Lasers, Light, and God: 3-D scanning assisted lighting analysis of a house of worship

Juan Sebastián Carrizo[1], William O'Brien[2], and Mario Santana Quintero[3]

[1] Energy Analyst, Hidi Rae Consulting Engineers Inc., Toronto, Ontario, Canada
[2] Assistant Professor, Architectural Conservation and Sustainability Engineering, Carleton University, Ottawa, Ontario, Canada
[3] Assistant Professor, Architectural Conservation and Sustainability, Carleton Immersive Media Studio (CIMS), Carleton University, Ottawa, Ontario, Canada

Abstract

As heritage buildings undergo either needed rehabilitation or optional improvements, inappropriate lighting alterations can compromise the original intent, character, and authenticity of the evaluated building. However, technology now exists to establish the optimal interplay between artificial lighting and daylighting in any given scenario. Therefore, a comprehensive audit of the lighting and daylighting features of a heritage building can actually provide opportunities to not only reclaim compromised historic character but also improve the building's energy efficiency and value.

This project aims to bridge the gap between heritage value and energy efficiency in the lighting/daylighting field. It will evaluate the lighting performance of a potential historic building (the St Barnabas Church of Ottawa) and determine areas for improvement.

By integrating surveying and energy analysis tools, this project presents an innovative methodology for the analysis of historic buildings and provides a template for further understanding of the importance of preservation and conservation in the building performance simulation community.

1. Introduction

Sustainability is an inherent principle of historic preservation. Historic preservation has always been about retaining well-designed, well-constructed resources for the present and the future. However, historic buildings are increasingly targeted for modern improvements that are often costly and unnecessary. One of the areas where these "improvements" are proposed is in lighting systems.

Although early construction lacked the modern techniques and simulations of today, historic buildings can be just as efficient in lighting design as new buildings. For example, "… the Pantheon in Rome, with its dome-top oculus, shows how daylighting was exploited in the construction of early large buildings. On the other hand, in today's architecture, much of the design rigour used in the consideration of daylighting has shifted towards the design of electric lighting" (Robertson 2005).

Despite the fact that many scholars and professionals have begun to realize the need to tackle historic preservation in sustainable ways, little literature directly addressed energy efficient lighting specifically. Within the preservation writings, energy efficiency is occasionally discussed, but typically as a peripheral issue within a larger context or in reference to the cost savings of energy efficiency. Attention to the larger subject of energy

efficiency focuses on space heating and cooling and makes little mention of lighting (Behm 2002).

In the United States, the National Park Service and The Secretary of the Interior's Standards for Rehabilitation frequently serve as the default source for information, guidelines and regulations for historic preservation. Many state and local regulations defer to these standards and federal regulations are often built upon them. In the brief titled "Improving Energy Efficiency in Historic Buildings" little mention is given to lighting as most of the brief focusses on envelope design, insulation and HVAC systems[1].

Within sustainable architecture and engineering, historic preservations is addressed only in passing or involve defining how historic buildings present a different set of rules and should be excluded from any energy efficiency requirements.

2. Background

Historic Overview

The Church of St. Barnabas, Apostle and Martyr (hereafter referred to as St. Barnabas) has been an Anglo-Catholic parish in the Anglican Communion since its inception in 1889. The choice of location (70 James Street) was made to accommodate the fast growing population in this portion of the city. The congregation quickly outgrew the capacity of this church which additionally hadn't been built to accommodate the specific needs of Anglo-Catholic worship. In 1929 and under Father Browne tenure the decision to build a new church took place. This church was designed by the Canadian architect Colin M. Drewitt and was specifically tailored to fit Anglo-Catholic traditions in a combination of Byzantine style and Romanesque style (Petrie 1989). It was praised by architects of the time "as a remarkable architectural unity, quite free of sentimentality and without a superfluous line or plane, while at the same time every detail fulfil[s] its correct aesthetic contribution and function…" (Peake 1997)

Since its construction in 1931 few changes have been made to the Church. Most of its structural elements remain in their original conditions. Some relevant changes include the addition, around 1951, of the stained glass windows in the apse (ordered by Father Browne), the relocation of the organ from the sanctuary to the upper alcove over the narthex and the covering of the original hardwood floors with tiles in 1960 (figure 1).

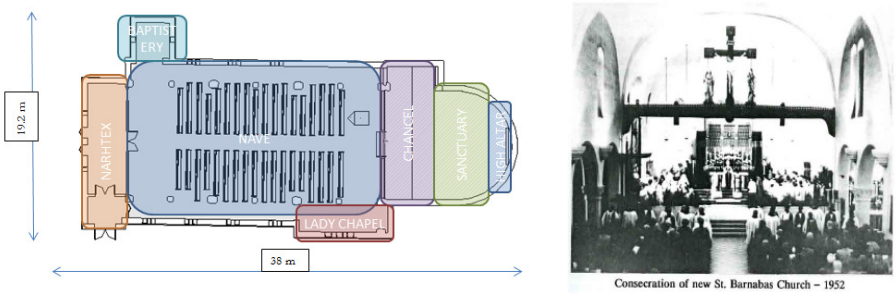


Figure 1- Blueprint and historic picture of the Church[2]

Architectural styles and Symbolism

Despite being described as a mixture of different architectural styles (Ontario Architecture 2012), St. Barnabas presents more elements in common with the Romanesque Revival than those of the Byzantine style. The defining feature of this style is the semi-circular arch used for all window and door openings. The typical plan is basilican, with a

[1] Brief available online at http://www.nps.gov/history/hps/tps/briefs/brief03.pdf
[2] (Petrie 2002)

long, narrow nave, vestibule, central tower or paired side towers, and self-contained massing. Broad, smooth wall surfaces of monochromatic brick were typical (Ontario Architecture 2012). Elements that can be found in Saint Barnabas Church include a broad, square bell tower, round Roman arches, columns with elaborate ornaments, and heavy block ledges (Ontario Architecture 2012).

