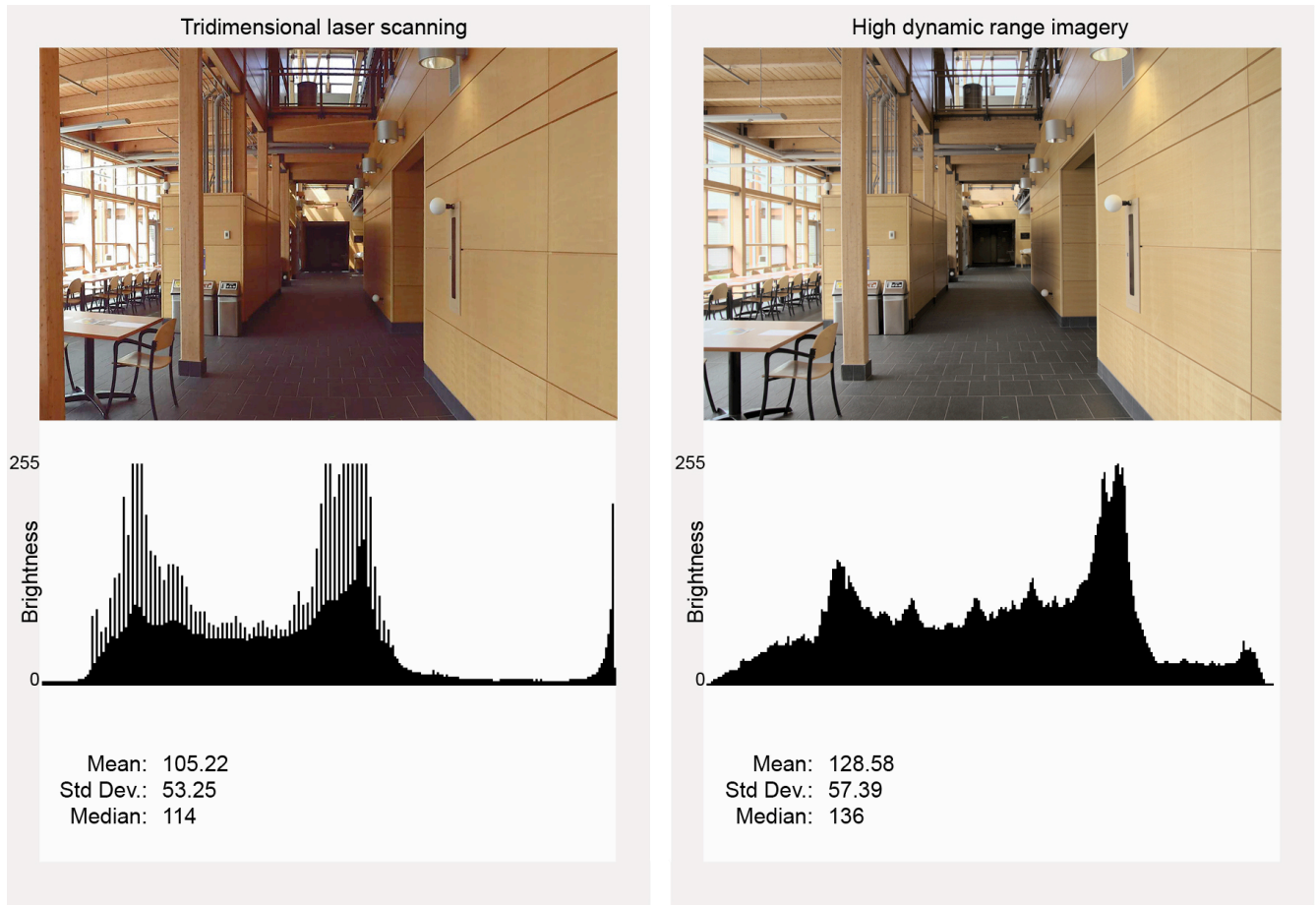


Figure 8. Comparison of histograms from the 3D point cloud model (left) and a homologous HDR image (right).

To further explore 3D laser scanning potentials, Figure 9 displays a rendering of a new sculptural object in the existing laser scanned cafeteria. The synthetic object is rendered according to existing building lighting conditions and ambience located in the scanned cafeteria. It was achieved by importing the new element in the 3D point cloud in Autodesk Revit. As panoramas can be generated from any viewpoints in a studied space, environment maps need to achieve image-based lighting. The rendering was obtained with the V-Ray plugin in Autodesk Revit [45]. An environmental map was generated from a panorama generated in Faro Scene.



