Factors defining Gothic lighting. Relationship between volume, structure and luminous result in Spanish cathedrals

Factores que definen la luz gótica. Relación entre volumen, estructura y resultado luminoso en las catedrales españolas

Juan Manuel Medina (Main author and Contact Author)

Universidad de los Andes. Facultad de Arquitectura y Diseño, Departamento de arquitectura, Colombia.
jm.medinad@uniandes.edu.co

Antonio Rodríguez

Universidad Politécnica de Madrid (ETSE-UPM). Escuela Técnica Superior Edificación, Spain.
antonio.rodriguezs@upm.es

Eduardo Medina

Universidad Camilo José Cela. Escuela Superior de Arquiectura y Tecnología, Spain.
eduardo.medina@upm.es

Maria Josefa Cassinello

Univ. Politécnica de Madrid (ETSA-UPM). Escuela Técnica Superior Arquitectura, Spain.
pepacassinello@yahoo.es

Abstract

Natural light and Gothic architecture are two inseparable concepts. The reality of Gothic cathedrals cannot be understood without comprehending its intrinsic relationship with the symbolic light of their spaces. Theories about Gothic light and its symbolic and theological value are abundant; yet, there is no study focusing on the fact that light as a physical reality can be quantified, qualified, and therefore, classified. This article explores the direct relationship between cathedral shape and volume and luminous result through the study of some unpublished factors and qualities found along the in-depth analysis of six unique Gothic spaces. This relationship between shape and light aims to become a new conditioning factor to be taken into account in the future, helping to understand and respect the main engine of the Gothic architectural project at its origins: light.

Key words: Gothic, cathedrals, lighting, volume, qualities.

Resumen

Luz natural y arquitectura gótica son dos conceptos inseparables. La realidad de las catedrales góticas no puede ser entendida sin comprender la realidad intrínsica existente entre luz simbólica y espacio arquitectónico. Existen abundantes teorías acerca de la Luz gótica y su simbolismo; sin embargo, no existe un estudio enfocado en la idea de la luz como una realidad física, cuantificable y cualificable que puede ser, por tanto, clasificada. El presente artículo explora la relación directa entre la forma y volumen de las catedrales y su resultado luminoso a través de un estudio de algunas cualidades y factores inéditos encontrados después de un profundo análisis de seis espacios góticos únicos. La relación entre forma y luz pretende ser un factor determinante en el futuro que ayude a entender y respetar un valor principal de la arquitectura gótica: su luz.

Palabras clave: Gótico, catedrales, luz, volumen, cualidades.

Introduction

Light, that intangible architectural value, has played a decisive role throughout history. However, it is in Gothic cathedrals where the magic of light has become space. Passing from Romanesque style to Gothic was a qualitative architectural leap. This structural evolution implied an unprecedented rupture with support limits. Once freed from the pressure the barrel vault applied on the walls, Gothic architecture evolved, making the implementation of real glass boxes possible, searching in its symbolic nature for the "loss of serenity" (Ortega y Gasset, 2009) and a kind of hypnotic effect that excites both the gaze of the layman and that of the expert eye–an experienced architect or a skillful artist. The expressiveness of the space is one of the milestones in the history of architecture, able to capture essence of the mystery with the use of a perfect scenery.

But why is Gothic architecture so hypnotic? There is a determining factor for Gothic architectural reality, an element of design which drastically distinguishes this change of style from any other development in the history of architecture: the evolution in the use of light.

Gothic art models light in a completely new way. The first walls with openings and stained glass windows lead to a recreation of new spaces with an unprecedented composition of light, resembling a tree, allowing light to filter through the leaves through the colorful stained glass windows. This sieved light bathes the interior of the architectural space recreating a new scenery, not known before, based not only on the amount of light or on its direction but also on the mysticism created by it (Jantzen, 1979).

Although Gothic architectural progression can be measured mainly by its structural evolution through the transfer of stresses following the ribbed directionality of loads, this structural display and its spatial consequence on their own would not be enough to overwhelm us the way they do unless there were "something else." The strength of this style lies, remarkably, in the light treatment provided by the stained glass windows in the cathedral walls. The color of medieval stained glass windows is precisely what makes architecture enchanting, lifting us up towards a contemplative state beyond mundane affairs, surrounded by the architectural boast of ribbed structured composition. Gothic light is, as can be seen later and as Jantzen (1979) and Nieto Alcaide (1978) claim, a unique light, a filtered light, colored and transfigured, loaded with mystery and symbolism. This light is fundamental to religious experience (Weightman, 1996). Gothic changing lighting contrasts with the gloom of Romanesque architecture, invaded with a sense of piety, and it differs from the later Renaissance churches, filled with "natural light."

Figure 1. "Natural white light" projected upon the main aisle of Saint Eustache of Paris.
Its construction was started in a Gothic style and completed in a Renaissance style.
Source: Self-elaboration.
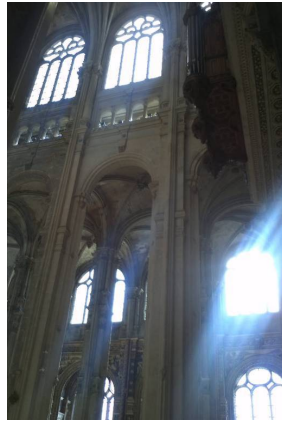
While the insights of scholars on Gothic light are rich in symbolic, philosophical, and even metaphysical descriptions, Gothic light requires much greater thorough study considering it the physical fact that shapes interior spaces. Light needs to be studied according to its intensity and color.