From an energy perspective it has a distinct advantage over Gothic (the other predominant style being used at the time), whose large areas of glass windows let in too much light in the summer and too much cold in the winter months of Canada.

The architectural symbolism of the church points towards a lighting system that moves in two directions, vertically towards a more lit ceiling, and forward towards the High Altar. As designer Andrew Gould explains, the liturgical axis creates a progression between the narthex and the High Altar. The narthex (front of the building) represents the fallen world and symbolizes the gates of heaven. The nave represents the redeemed world, where the faithful gather for the worship of God. The sanctuary stands for the highest heaven, and the altar is the throne of God (Gould 2006).

This axis usually matches the cardinal axis having the narthex at the west end and the high Altar on the east (Davis 1982). As is the case in St Barnabas (where the main entrance had to be placed on the main street James) limitations in the building's site and ease of access make this coincidence of axis not always possible. It is then accepted to diverge from cardinal eastward and assume liturgical east as the direction of the High Altar.

The vertical axis can be though as the approach of God and man. The dome and ceiling (most brightly lit), is heaven, it touches the nave and transmits its light onto mankind.

In St Barnabas specifically one finds that walls appear thick and strong in comparison to those found in Gothic styles. The windows are small and set up high and deep into the openings. This leads light to be seen as a diffused reflection off the walls rather than directly through the windows. Aisles behind arches appear as "mysterious shadows in the distance", giving the church a brighter appearance by the contrast obtained (Gould 2006)

Lighting requirements

From a practical perspective, the need for lighting in St. Barnabas can be divided into four categories: general ambient lighting, choir and musician lighting, chancel lighting, and highlighting of religious elements.

- General lighting: One of the most basic functions involved in all types of activities that occur in a worship space is reading. Attendants need to read materials related to the service such as Bibles and hymnals. Light levels at the horizontal work plane (0.8m or 1.4m if standing) should be enough to allow reading but low enough to create the right liturgical mood.
- Choir/musician lighting: Choir members and musicians need to read their music. Special luminaires should be aimed at the choir gallery to provide sufficient lighting levels.
- Front lighting: It is important to be able to see the worship leaders clearly during a service. This layer of light assures that the officiants are brightly lit from the same direction that the congregation is viewing them from the front. Studies have shown that seeing facial features has a direct effect on how well people hear; hence good lighting is a positive step toward better understanding.
- Highlighting of religious elements: There are distinct spaces in St Barnabas that require special highlighting. These include: the shrine of our lady, the nativity painting and the Lady Chapel. Within the already highlighted Sanctuary, the Triptych (High Altar) is the most important and central element and should get the appropriate illumination to draw the congregation's eyes.

3. Methodology

As is the case with many heritage buildings, there are several obstacles to correctly modelling the dimensions of St. Barnabas Church. As time passes, both blueprints and measurements become inaccurate given natural changes to structures. Many heritage buildings are also complex in shape and have envelope assemblies with hidden conditions. Accurately modelling forms and assemblies is a time consuming challenge, and not all software can accommodate these variations. It is these particular challenges that encourage the use of laser scanning as a tool to develop a 3-D model of the studied building.

The unique feature of this analysis will be to determine how to increase lighting efficiency while accounting for the building's architectural purpose and heritage character. Throughout this analysis an "energy-heritage perspective" will be taken, where the focus will be on optimizing energy use while maintaining the original objectives of light in this building of worship.

4. Model Development

For a lighting analysis to be conducted a model must possess three aspects of a building: geometrical accuracy (this relates particularly to daylight portals, e.g. windows), the materials and finishes need to be properly assessed (this relates to the properties that different finishes and color have on propagating light), and finally the appropriate artificial interior light sources need to be determined. Each one of the following subsections aims to address one of these aspects.

Laser Scanning - Geometrical Accuracy

3D Laser Scanning is a non-contact, non-destructive technology that digitally captures the shape of physical objects using a line of laser light. 3D laser scanners create "point clouds" of data from the surface of objects. Simply stated, a three dimensional laser scan is like an image from a digital camera, except that each and every pixel can be established in a real world 3D coordinate system. One of the great advantages of laser scanning is that it can record a large number of points with a high accuracy in a relatively short period of time. (Quintero 2008).

This technology relies on a line of sight approach. Consequently multiple scan positions are required to ensure a complete coverage of spaces. Hence, these scans need to be registered (or linked) in a common coordinate system. The standard technique to achieve this registration is to place artificial targets in the scene and identify them in the different scans. These targets are usually objects that remain unchanged with the scanner viewpoint (spheres or cones for example) and are generally made of highly reflective material to simplify their automatic recognition (Figure 2).

For this project, a two-step procedure was followed to scan St Barnabas: first a general scan was conducted that was fit for the end deliverable (a resolution of 10 mm was used). In a second scan, targets were individually scanned at a higher resolution (1 mm) to ensure a high accuracy when determining center points.

