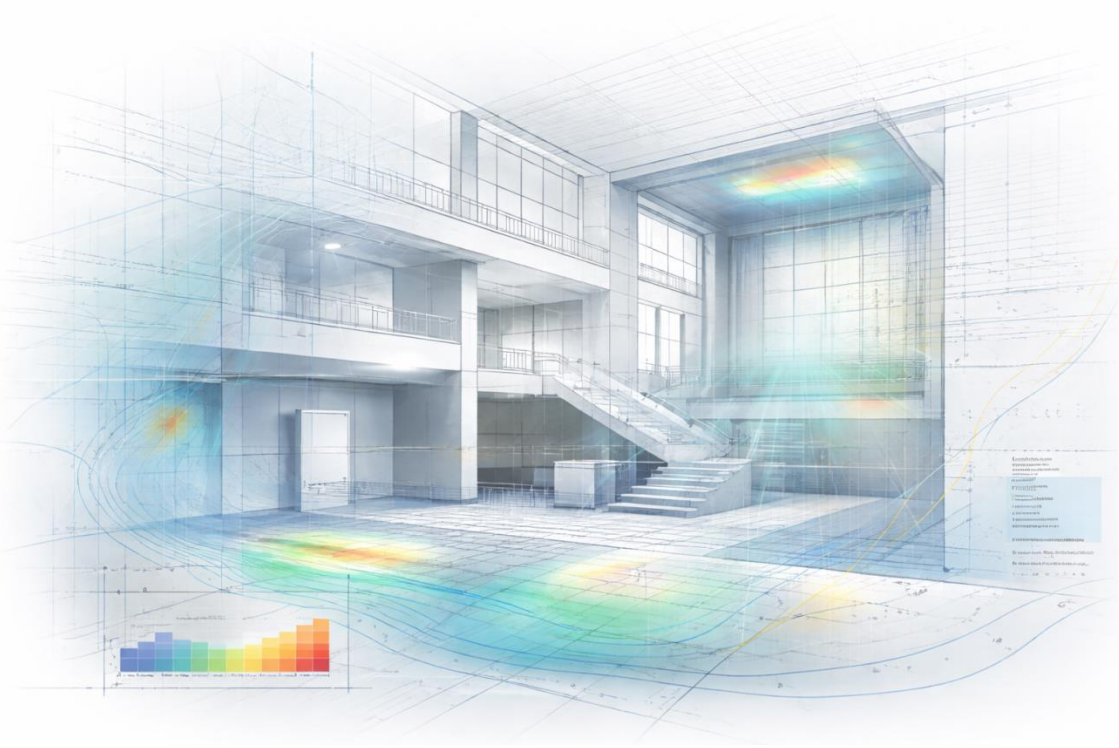

Frontiers of Lighting Design with CAD and BIM

Maurizio Rossi

Research Culture And Science Books series - Vol. 018

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Preface

This text, through the presentation of design problems and applications, describes/demonstrates methods and tools that enable the inclusion of quantitative and qualitative evaluations of lighting in the project development process, prior to the installation. The tools that have been consolidated in the new millennium are primarily CAD systems made available by information technology, specifically those aimed at accurate lighting calculation. The purpose is not to create beautiful images, like those in cartoons, but to provide automatic calculation tools for virtual verification of the lighting design. After CAD, in more recent times, the way buildings are designed and maintained is changing even more radically, thanks to the Building Information Modeling (BIM) methodology. This further methodological revolution is also starting to affect Lighting Design, although with still limited software tools. The book is aimed at designers and researchers, to all those who are interested in understanding how the way of designing lighting has evolved and knowing how to simulate the behavior of artificial and natural light, in interiors and exteriors, using software tools that can be on anyone's desk, with low costs but with enormous potential.

The text introduces the aspects of the inclusion of virtual prototyping tools in the process of light design, with insights regarding the latest regulations and recommendations of the lighting industry, and then analyzes in a comprehensive but accessible way the technological limits, the perceptual problems of the tools available for the virtual analysis of light, and methods to reasonably manage these issues in the relationship of the designer with the use of computer tools. Case studies of increasing complexity are presented, ranging from artificial and natural lighting for interiors to artificial lighting for exteriors, and including solutions for addressing problems related to lighting cultural sites and monuments. The text then examines the ways of using computational tools for virtual photometric

measurements and, finally, addresses the actual usability of virtual photographs for qualitative assessment of illumination.