This article proposes a study of Gothic cathedrals analyzing the quantification and detailed qualification of their light, linking its intangible "luminous fact" to the shape, structure, and volume of said cathedrals.

Historical background and overview of knowledge sources

Delving deeper into the knowledge of Gothic light requires dealing with two levels of documentation: on the one hand, the legacy of written documents of the period in which cathedrals were built, and on the other hand, all those schools of thought that have studied the reality of light in Gothic style subsequently until the present day.

The first level of research shows a bleak outcome. Immersion into the study of the Gothic manuscripts that have survived up to this day shows a weak, inaccurate, and disjointed documentation, which describes mainly constructive and formal features of the architecture of the period.
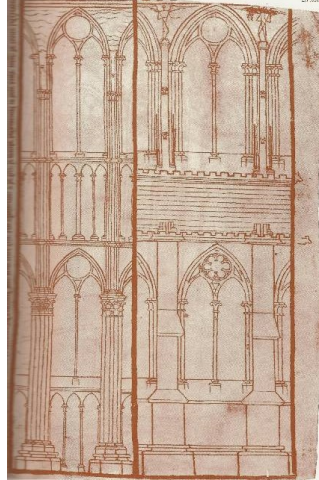
The second research level of sources would be the later Gothic schools of thought related to the composition of light. From Hugo of San Victor to Saint Thomas Aquinas, Dante, Plato, Pseudo-Dionysius the Areopagite, and even Saint Augustine of Hippo and Abbot Suger, the first "instigator" of the Luminous Gothic.

More contemporary authors such as Panofsky, followers of the theories of Viollet-le-Duc, Otto von Simson (1956), Nieto Alcaide (1987), or even Cassinello (2005) have tried to explain Gothic lighting phenomena.

In trying to summarize what has been written and theorized about Gothic light, we can conclude that all authors agree upon describing light from the point of view of its symbolic inherent being. Descriptions are always distant from the reality of light as a physical, measurable, and quantifiable fact. This is the knowledge niche that this article aims to fulfill through the study of quantifiable relationships between volumetric factors that shape Cathedral spaces and their luminous reality.

Previous factors considered for the selection of cathedrals. Sample of selected cathedrals

In order to delve deeper into the knowledge of Gothic light and the factors that influence its definition, this study first establishes a classification of 6 sample cathedrals covering all the variety of shapes and volumes identified among cathedrals of the Spanish Gothic landscape. This sample shall serve as an authentic source of knowledge used to discover relationships between shape, volumetric spaces, and the luminous reality of cathedrals. The legacy of light is composed by the cathedrals themselves, and as the only living proof of constructed reality, they are the basis under study for obtaining any specific knowledge about the way medieval masters projected, understood, and built architectural spaces. These sample cathedrals have been analyzed in depth to understand their light and have been connected to each other in order to obtain the determining factors that modulate the different qualities of their composition.

The pre-selected cathedrals have been chosen based on previous parameters that encompass the different types of Gothic spaces. These are divided into volumetric parameters and transparency parameters.

The first previous volumetric parameter taken into account is the degree of shift factor present at a cathedral's staggered section (Viollet-le-Duc, 1868). The Gothic cathedral is the first architectural space that uses the staggered section in a widespread manner in order to allow light to enter inside. It also favors a structural function, which is to counteract horizontal thrusts of the central body with the side bodies acting as buttresses (Figure 3).

Figure 3. Sketch of a staggered section showing the incidence of light inside a cathedral, according to Robert Mark.
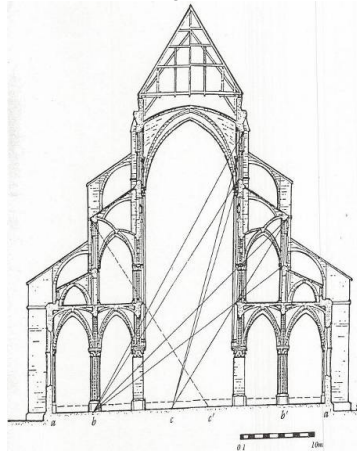
Figure 4. Cross section of Toledo's Cathedral, from the entrance of the church. Source: Self-elaboration.
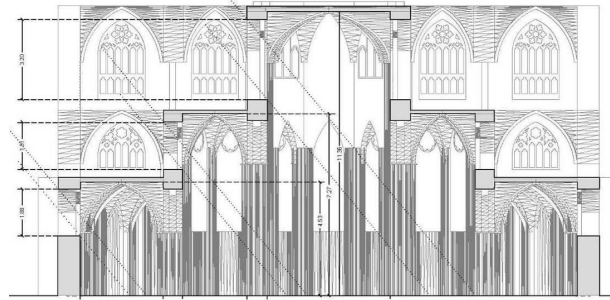
The second previous volume parameter, which is key for understanding the behavior of lighting in Gothic space in general, is to establish the number of naves forming each cathedral.

Finally, among the previous volumetric parameters to be considered, the influence the opening height has on defining the resulting light at a viewer's level needs to be established. Following the emerging section schemes of Robert Mark (Figure 3) and his studies on lighting in cathedrals, we know that light is associated with conditions of hue, saturation, and brightness. Although hue and saturation refer to colors, brightness on the other hand refers to illumination surfaces and can be measured by using a photocell or luxmeter in lux, following the scheme of the "path of light" applied to a specific surface. The light power measured in lux is determined by the equation:

$$B = I / S^2 \tag{1}$$

Where B is the illumination surface (in lux by cm), I refers to the intensity of the light emitter, and S refers to the distance from the source of light ("length of the path of light") to the illumination surface (cm).