In order to assure that the registration of all scans could be done accurately, a minimum of three targets had to be visible to the scanner for any given scan. This allowed for an accurate triangulation and minimized errors in the final point cloud. The final point cloud had an error discrepancy of 8 mm, which is perfectly acceptable for the inherent scanner margin of error of 5 mm, as well as the final model's expectations and requirements. Figure 2 presents the different scanning positions, the artificial target placement, and also showcases the final raw registered point cloud.

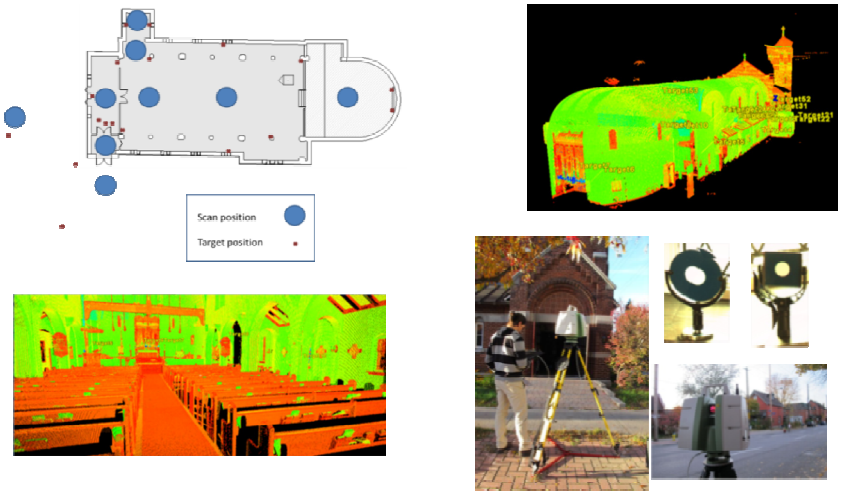
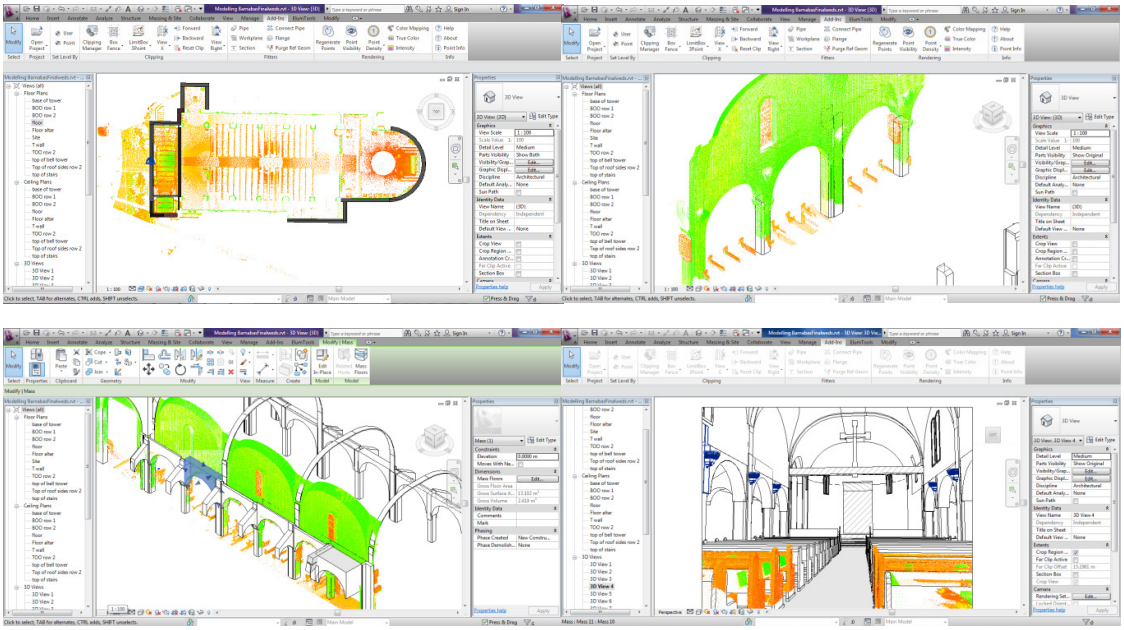


Figure 2- Scanner position, final point cloud (outside and inside view), and scanning equipment

Point Cloud Processing and Physical Modelling

Having obtained a final cloud point that accurately combines all the scans conducted, it was time to generate a physical model from it. To do so, Leica's Cloudworks plug-in for Revit was used. This application allows users to take advantage of rich, 3D point clouds directly within Autodesk Revit, transforming this cloud into a template over which Revit components can be accurately modelled and designed without the need of on-site measurements. This plugin allows the modeller to selectively hide segments of the point cloud (through the use of fences, slices, and user-defined cut planes), to focus on specific areas of interest (figure 3). As with any lighting analysis, it is important to think of the model as a boat: if it cannot hold water, it will leak daylight.[3]