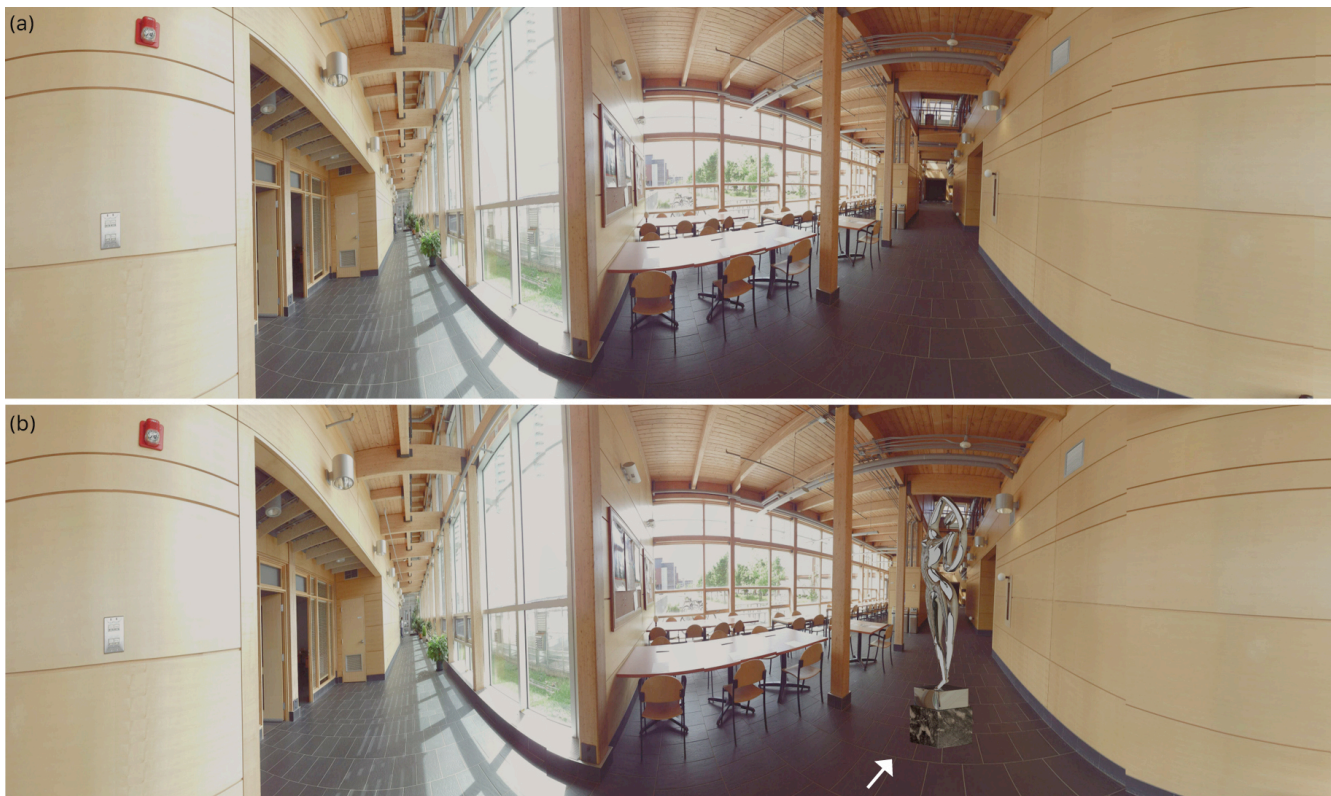


Figure 9. (a) Original scene. (b) Sculpture rendered according to the lighting ambiances of the 3D point cloud model.

## 4. Discussion

The survey and visualization processes developed in the research have shown that the 3D laser scanning method offers new visualization possibilities to discuss lighting distribution patterns in vast and geometrically complex spaces. The 3D point cloud model allows virtually revisiting existing spaces after completing the on-site survey. It facilitates the understanding of lighting distribution patterns by allowing designers to visualize them in their context: in the surveyed geometry, the position of the lighting sources and surfaces and their materiality. The point cloud model can be revisited through a video representation such as the example provided in the supplementary materials. The model facilitates the holistic understanding of lighting distribution patterns in the entire building as captured images are moved, rotated and projected on the 3D point cloud model.

An unlimited number and types of images could have been generated from the 3D point cloud model. This potential enables non-humanly accessible imagery, such as an axonometric view and a reflected ceiling plan and wide-view cross-section. Such views and images are useful for architects when redesigning or altering a space. As presented, the cafeteria can be seen under various viewpoints that differ from the location of the scans. The axonometric view, the plan and a reflected ceiling plan, which consist of images similar to architectural presentation drawings, allow visualizing lighting distribution between contiguous, fragmented and non-intervisible spaces in a single representation. This potential offers simultaneously illustrating several spaces connected one to another, even if they are not altogether visible in reality. It also enables dynamic views of moving and circulating in the studied space, whereas observing the entire space and circulating in parts of a space are not possible by HDR images. Moreover, the ceiling is often one of the main internal reflectors of daylight in architectural spaces. Surveying and representing the ceiling can be a laborious task through conventional methods. 3D laser scanning could offer an affordable solution for undertaking such missions.