At the same time, the previous parameters of transparency of walls, which are basic parameters during the final development of the Gothic lighting of interior spaces, are to be considered. These parameters have to do with the existing relationship between the wall surfaces and the openings at those walls. As already mentioned, the new structural system of "arch ribs" directs the load linearly, freeing the walls to include stained glass windows and allowing light to pass into the interior. Nevertheless, not all cathedrals take advantage of the entire wall surface free of loads to make openings in their interior. If the configuration of the staggered walls of the Cathedral of León is compared to that of the Basilica of Santa María del Mar (Figure 5), it can be observed that the first one uses up almost all the possible space for openings, while the second one selects the amount of wall to be opened.

Figure 5. Longitudinal bay of the Cathedral of León and Santa María del Mar. Source: Self-elaboration.

A)   B)   C)
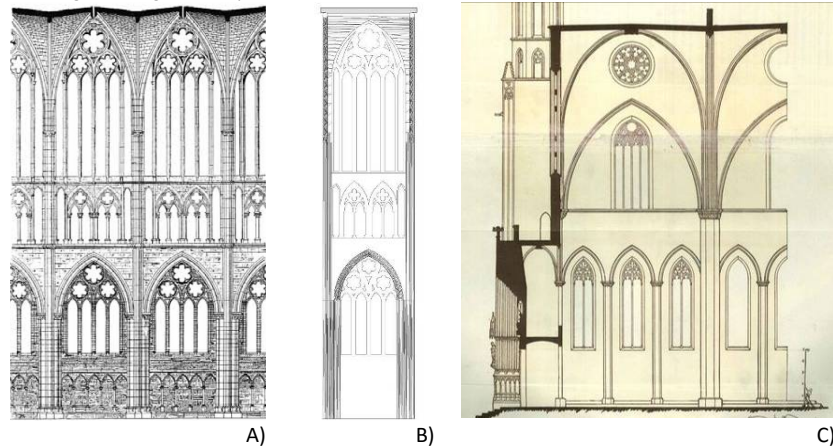
Levels of transparency were not performed in an arbitrary manner or because of design issues exclusively; they responded to complex problems, primarily of structural concepts. While the Gothic system theoretically frees structural load-bearing walls, it fails to do so when the cathedrals are built in areas of seismic risk. As Cassinello (2005) demonstrated, there are cathedrals in the Mediterranean region of Spain that require walls to have a structural bearing capacity resilient to possible horizontal movements of the whole building.

Taking into account all the previous factors, six sample cathedrals have been selected covering the different types of Gothic spaces, depending on the degree of shift factor at their staggered section, plan distribution, the number and shape of naves, and the level of transparency of walls according to their seismic degree (Medina & Cassinello, 2011) and the location of buttresses (indoor or outdoor) (Cassinello, 2003).

Out of the selected cathedrals, three have an anti-seismic structure: the Gerona Cathedral, the Basilica of Santa María del Mar and the Cathedral of Seville, while the other three have a French-type structure: the Cathedral of Toledo, León Cathedral and the Sainte-Chapelle of Paris (Figure 6).

Figure 6. Recreation of the original Gothic plans of the selected sample cathedrals: Gerona, Santa María del Mar, Seville, Toledo, León, and Sainte-Chapelle. Source: Self-elaboration.
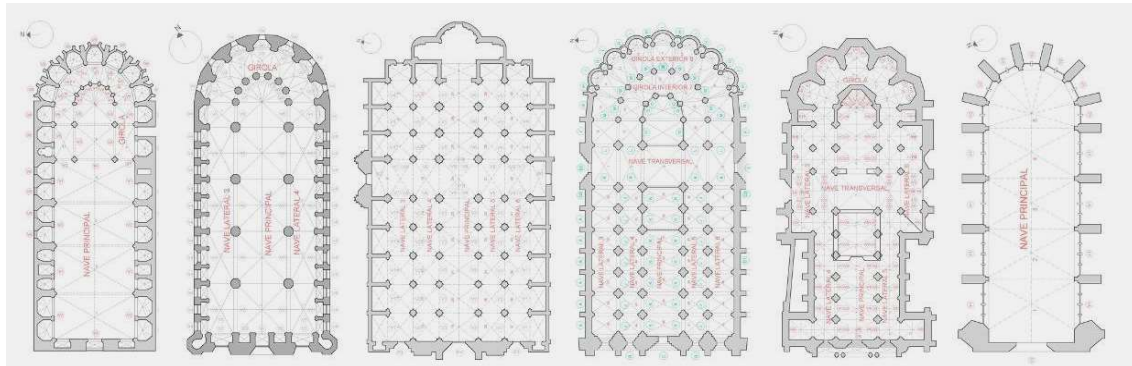
Analysis of the selected sample. New factors detected