[3] Eddy Krygiel, Autodesk University 2010

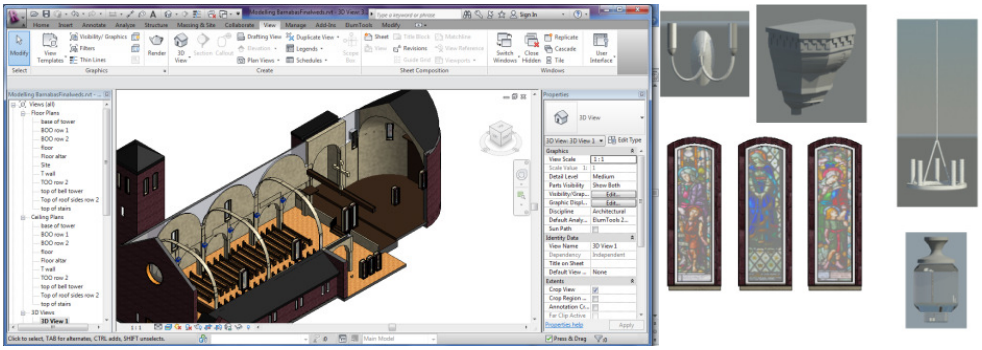


Figure 3- Steps in model generation and detailed components

Materials and Finishes

Once all the geometries were developed, positioned, and properly linked to the different elements in the model, it was time to give each surface the appropriate material finishing. It should be noted that although this model is geometrically accurate, the materials used (from a structural perspective) are not, so any future analysis of mechanical load or stress test of the structure would require a proper assignment of materials for each of the different elements developed. As the main object of this study is light, we need only be concerned with the color and finishing of the different surfaces.

Light source definition and Sun parameters

To render the model's lighting performance, 3Ds Max Design software from the Autodesk suite has been selected. This software not only allows for a seamless integration with the Revit model generated, but also provides the appropriate output required to conduct lighting analysis. By means of ray tracing mental ray methods, 3Ds Max allows for the evaluation of point to point lighting illuminance. This software has been experimentally tested to ensure the accuracy of its results (Reinhart and Breton, 2009).

The final element required to conduct a lighting analysis is the definition of each one of the artificial light sources found in the building. To do this, the IES (Illumination Engineering Society) has developed a file format that allows for the electronic transfer of photometric data over the web. It has been widely used by many lighting manufacturers and is one of the industry standards in regards to photometric data distribution. An IES file is basically the measurement of distribution of light (intensity) stored in ASCII (American Standard Code for Information Interchange)[4] format. Each of the light sources found in the building has been assigned an appropriate IES file to describe its intensity distribution. Color temperature has also been modelled following the values described in Table 1.

Table 1- Color temperature for each light source

Technology	Description	Color Temperature (K)
Incandescent	B10 60w	2700
Incandescent	Standard 100w	2700
Halogen	PAR 38 90 w flood	3000
Compact Fluorescent	17w	5500
Halogen	PAR 38 90w spot	3000
Halogen	Bi pin 30W	3000

As this project includes the effects of daylighting, it is important to add proper positioning and neighbouring buildings that directly affect access to daylight throughout the

[4] ASCII is a character encoding scheme.

day as their size can reduce the solar exposure of the different daylight portals modelled.[5] Figure 4 shows the approximations used to account for this shadowing effect.

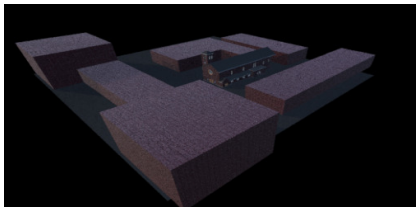


Figure 4 – Neighbouring building approximations

To simulate the sky conditions, the Perez All-weather Sky model was used. This model relies on historical weather profiles from Ottawa (included in the model via an EnergyPlus Weather file)[6] and requires the following input: Direct Normal Illuminance (in lux) and the Diffuse Horizontal Illuminance (in lux). As part of the validation process, actual measurements for these parameters were taken before each sampled scenario. This will ensure an accurate comparison between measured and simulated results (see table 2).

3. Model Validation

A fully developed model cannot be used to predict or estimate lighting performance if it has not been validated and proven to fit its real life counterpart. To do this, measurements were taken on 3 different days under different sky conditions and at different times (see table 2). Figure 5 shows the measurement grid used to record measurements which correspond to the center of the section of the building being measured (each section has a size of 3m x 3m).

Table 2 – Weather conditions on measurement samples

Scenario	Lighting conditions	Date	Time	Sky Conditions	Direct Normal Illuminance[7]	Diffuse Horizontal Illuminance[8]
1	daylight	26/11/2012	14.30	Partially Cloudy	5000 lux	4050 lux
2	Daylight and artificial light	26/11/2012	16.00	Partially Cloudy	1500 lux	1100 lux
3	daylight	4/12/2012	11.00	Partially Cloudy	8950 lux	6650 lux
4	Daylight and artificial light	4/12/2012	12.30	Partially Cloudy	8000 lux	5600 lux
5[9]	Artificial light	9/12/2012	18.30	Night-time	0[10]	0[11]

Table 3 presents the average measured and simulated illuminance levels for the sampled scenarios. Discrepancies are calculated as a percentage of the measured value. As shown, the percentage difference in average illuminance was of 14.6%. The modelled levels

[5] The diffuse reflectance of the surrounding buildings has been assumed to be 50%.
[6] These files are provided by the US Department of Energy and can be accessed at http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm.
[7] Due to the dispersion of values obtained while measuring outdoor conditions (± 40 lux), values have been rounded to the closest 50 lux interval.
[8] Ibid footnote 7.
[9] The CIE sky model was used for nighttime analysis due to the reduced accuracy of Perez Sky model under these conditions (Kensek and Suk, 2011).
[10] Measured values were influenced by artificial lighting from street lamps. For modelling purposes, 0 was used to represent nighttime situations.
[11] Ibid footnote 10.

consistently overestimated the illuminance levels both for daylight and artificial lighting conditions. This is in part due to the non-instantaneous nature of the measuring process (which took approximately one hour in total) meaning that the setting sun impacted but not modelled illuminance.