Considering the shortcomings of existing methods discussed in section 2, the proposed methodological process could further benefit the visualization of lighting distribution patterns in existing architectural spaces. As explored by the case study, the 3D laser scanning method has added benefit in spatial understanding of interplays between lighting sources and surfaces of surveyed existing interior environment. As shown in the results, visualizing lighting distribution patterns on surfaces of the cafeteria and the adjacent spaces requires less spatial cognition skills with the axonometric view, the plan and the reflected ceiling plan than with the HDR images captured on-site. When the space is overly vast and complex, even an experienced designer needs to hypothesize on the selection of viewpoints. Such viewpoints could produce results which are not representative of the actual visual experience of light in the space. The present paper argues that the selection of survey points becomes less arbitrary by using 3D scans since designers have access to an entire model in bird eye views and a higher ability to compare several viewpoints for further analysis, including visual comfort assessments. Designers can, moreover, visually acknowledge the relative illuminance of areas of a studied space to identify the lack of light or uniformity of its distribution on surfaces. With the 3D laser scanning method, the number of scenes to be analyzed is independent of survey locations as the 3D point cloud model of the space offers unlimited number of viewpoints and inhabitation scenarios for its occupants. Choosing survey locations only influences the speed required to post-process and align the point clouds which is almost automatic. A designer could, for example, generate several fisheye images, layer them under a foveal graph and select the viewpoints which are most representative of the brightness perception. The method is, therefore, very promising for determining the percentage of a space that is visually comfortable and to spatially map visual comfort risks of existing spaces because the position between every surface and every humanly accessible viewpoint could easily be calculated. By computing and treating the data of the point cloud, it would also be possible to develop an algorithm for defining the position of each colored points in every users' field of view.

Furthermore, the potential of rendering new elements in relation to the lighting ambience of an existing environment bears several advantages in architectural applications. For instance, it could allow architects to visualize existing lighting ambience of new interiors or exterior installations such as interior partitions or objects like sculptures, as illustrated in Figure 9.

## **5. Limitations and future developments**

The 3D laser scanning method can be further developed for lighting design and architectural applications. The method seems less potent for surveying lighting patterns of small and geometrically simple environments because of the cost of current 3D laser scanning devices. Furthermore, future research could explore projecting calibrated HDR imagery on point clouds for increased effectiveness in the extraction of luminance data from 3D laser scanned models and generate more precise results. As exterior environmental conditions might change during the capture of several 3D laser scans, the variation of daylighting could affect the representation of lighting patterns. Lighting variation during a survey induce chromatic errors. This uncertainty also exists in HDR imagery [20]. However, as a point cloud gives more information about the context, it may be easier to identify such chromatic aberrations. The fusion of several 3D laser scans captured under varying lighting conditions also seems to induce chromatic errors. Hence, if a same surface is captured under different lighting, its color after the fusion of the point cloud will be an average color of the 2 expositions. The number of points captured in each of the two scans will affect the final average color. Therefore, capturing an accurate chromaticity requires future studies and developments. Future studies could focus on conceiving an algorithm to tone map all the scans of a space to a reference scan for preventing exterior natural light changes during the scanning process in order to minimize chromatic aberrations. Using Macbeth Color Charts to tonemap all scans similarly, independently of outside conditions, may solve parts of the problem. Laser scanning method could also be combined with augmented reality technologies to offer architects and designers further possibilities to explore different ideas and strategies for renovating and altering existing spaces.

## 6. Conclusions

This research presented a new lighting survey and visualization method with 3D laser scanning for existing built environments with vast complex geometries. This is a complementary daylighting survey method responding to the limitations of existing tools and methods including photometric measurements and HDR imagery. Potentials and limitations of the proposed method are explored by surveying a case study with a vast complex geometry space. Results indicate that the method is effective and a relatively rapid process because of the laser range capacities of actual 3D laser scanners. The study showed that architects and designers can survey and visualize the lighting distribution patterns of spaces of different areas from small interiors to vast fragmented exterior urban lighting spaces. The 3D point cloud model offers the possibility to revisit a studied space after completing its on-site survey. In contrast with present lighting survey methods for surveying lighting in existing environments, the survey and visualization process presented in this research has advantageously allowed the generation of images from viewpoints differing from the location of the data captured during the field measures. This could allow evaluating and mapping the percentage of an existing space that is visually comfortable. Moreover, the method enables generating unlimited viewpoints and images in bird eye, axonometric, plan or cross-section views. Results showed that such imagery types allow a thorough discussion on the relations between lighting distribution patterns and variables such as the position of windows, walls, materiality of surfaces, as well as artificial and natural lighting sources. The proposed method yet needs further developments for lighting and architectural applications, as mentioned in the previous section. One of the shortcomings of the proposed method is responding to varying lighting conditions of naturally lit environments. This limitation can be addressed in future research, hypothetically by defining an algorithm for tone mapping the colors of all scans according to a reference scan.

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