The samples studied have been sorted through a methodological analysis to get to know the state of the original Gothic lighting, i.e., when it was conceived. To this end, the initial conditions of the project have been surveyed in an elevation (two-dimension surveys), as well as their plan distribution, sections, composition of openings, traceries, and disposition of windows along the walls. Later, a computer model in three dimensions of each sample has been developed (Figure 7).
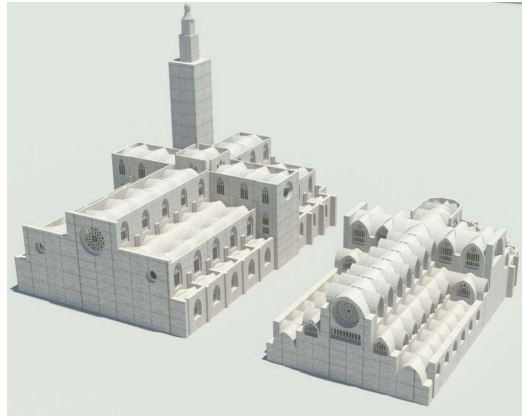
The study method finally employed for the luminance data was the use of 3D Studio Max Design 2011 software with a computer application to calculate interior space lighting by studying the radiance of materials. This method allows taking indirect lighting data (Figure 8), the result of visible radiations from direct sunlight and scattered atmospheric light from the internal reflected component (IRC) and the sky component (CC) of a representative overcast sky, taken from the exact geodesic position of each building. Likewise, direct illumination data (Figure 8) is obtained from the projected light beam, which would, in turn, trespass the stained glass windows and impact the cathedral floor at all times.
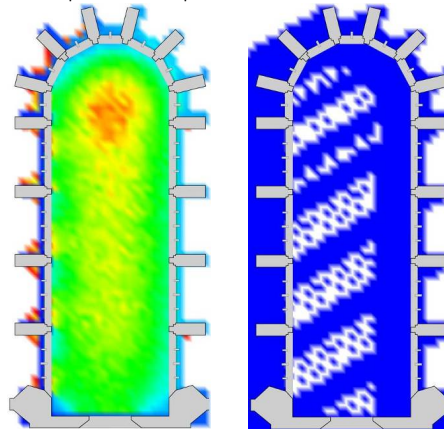
Figure 8. Indirect and direct lighting data projected on the lighting schemes of the floor of the Sainte-Chapelle in Paris. September 21st at 12:00. Source: Self-elaboration.

The texture material used in the reconstruction of the 3D model of the cathedral was a neutral material of constant reflection, such as "gray speckled granite stone," with a level of diffuse reflection. For glass, a filtering factor obtained as a mean of light filtering from the different windows in the sample was selected. This glass is assumed to have no color, so as to perfectly identify the effect of direct lighting on the ground, providing white-on-blue images that outline the radiation map projected on the observers.

The study of each sample was performed to include light variability due to seasonal changes. It was made to cover the "extreme" days of each season of the year: summer and winter solstices and the spring and autumn equinoxes (March 21st, June 21st, September 21st, and December 21st, respectively) and for four different times each day: 10:00, 12:00, 14:00, and 16:00.

Once the analytical method was applied on the selected sample, the main indicators comprised in Gothic lighting were obtained. These indicators are, on the one hand, intrinsic and invariable factors, specific to each cathedral, and on the other hand, a circumstantial factor which does not depend on the cathedral itself, but on its current situation nowadays; that is, on the use the cathedral has today. This is the distortion factor that has been excluded from this study precisely because of its circumstantial and variable character.

The intrinsic indicators include, firstly, those defined by the shape and specific volume of each cathedral; these will be referred to as form factors. Secondly, there are indicators relating the amount of openings on walls to the interior-space surfaces and volumes that are being served, which will be called transparency factors. Thirdly, there is the indicator that defines the color of the stained glass windows, which we have called color factor. All factors can be determined according to the key metric dimensions of each cathedral (Figure 9 and Table 1) and the composition of their stained glass windows.

With these dimensions, we are now able to define the factors. First, in terms of shape factors, a *slenderness factor Fe* can be found, which relates the width of each nave to its height. The second factor is the *clerestory starting height factor Fhc*, which defines the height at which windows of the nave start—a relevant factor for the definition of indirect lighting and essential for the definition of direct lighting.

On the other hand, the *factor of transparency of walls Ftm* is the first of the transparency factors to be found. This measures the amount of an opening trespassing the wall, or in other words, the relationship between opening and solid façade wall. This is followed by the *factor of light projection Fpl*, which relates the amount of existing openings on the wall to the plan surface it serves. The last factor is the *total transparency factor FtT*, which describes the amount of openings in the bay in relation to the total volume of served space.

The two shape factors and the three transparency ones (Table 2) affect the entrance of direct light into the spaces of the cathedral, and they also alter the number of reflections necessary to let indirect light into the interior spaces of each aisle.

Finally, the above-mentioned *color factor* relates the amount of each color present in the window to the entire stained glass. This factor modulates each stained glass window's light filtering capacity, which increases when colors are darker and diminishes when they are lighter. In addition, it allows describing what the light is like when going through the interior spaces depending on its color temperature.

Figure 9. Section scheme of one of the studied samples. Source: Self-elaboration.
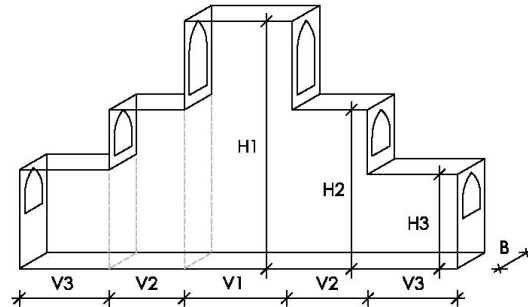
Table 1. Metric dimensions of the studied samples as they are shown in Figure 9. Source: Self-elaboration.