Table 3 – Validation scenarios' results

Scenario #	Measured illuminance	Modelled Illuminance	Discrepancy
i	18.5 lux	21.7 lux	+17.3 %
ii	29.3 lux	35.9 lux	+22.5 %
iii	26.6 lux	28.8 lux	+8.3 %
iv	48.0 lux	56.3 lux	+17.3 %
v	26.1 lux	27.5 lux	+5.4 %
Overall			**+14.6 %**

Scenario *iii* presents a unique situation were the opposite effect is perceived. As the measurement process was carried out, light levels outside rose because the measurement was taken before solar noon. This has led to lower discrepancy values.

Scenarios *i* and *ii* present the highest discrepancy partially due to the fluctuating sky conditions. Throughout the measuring process certain areas had to be re-measured (stations located near windows) as the overcast conditions had ceased and clear skies were observed.

Figure 5 displays the output developed to analyze similarities in the light patterns. The figure on the left represents the simulated results and the figure on the right sows the contour map generated from the measured values. Averages were calculated by exporting the values into spreadsheets.

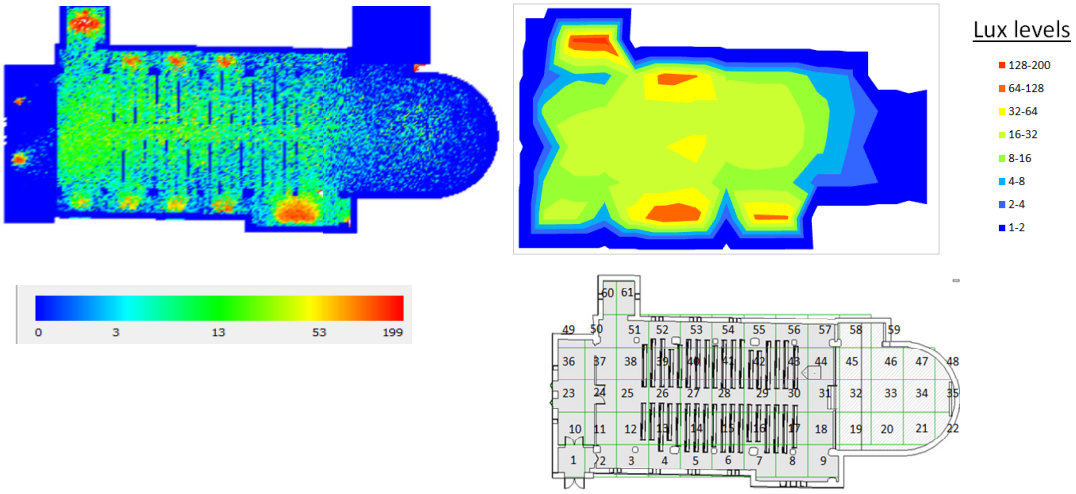


Figure 5 – Scenario *iii* Results- Simulated (left) vs Measured (right) Illuminance levels in lux) and measurement grid

Although the gap is almost 15% the sources of error are the high values near the windows that increase the overall average. Values in the center of the nave (close to the real measured spots) are in fact accurate and validate the model.

In summary, patterns are consistent with those observed during the different visits and are in line with theoretical expectations (higher values of illuminance during the day closer to windows and similarly higher values closer to artificial light sources). Although the discrepancies seem to suggest flaws in the model, a closer look at outliers, extreme values close to the windows, and fluctuations in the sky patterns provides the certainty that the model responds like the real building. Further validation could require more in depth collection of

data and data processing from the light model. These steps exceed the scope of this project but are suggested as possible future research.

4. Results

Illuminance

If we compare any of the real measurements conducted or scenarios simulated and analyze the Illuminating Engineering Society of North America (IESNA) expected illuminance values, we will find a significant difference. IESNA suggests values of: 300 lux for the chancel and 150 lux for the main worship area. The measured scenarios developed in this model present illuminance levels (refer to table 3) that range on average from 18 lux to 48 lux (depending on whether artificial light is on during the day or only daylight is in use) and 26 lux during nighttime (only artificial lighting is assumed present).

Despite this difference in values, Rev. Canon Stewart Murray (the current rector at St. Barnabas) explained that no issues have been raised regarding lighting levels but that "people were quite content with the ambiance established inside the Church during his services" (Murray 2013). This is consistent with the opinions of researcher Theodora Antonakaki who writes that "Light levels in churches are mostly related to the creation of an environment where the worshipper can fulfil his religious needs and feel the essence of the religion, rather than to regular visual comfort objectives" (Antonakaki 2007).

In order to achieve the appropriate balance between reading and ambiance needs, models with increasing illuminance levels were generated. This analysis included the simulation of five daily conditions (when service is usually carried out) in both equinoxes (fall and spring) and both solstices (winter and summer). Evaluating both overall ambiance (by means of renders similar to figure 6) and workplane illuminance, it was found that an average level of 40 lux for the nave represents an improvement in the workplane illuminance. These levels provide sufficient illuminance for easy reading (especially considering that the mean age of the congregation is around 60 years old) but will maintain the mood that parishioners have learned to associate with the Church and will allow for peaceful unobtrusive lighting when individually praying.

Since IESNA recommends that the chancel & high altar be illuminated at twice the levels of the nave, 80 lux is the average illuminance required to properly accentuate this important element of the building. Figure 6 shows a render of the artificial lighting setup compared to a picture taken inside the church at the current lighting levels.

Figure 6 – Render of final model (left) and interior picture (right)

The need to increase the illuminance levels of the church was further confirmed by the presence of existing (but non-functional) halogen spot lights located throughout the nave. These fixture were added as a way to increase the overall illuminance but did so by flooding

the entire space and creating a uniform illuminance plane rather than focusing on improving specific areas. As these fixtures also fail to cater to the architectural needs of the building, Father Murray has decided to ignore their use during service.
This speaks to a need for a lighting solution that satisfies cultural as well as technical needs. As Hord mentions "The style or period of a particular fixture has a lot to do with how coherent the interior design is […]. You can spend thousands of hours detailing a really spectacular building, and if you don't put the right sort of light fixtures in that space, it can really be unfortunate."[12]

Installed Power Density

This metric corresponds to the power requirement at full lighting output of all luminaries in a determined space. It is measured in W/ft^2 or W/m^2. Current standards impose maximum levels of power density (as percentage) according to the type of space in study. [13]
The total installed power in St Barnabas is 5450 W (this value was calculated by conducting an inventory of the current lighting bulbs and their wattage rating) over an approximate area of 570 m^2, yielding a power density equal to: **9.4 W/m^2.** Comparing this value with Model National Energy Code for Buildings standards 1995 developed by the National Research Council (table 4), we see that St Barnabas is currently considerably below the maximum levels prescribed.

Table 4- Maximum power density for Assembly Spaces

Assembly Spaces	Max. Lighting Power Density	
	[W/m2]	[W/ft2]
Auditoria	17.2	1.6
Conference Centres - multi-purpose rooms	25.8	2.4
- meeting rooms	19.4	1.8
Exhibition halls	28.0	2.6
Lecture halls / Classrooms	21.5	2.0

Figure 7 shows the lighting inventory of the building. Halogen technology represents 50% of the number of installed bulbs and accounts for 64% of the installed power.

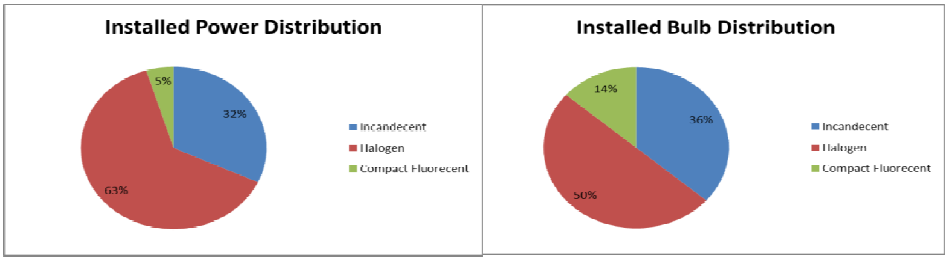


Figure 7 – Current lighting inventory

Daylight Factor

Daylight Factor (DF) is a ratio (measured in percentage) that evaluates the illuminance available indoors relative to that of the outdoors at the same time under overcast skies. As a design metric, the DF functions mainly as a way to proportion window and skylight openings, as well as interior space dimensions so that there is sufficient daylight available within a space under worst case scenarios (Kensek and Suk, 2011).

[12] Carter Hord, principal of Memphis, TN-based Hord Architects
[13] For more information refer to Maximum Lighting Power Densities; Canadian Model National Energy Code for Buildings 1995 and Maximum Lighting Power Densities; Energy Standard for Buildings except low-rise residential Buildings; ASHREA/IESNA Standard 90.1-1999, Section 9 Lighting

The minimum and average DF recommended for different spaces are given in the Chartered Institution of Building Services Engineers (CIBSE) Applications Manual 'Window design' (see figure 8).

For a daylight factor of 1% in a church with windows, supplementary artificial lighting will be required for church services; for a factor of between 2 and 4%, church services can be held without the need for artificial lighting (Kensek and Suk, 2011).

3Ds Max Design allows for the evaluation of daylight factor on a light meter to light meter basis. In order to obtain values for the different areas of the church (see figure 1) daylight factors were averaged for those meters that fell into each area. The following are the resulting DF values:

- Nave: 0.9%
- Chancel: 2.5 %
- Sanctuary and High Altar: 1.8%

Building Type	Location	$DF_{average}$,%	DF_{min},%
Concert Halls	Foyers, auditoria	1	0.6
	Corridors	2	0.6
	Stairs	2	0.6
Churches	Body of church	5	1
	Pulpit chancel choir	5	1.5
	Alter	5	2
General areas	Entrance halls	2	0.6
Schools	Classrooms	5	2
	Assembly halls	1	0.3
Domestic	Lounges	1.5	0.5
	Bedrooms	1	0.3
	Kitchens	2	0.6

Figure 8 - Recommended daylight factors for different types of building

These numbers show that this building relies on artificial lighting to supplement limited daylight access in order to accommodate its services. As the envelope and windows of this building represent a heritage feature that adds character, little can be done to increase daylight capabilities.