Cathedral	# Naves	Dimensions (m)						
		B	H1	H2	H3	V1	V2	V3
Gerona	1	11.60	34.00	-	-	22.04	-	-
S.M. Mar	3	13.50	32.00	32.00	-	28.07	28.07	-
Seville	5	10.97	35.77	25.14	25.14	15.70	11.26	10.31
Toledo	5	7.62	29.40	18.73	11.68	12.84	9.86	9.64
León	3	6.49	30.00	13.29	-	12.07	7.03	-
Sainte-Ch.	3	6.77	20.40	-	-	12.72	-	-

Table 2. Summary of shape and transparency factors from the studied samples. Source: Self-elaboration.

Cathedral	Slenderness factor Fe (%)			Transparency factors (%)			Clerestory starting height factor (%)
	Fe1	Fe2	Fe3	Ftm	Fpl	FtT	Fhc
Gerona	1.54			16.44	0.12	1.12	18.95
S.M. Mar	1.14			11.88	0.09	0.66	17.22
Seville	2.28	2.23	2.44	10.47	0.04	0.37	25.66
Toledo	2.29	1.90	1.21	21.26	0.08	0.97	20.19
León	2.49	1.89		33.59	0.21	3.34	13.56
Sainte-Ch.	1.60			89.30	0.42	6.60	3.86

Once the factors determining Gothic lighting have been defined, the light qualities of these spaces can be stated. For this purpose, both indirect and direct illuminations from the different samples have been compared, either for cathedrals as a whole or specifically for singular points in them. The illumination values used for comparison are obtained from the computer program with a glass of similar filtering capacity for all openings of the selected samples. Glass filtration capacity is obtained by averaging the various *factors of scaling* of the studied cathedrals. These factors vary according to the windows present (color intensity and thickness of glass) and according to the time in which the scaling is done (luminous intensity from the outside). However, the average of the different samples, taking as a reference all the measurements performed on site, gives a filtering value–though not accurate for each cathedral–that is very close to the original Gothic glass transparency factor. Taking this value as equal for all cathedrals, comparison of the lighting between samples can be made, and thus, the influence lighting has in the shape and volume of spaces can be determined.

Having studied the samples in depth and considering their particularities as Gothic buildings, five fundamental qualities have been detected which can define their lighting. Four of them are inherent to their own formal configuration, and are thus constant and perfectly defined, while the last one is a circumstantial quality as will be seen in its definition. These qualities include Gothic lighting hues. The sum of these parts facilitates an understanding of an otherwise intangible reality. The detected qualities are: expressiveness, intensity, itinerary, and color.

Expressiveness

Expressiveness is defined as a Gothic space's ability to receive impacts of direct colored light on the observer. The cathedral will be more or less expressive depending on the amount of light that stained glass projects on the ground. This depends on a combination of three factors: total transparency factor *FtT* or surface of served volume per opening, light projection factor *Fpl* or opening surface by served ground surface, and the factor of the starting height of the clerestory windows *Fhc*.

Thus, the greater the cathedral *FtT* and *Fpl* are, and the smaller the *Fhc* is, the more *expressive* the cathedral will be. Thus, León has the biggest factor of full transparency (*FtT* = 3.34) of the Spanish cathedrals as well as the largest *Fpl*. This, coupled to a very low starting window height (*Fhc* = 13.56), makes this cathedral the most expressive among the Spanish cathedrals studied.

Seville, on the contrary, has the smallest total transparency factor (*FtT* = 0.37), as well as the smallest light projection factor (*Fpl* = 0.04). Finally, the starting height of windows is very high (*Fhc* = 25.66). The combination of these three factors makes this cathedral the least expressive cathedral studied. In between these two extremes the other cases studied can be found (Table 3).

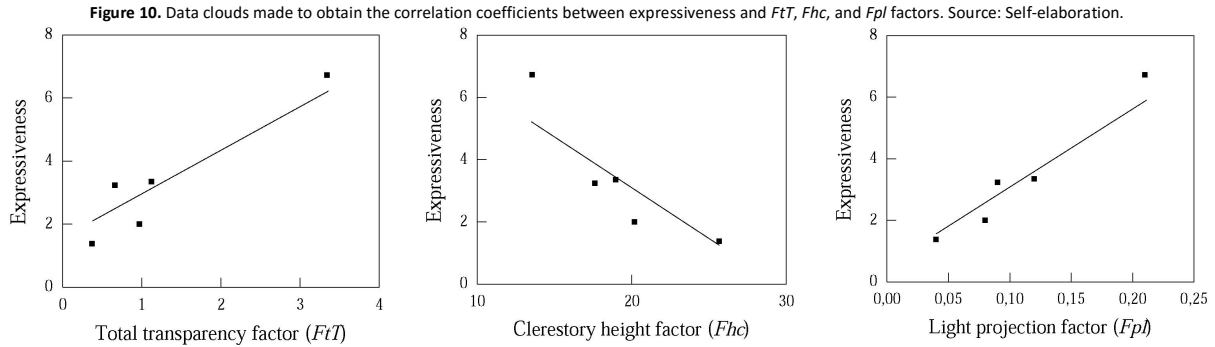**Table 3.** Degree of expressiveness of the studied cathedrals. Source: Self-elaboration.

Cathedral	Expressiveness (m² impacts/m² floor)
Sainte-Chapelle	78.31
León	6.72
Gerona	3.35
Santa María del Mar	3.24
Toledo	2.00
Seville	1.38

To measure the weight of each of the factors affecting the quality of expressiveness, correlation coefficients for each factor with the final value of expressiveness have been obtained. The values obtained for the Sainte-Chapelle in Paris, as can be seen in the Table 3, are disproportionately high, so their inclusion in this study of correlations could distort the model. This is why it has been excluded from the study.