To evaluate the original daylighting intent, DF was calculated with all stained glass and nearby buildings removed. Architectural knowledge of the predominant style used in this building paired with the results of this experiment (DF value of 2.6%[14]) show that in its original design, the daylighting capabilities of this building could have potentially kept rooms sufficiently lit.

Although it may not seem like a good design decision to keep daylighting so low, understanding that worship mood setting and related emotions should be experienced when entering or worshiping inside a church helps reconcile both worlds. Warmth is important in a house of worship, and since it not necessarily a characteristic of daylighting (associated with a bluer colour temperature), this further shows the need to minimize daylighting.

Architectural match

The narthex (entrance) seems to have a difference between lighting levels and architectural symbolism that should be addressed. The halogen array of spotlights generates inconsistent light levels that fail to provide a darker room that serves as a gateway into the church. IES makes a point of suggesting brightly lit entrances as "it enables the quick recognition of faces, facilitates the taking of notes, of names, and requests. [...] and provides a transition between the exterior and the nave". It is clear that the suggestion of IES does not match the original architectural intent of the narthex. To correct this, either a full removal of the light fixtures in the narthex (as well as an upgrade on the CFL bulbs located in the area) or a switch to LED (light emitting diode) systems would need to be implemented to create the appropriate mood and lighting levels expected of this area. LED solutions would also reduce the cost of both operation and maintenance.

Color temperature

The color temperature of a lamp (bulb) describes how the light appears when the human eye looks directly at the illuminated bulb. Color temperature is measured in Kelvin (K). A light bulb that produces light perceived as yellowish white will have a color

[14] This value was calculated by doing a weighted average of the light meters' readings.

temperature of around 2700K. As the color temperature increases to 3000K - 3500K, the color of the light appears less yellow and whiter. When the color temperature is 5000K or higher the light produced appears bluish white. The color temperature of daylight varies, but is often in the 5000K to 7000K range.

Throughout the building the overall color temperature is close to 3000K (as all exposed bulbs are incandescent and halogen based) and those that have CFL (compact fluorescent light) bulbs have a diffusing shade that "warms" the color of the bulbs. One small change that should be addressed is in the Baptistery. The light bulbs used in the pendant fixture should be matched to those found in the side chandelier's (B10 bullet profiles) in order to restore the original color temperature 2800K. Although no formal experiment or analysis was conducted in this area there is a clear predominance of "warmth" in the building that emanates from almost all of the light sources in it.

4. Discussion

The overall analysis of lighting in St Barnabas indicates a well thought out system that has been altered throughout the life of the building. Under Father Murray's tenure, it has been purposely returned closer to its original design and intent. This is showcased by the active decision not to use certain light fixtures and to replace light bulbs with more aesthetically pleasing ones (the side candelabra used to have white 60w incandescent light bulb that have been replace by B10 bullet bulbs that fit better with the luminaries' characteristics).

Throughout the building, light sources and daylight portals are matched in "strength" to obtain similar lighting patterns regardless of time of day. This has allowed some of the architectural symbolism to become more evident and present, for example the increase in illuminance along with height at the vertical axis.

On the other hand, there is a need to increase the general illuminance levels of the church to better serve the different activities carried out during services (from the current values to a maintained target of 40 lux in the nave). To do this, while not compromising the heritage qualities of the building, more efficient and powerful flood lamps should be placed on the side lighting fixtures. LED systems could provide the required increase in illuminance and reduce maintenance requirements (by increasing the life expectancy of bulbs). However, this could increase the color temperature of the space towards a "colder room" which works against the mood intended.

A government regulation which will soon come into effect should be mentioned as it directly relates to all light sources used in the building. Regulation 17724[15] states that by December 2014, no importation or manufacture of non-compliant light bulbs will be allowed in Canada. The fixtures affected by this new regulation include all incandescent light bulbs over 40W and all halogen systems that are non infrared coated (traditional PAR38 bulbs are not coated). This will greatly affect St Barnabas Church as it has less than 5% CFL bulbs installed, which are the only bulbs that would not need to be updated. Although not an immediate issue, stock of the selected lighting supplies will become scarce, affecting availability and pricing. To prevent this from happening, a slow transition should be made towards more efficient systems.

For any incandescent bulb not in plain view (e.g. behind the beam aimed at the Sanctuary there are five incandescent bulbs, and one more behind the Lady) the quick and easy fix is to upgrade to compact fluorescent light bulbs (27W are equivalent to 100 W incandescent). If the option exists, the buyer should always aim at warmer colors, with color temperatures closer to 3000K (as we have seen, CFL tend to have temperatures closer to 5000K). It should be noted that, as low-cost solid state replacements (LED) for incandescent

[15] Available online at http://oee.nrcan.gc.ca/regulations/17724

light bulbs become more available, these options should be favoured given their higher energy efficiency, range of light intensity, and faster warm-up periods.

For all B10 bullet 60W incandescent light bulbs, an LED solution should be found. The current options are not appropriate for the needs of St Barnabas but in the near future, candle like B10 LED bulbs,[16] once they exist; they should provide the required illuminance and color temperature. As with all replacements, the goal is to get color temperatures of around 2700K ~ 3000K. Frosted systems should be encouraged as they will reduce glare problems faced today.

PAR38 bulbs will be the hardest to improve as they have a unique combination of characteristics that make them a very good fit for the uses in the Church. As explained before an IR coated halogen lamp could meet the energy requirements of the new regulation but would not present a high increase in efficiency. There are PAR LED replacements that have been successfully implemented in churches and should be considered. As the objective is to use the current fixtures and set up, and we need a higher general illuminance, 24W LED PPR replacements would be encouraged (equivalent to 120W traditional halogen PAR). [17] These fixtures would provide the extra illuminance required at lower power costs. Color temperature should still aim for 3000K.

In all the cases described, LEDs present a steep capital cost, but they have a longer life span and reduced operational costs. Knowing that regulation will force some of the bulbs to change is a positive motivator for the church to become more efficient, while keeping its technical and cultural requirements.

5. Conclusions

This project has tackled the analysis of lighting efficiency and performance in a historic building. Throughout this report, a heritage-efficient approach has been taken. A model has been developed that accurately describes the behaviour of the real church and has allowed for the generation of several different situations and scenarios.

The current state of the church's lighting systems presents a few areas for improvement, but is overall well thought out and in line with the principles and objectives herein described.

This project combines the use of a non-contact, non-destructive technology recording technique, with software that allows for a simple transition between the different platforms. With the development of simulation models, one can easily conduct analyses of different alternative designs. These tools were integrated with user perception of space and a qualitative analysis of the historic role of light in a particular space. The methodology described in this work presents a bright future in further integrating building recording, modelling and analysis.

As with any new technique, it is important to present some of its limitations and shortcomings. The following list highlights some encountered while developing this study:

- The importance given to a proper analysis of the historic and heritage value of light leads to non-transferable studies or rules of thumb (e.g. mosques and cathedrals would present different needs and characteristics while all being religious spaces).
- Model validation proved to be a very important and time consuming task. Until a model is validated very little analysis can be conducted or conclusions be drawn.

[16] 2.5 Watt B10.5 Philips Endura LED Frosted Candelabra Light Bulb is an example of what to look for.
[17] 24 Watt - LED - PAR38 - 2700K Warm White - Flood - Lighting Science DFN38W27V2FL120 is a perfect fit for the Church.

- Validation of models makes this technique impractical for early design alternatives of new buildings (especially those where the envelope and materials have not be finalized).
- Lighting input is hard to obtain for older fixtures, e.g. due to the angle of some fixtures, IES profiles.
- Daylight Factor is a very simplified method of evaluating daylighting conditions. Researchers and practitioners advocate for more dynamic indices such as spatial daylight autonomy and useful daylight illuminance.

Further analysis could be conducted of St Barnabas, including an in depth analysis of alternative lighting configurations, using HDR photography to conduct glare analysis, and a full integration with mechanical analysis software could shed some light on other areas for improvement (EnergyPlus could be a used for whole building energy analysis).

Although the current methodology includes a study of the user perception and historic role of light, there is a need to standardize the inclusion of subjective metrics, e.g. warmth, and mood setting, to fairly assess different improvement alternatives.

By integrating surveying and energy analysis tools, this project presents an innovative methodology for the analysis of historic buildings and provides a template for further understanding of the importance of preservation and conservation in the building performance simulation community.

6. References

Behm, Gary. "In Luce Veritas: Or Why You Should Use a Lighting Consultant on Your Next Historic Project," Clem Labine's Traditional Building Nov.-Dec. 2002: 158.

Davies, J.G., 1982, *Temples, Churches and Mosques: A Guide to the Appreciation of Religious Architecture*, Blackwell, Oxford.

Father Murray (2013). Personal Interview

Gould, Andrew: On Earth as It Is in Heaven: Form and Meaning in Orthodox Architecture. 2006

Kensek, K. Suk, Jae Young. "Daylight Factor (overcast sky) versus Daylight Availability (clear sky) in Computer-based Daylighting Simulations. Journal of Creative Architecture & Built Environment. SBABE. Vol 1. 2011

Ontario Architecture. *Romanesque Revival.* http://www.ontarioarchitecture.com/romanesque.html (accessed Dec 9 2012)

Peake, Frank Allen. *Anglicanism in the Ottawa Valley: Essays for the Centenary of the Diocese of Ottawa.* (McGill-Queen's University Press, 1997)

Petrie, Helen. *Merrily on high in Ottawa: the Story of the Church of St. Barnabas, Apostle and Martyr, 1889-1989* (Abacus Print Services Ltd, 1989)

Reinhart C F, Breton P-F, "Experimental Validation of Autodesk's 3ds Max® Design 2009 and Daysim3.0", Leukos 6:1, 2009. http://www.ies.org/leukos/volume6/number1.cfm

Robertson, K. "Daylight Guide for Buildings" (2005) pg. 1, The Alberta Association of Architects

Santana Quintero, Mario. *Theory and practice on Terrestrial Laser Scanning*. Editorial Universidad Politecnica de Valencia (2008)

Stalder, L. "New Approaches to Architectural Theory", en Workshop on Architectural Theory, Hasselt. 2006

Theodora Antonakaki. *Lighting and Spatial Structure in Religious Architecture: a comparative study of a Byzantine church and an early Ottoman mosque in the city of Thessaloniki.* 2007