In this way, first and foremost, a data cloud has been designed where the obtained expressiveness values are represented together with the total transparency factors *FtT* of each sample. After finding the corresponding regression line, it can be concluded that there is a correlation coefficient of 0.76 between expressiveness and *FtT*.

Secondly, a data cloud has been designed where the expressiveness values obtained are represented together with the factors of starting height of the clerestory *Fhc* of each sample. After finding the corresponding regression line, it is observed that there is a correlation coefficient of -0.73 between the expressiveness and *Fhc*.

Finally, a data cloud has been designed showing expressiveness values and the light projection factors *Fpl* of each sample. After finding the corresponding regression line, a correlation coefficient of 0.79 between the expressiveness and *Fpl* is found (Figure 10).

Figure 10. Data clouds made to obtain the correlation coefficients between expressiveness and *FtT*, *Fhc*, and *Fpl* factors. Source: Self-elaboration.

Having analyzed these factors, we can clearly see how decisive they are in the final composition of the expressiveness of the cathedral. There is a direct correlation between the two concepts. Once the regression lines for each factor have been defined, the factor having a greater weight in the expressiveness outcome has been determined, regarding the correlation degree between the two. With these data, the final equation with weight distribution to obtain the *expected expressiveness* (*E*) of a cathedral can be obtained:

$$E = 0.33 \cdot E(FtT) + 0.32 \cdot E(Fhc) + 0.35 \cdot E(Fpl) \tag{2}$$

Where:
$$E(FtT) = 1.32 \cdot FtT + 1.63 \tag{3}$$
$$E(Fhc) = -0.34 \cdot Fhc + 9.88 \tag{4}$$
$$E(Fpl) = 25.43 \cdot Fpl + 0.59 \tag{5}$$

According to these measurements, a first classification can be established regarding expressiveness through the determination of numerical ranges. According to these ranges, the level of expressiveness *E* of each cathedral is stated, measured as the proportion of square meters of light projected on the floor (*impacts*) considering the total ground surface (m^2 impacts/m^2 floor). Three levels can be defined: *very expressive* (*E* > 4), *expressive* (2 < *E* < 4), and *silent* (*E* < 2).

Intensity

Intensity is defined as the ability of a Gothic space to allow light into the interior in an indirect way, i.e., environmental light. It depends on a combination of three factors: the factor of full transparency *FtT* or surface of the opening by served volume, the wall transparency factor *Ftm* or surface span in relation to the wall, and the factor of starting height of the clerestory windows *Fhc*.

Thus, the greater its *FtT* is, the greater the light intensity of a cathedral will be. In case of similar total transparency factors, the greater the *Ftm*, the smaller the *Fhc*. Also, a smaller shift factor also has an impact, although at a lesser extent. As a result, the Sainte-Chapelle of Paris and the León Cathedral have the greatest *FtT*, and this implies they have the greatest light intensity in general.

Toledo and Gerona have similar *FtT* (0.97 and 1.12 respectively), being the *Ftm* of Gerona somewhat smaller (16.44 to 21.26). This is compensated with a lower starting height of the clerestory windows (*Fhc* = 18.95 as opposed to Toledo's 20.19), so that the lighting intensity between them is very similar.

Finally, it can be observed that the *FtT* of Seville's conditions is low-level general lighting intensity (0.37), as it is the cathedral with the least lighting out of the studied ones. The other cases can be found in between (Table 4).

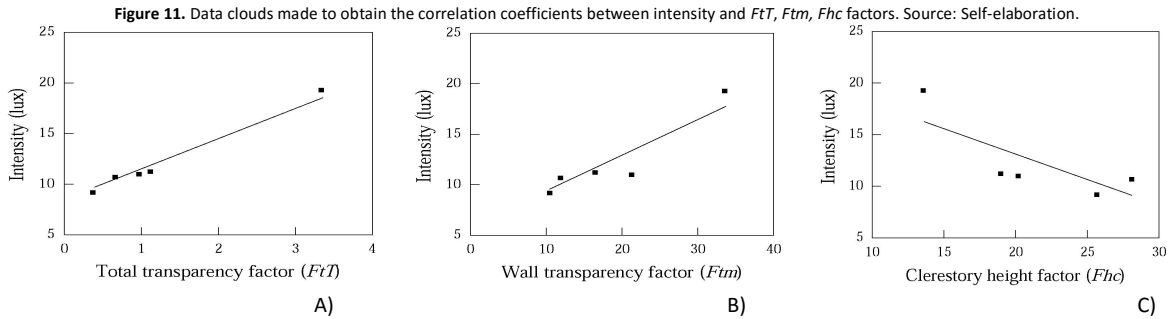Table 4. Degrees of total mean lighting of the studied cathedrals. Source: Self-elaboration.

Cathedral	Total mean lighting (lux)
Sainte-Chapelle	69.44
León	19.29
Gerona	11.21
Toledo	10.98
Santa María del Mar	10.67
Seville	9.18

Correlation coefficients between factors and intensity have been sought in order to calculate the weight each of the factors affecting the quality of lighting intensity has.

As in the case of expressiveness, the values obtained for the Sainte-Chapelle in Paris, as can be seen in Table 4, are disproportionately high, so they were excluded from the study of correlations.

In this way, first of all, a data cloud has been designed showing the intensity values and factors of total transparency *FtT* obtained for each sample. After finding the corresponding regression line, it can be concluded that there is a correlation coefficient of 0.80 between intensity and *FtT*.

Secondly, a data cloud representing intensity values along with the factors of transparency of wall *Ftm* for each sample has been designed. After finding the corresponding regression line, a correlation coefficient of 0.75 between intensity and *Ftm* can be observed**.** Finally, a data cloud is obtained in which intensity values along with the factors of starting height of clerestory *Fhc* from each sample are represented. After finding the corresponding regression line, a correlation coefficient of -0.65 between intensity and *Fhc* is found (Figure 11).

Figure 11. Data clouds made to obtain the correlation coefficients between intensity and *FtT*, *Ftm, Fhc* factors. Source: Self-elaboration.

Once the factors are studied, they appear to be decisive for the final composition of the lighting intensity of the cathedral. There is a direct correlation between the two concepts. Once the regression lines of each factor have been defined, we can determine which factor has a greater weight in the final intensity result regarding the degree of correlation between the two. With these data, a definite equation with distribution of weights to obtain the *expected intensity* (*I*) of a cathedral can be stated:

$$I = 0.34 \cdot I(Ftm) + 0.36 \cdot I(FtT) + 0.30 \cdot I(Fhc) \tag{6}$$
Where:
$$I(Ftm) = 0.32 \cdot Ftm + 6, 23 \tag{7}$$
$$I(FtT) = 2.70 \cdot FtT + 8.78 \tag{8}$$
$$I(Fhc) = - 0.45 \cdot Fhc + 21.92 \tag{9}$$

Based on the measurements carried out, a second classification according to the intensity can be established, defined trough numerical ranges. According to these ranges, the levels of intensity, measured in average total lux over the total registered points and averaged among different day hours and different days of the year, are: *high* ($I > 15$), *average* ($10 < I < 15$), and *low* ($I < 10$).

**Itinerary**

The third quality determines the direction of growth or decrease of lighting along the nave. Once all light itineraries have been studied in detail along the naves of each cathedral, it can be observed that lighting varies depending on a particular "tour of stained glass," which depends on the shape of the Cathedral, and it includes the following singular

points: entrance, transept, and presbytery. Thus, comparing all the samples this way, two different light itineraries are found: increasing itinerary and decreasing itinerary. This depends on whether the lighting grows from the entrance towards the transept (increasing itinerary) or in the opposite direction (decreasing itinerary).

Thus, the cathedrals of Seville, Toledo, and León are "decreasing" types, whose west rose windows are 3 bays away from the presbytery and their central nave advances after its intersection with the transept. These cathedrals have at the same time a long transept (5 and even 7 bays), and therefore, the influence of east and west rose windows is smaller. However, the other three samples are "increasing" types: Gerona, Santa María, and the Sainte-Chapelle. This is because the transept and presbytery practically coincide. In addition, there are no transversal arms that separate the east and west sides from the center of the cathedral (Figure 12).

Figure 12. Comparative charts between samples. Development of the lighting along the central nave, from the entrance to the transept. Source: Self-elaboration.
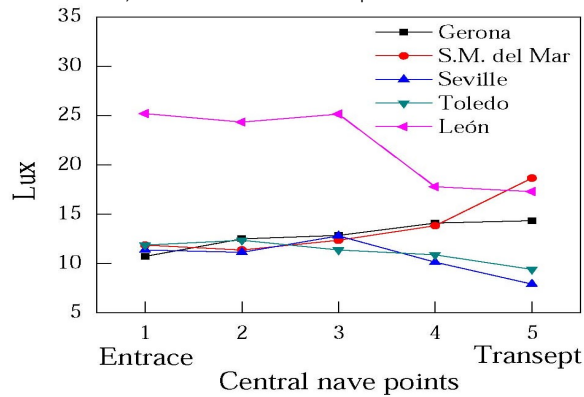
Color

This fourth quality of lighting, which is not related to the shape and volume of the cathedrals, is an important feature when defining Gothic lighting. However, it is a circumstantial factor, which cannot be analyzed in a methodical way. Color is the quality that determines the symbolism of the selected cathedral and which clarifies the coloration of its inner light.

The variety of colors included in the different windows of classic Gothic is wide, which makes the accurate determination of the colors of each of the cathedrals incomplete. In order to establish a rigorous method, whose analysis could have produced valuable conclusions, all or much of the original stained glass windows of different samples would have needed to be observed. Then, a study of their color palette could be carried out. Such an undertaking is impossible nowadays, since just a small percentage of the original stained glass windows still exist. And when there actually are original stained glass windows, which in many cases respond to the Gothic concept of distribution of glass and lead, they do not respond to the original color proportions, since many of these have been restored and altered. Therefore, colors can be grouped according to two main groups: *Gothic* and *non-Gothic colors*.

Approach to the lighting of cathedrals. Abbreviated approximate procedure

Out of the four qualities observed, three of them are directly related to the volume and shape of cathedrals. They are expressiveness, intensity, and itinerary, while color depends on the particular composition of the stained glass windows, which as already mentioned, is not always genuine. Therefore, this article presents an approach to the knowledge of Gothic light through the analysis of three major qualities, following an approximate abbreviated procedure.

Considering each quality and the factor or factors influencing the definition of light, as described in the previous chapter, it can be predicted that if new Gothic space factors are found and they are applied as a whole, we will be able to approach their lighting qualities. To do this, we only need to have a simple section of the Cathedral to find the factors that determine the qualities. Given those, at least three qualities can be reached: expressiveness, intensity, and itinerary, always in approximate terms as an "expected attribute." All this can be logically corroborated with the application of the complete method of analysis through the recreation of a 3D model, which enables specifically

deepening our knowledge. To attain knowledge of the quality of color, however, the detailed study of stained glass is compulsory. The *expected expressiveness* and *expected intensity* can be obtained with equations (2) and (6).

For the *expected itinerary* of light in the central nave to be considered, the factors already described in the *itinerary* quality should be employed. These are closeness of the transept to the presbytery and disposition of the naves. This way, and to demonstrate the validity of the procedure, we have carried out an exercise to obtain *expected expression* and *expected intensity* for the studied samples, as if they had only been studied through the abbreviated procedure, introducing factors obtained from the sections of each sample within the formulas already described. The results are shown in Table 5 below.

Table 5. Values of expressiveness and intensity obtained by the brief procedure compared to the real ones obtained by the complete method. Source: Self-elaboration.

Cathedral	Expected expression (abbreviated procedure)	Real expression (full method)	Standard deviation (%)	Expected intensity (abbreviated procedure)	Real intensity (full method)	Standard deviation (%)
Gerona	3.40	3.35	1.37	12.15	11.21	7.76
S.M. Mar	3.08	3.24	-5.35	9.99	10.67	-6.82
Sevilla	1.62	1.38	15.07	9.87	9.18	6.96
Toledo	2.40	2.00	16.67	12.36	10.98	11.19
León	5.75	6.72	-16.77	16.96	19.29	-13.75
Standard deviation of abbreviated procedure			11.05			9.30

These equations are therefore valid as an approach to lighting in a cathedral in regard to its expressiveness and intensity. They allow us to obtain very accurate values without having to recreate 3D models or follow the hazardous method of analysis presented in this document. These results let us face any restoration or intervention in a cathedral with prior knowledge of its Gothic lighting, and thus, respecting it.

Conclusions

The first conclusion to be highlighted from our proposed study can be summarized under the idea that Gothic architecture not only seeks to introduce light into spaces but also to control it and manipulate it. Gothic architecture, as an evolution of a complete architectural system, greatly succeeds in introducing light inside spaces that are defined by their architecture through large openings in their outer walls. However, medieval architects sought not only to insert light into interior spaces, but also tried to capture and transform it, so that once transformed and hued, it would be projected to the observer or the "scene" in the form of color. Therefore, Gothic churches are not a hymn to light, but to the symbolism of color shaped through stained glass windows. The empirical demonstration of this fact has been determined in this article with the recreation of the initial project conditions and data of indirect lighting that show how Gothic architecture is an eminently dark, hued, manipulated, and colored architecture.

The second conclusion revolves around the idea that there are few volumetric determinants in the formal configuration of the cathedrals that permanently affect the lighting result of the interior space. These factors are determined according to various cathedral morphology aspects but mainly fall into three groups: first, the factors of transparency, such as wall transparency factor *Ftm*, the factor of transparency by volume, and the projected light factor *Fpl*. Secondly, volumetric factors, such as the factor in slenderness *Fe*, and the starting height of the clerestory factor *Fhc*. Finally, there is a unique factor to every cathedral, the factor of stained glass color *Fc*, which determines the filtration capacity of direct light inwards through the stained glass windows, and of course, its Gothic color symbolism.

All of these affect the entrance of direct light. They decisively shape light behaviors in the spaces inside, and when properly combined, they facilitate the understanding of the light qualities of the cathedrals.

The third conclusion determines that light manipulation, as previously discussed, materializes in a changing and identifiable manner in low light levels throughout the different spaces that make up the cathedrals and between the different cathedrals themselves. This enables quantifying and qualifying these cathedral spaces according to their lighting, and hence classifying them.

Quantification can be performed through a detailed study of cathedrals by the recreation of a 3D model of the original architectural design, but this article provides an approximate abbreviated procedure to the reality of Gothic light through formulas that relate Gothic light qualities with the geometric factors that define their volume. This abbreviated procedure is applicable to 3 of the 4 Gothic qualities detected. The first one is expressiveness *E*, determined according to the itinerary of stained glass and the amount of light impacts that these are capable of

projecting on the observer. We can then sort cathedrals according to whether they are *very expressive* (*E* > 4), *expressive* (2 < *E* < 4), or *silent* (*E* < 2).

The second quality to which the procedure applies is intensity *I*, or the amount of indirect lighting in the different spaces of the cathedral. As in the previous case, cathedrals can be sorted according to three degrees of luminous intensity: *high* (*I* > 15), *average* (10 < *I* < 15), and *low* (*I* < 10).

Finally, cathedrals can be classified according to the "increasing or decreasing" *lighting itinerary* of their central nave, according to the shape of its architecture (closeness of architectural elements), and whether lighting manifests itself more intensely at the entrance of the cathedral or at the transept. This study analyzes 6 samples in depth, providing qualitative values of their exact illumination through the complete method, so analyzing the sections of other Spanish Gothic cathedrals under the abbreviated procedure, their expected qualities on the basis of the volumetric factors can be obtained. This abbreviated method applied to any Gothic space provides quantified qualitative values of light which were originally present at the building, with an error average of 10%. This conditioning factor of any project, fundamental for understanding the architectural space, must be known when it comes to intervening any of the cathedrals and Gothic spaces of our architectural landscape, in order to preserve them without disfiguring their symbolic essence: light.

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