In the first chapter, digital lighting design is introduced as a multidisciplinary field that integrates physical measurement, perceptual evaluation, and design intent. The chapter outlines the fundamental role of light in shaping visual performance, psychological response, and spatial experience, emphasizing the need for an integrated management of illuminance, material properties, color, and visual tasks under both natural and artificial conditions. Given the impossibility of physical prototyping in lighting design, the chapter frames digital simulation as an essential methodological tool. A clear distinction is established between rendering-oriented tools and Lighting CAD systems developed for physically based calculation and quantitative verification, highlighting both the potential and the limitations of current digital approaches.

In the second chapter, computer-based tools for lighting design and verification are presented as components of a virtual design workshop supporting both quantitative evaluation and qualitative assessment of light in built environments. The chapter outlines the technical skills required to operate within this digital framework and examines software systems for artificial lighting calculation, focusing on space modelling, photometric data management, and the assessment of illuminance, luminance, and visual comfort using established metrics. Particular emphasis is placed on the limitations of rendering as a perceptual aid and on the necessity of technically grounded representations. Through applied case studies and references to optical simulation software, the chapter highlights the role of digital tools in integrating environmental lighting design with product-level analysis.

In the third chapter, the integration of lighting design within Building Information Modeling (BIM) workflows is examined, with a focus on tools and methodologies for verifying lighting and evaluating performance. While BIM is widely used for coordinating architectural and engineering disciplines, the chapter highlights how lighting design remains only partially integrated into BIM authoring environments, often depending on external software or proprietary add-ins. A clear distinction is drawn between Closed BIM approaches, based on integrated plugins, and Open BIM workflows, which rely on standardized interoperability formats such as IFC. Through the analysis of representative software tools, the chapter discusses issues of interoperability, workflow continuity, analytical scope, and data resilience, emphasizing the need for methodological awareness and informed tool selection in BIM-based lighting design.

In the fourth chapter, photorealistic rendering is examined as a complementary instrument in lighting design, primarily supporting perceptual evaluation rather than normative verification. The chapter discusses the inherent limits of photographic representation and human visual perception, clarifying why perfectly photorealistic images remain unattainable and what this implies for digital lighting simulation. It introduces key global illumination models, outlining their theoretical foundations and computational implications within lighting design workflows. Particular attention is given to the management of geometry, materials, light sources, and calculation parameters, with an emphasis on the distinction between quantitative lighting analysis and qualitative visual synthesis. Through applied examples, the chapter illustrates how rendering functions as a virtual prototyping tool that connects measurable data with experiential assessment in both professional and educational contexts.

Maurizio Rossi

Short biography of the author

Full Professor of Design (ICAR/13) at the Department of Design, Politecnico di Milano, where he has been in service since 2019. Previously, he was Associate Professor (2010–2019) and Assistant Professor (2002–2010) at the same institution. He has been Scientific Manager of the Laboratorio Luce at Politecnico di Milano since 2002 and a member of the Faculty of the PhD in Design.

Since 1998, he has directed more than 30 research projects on light and colour, funded through public tenders and research contracts. In 2021, he received the ADI Design Index for the research Circadian Lighting Design in the LED Era.

He is President of the AIC – International Colour Association (2024–2025), Vice-President (2022–2023), and a member of its Executive Committee since 2018. He served as President of the GdC – Associazione Italiana Colore from 2012 to 2018 and was a member of the Board of Directors of SID – Società Italiana Design from 2021 to 2024.

Since 2014, he has been Editor-in-Chief of the Color Culture & Science Journal. He has published more than 200 scientific works, including books, edited volumes, journal articles, and conference proceedings. He has chaired 10 international conferences.

At Politecnico di Milano, he teaches Lighting Design, Design Methods and Interaction Design. He has been Director of the Master in Lighting Design & LED Technology since 2010 and of the Master in Color Design & Technology since 2014. He has also directed 51 lifelong learning courses and 33 higher education courses.

He holds a PhD in Computer Science (2004) and a degree in Science (1989), both from the Università degli Studi di Milano.

1. Introduction to digital lighting design

Maurizio Rossi, Politecnico di Milano

Abstract

Lighting design plays a fundamental role in shaping human environments, influencing visual perception, psychological responses, and functional performance. Beyond the formal design of luminaires, effective lighting design requires the integrated management of illuminance distribution, material reflectance, chromatic properties, and visual tasks, within both natural and artificial lighting conditions. Over the last two decades, the growing complexity of these parameters has led to the widespread adoption of digital tools for lighting simulation and analysis. Unlike rapid prototyping in industrial design, lighting design cannot rely on physical prototypes, making virtual prototyping an essential methodological approach. This chapter critically examines the role of digital lighting simulation, distinguishing between communication-oriented rendering tools and Lighting CAD systems developed for physically based calculation and quantitative verification. The limits of current software solutions are discussed in relation to computational accuracy, perceptual modeling, and the representation of human visual response. Despite these limitations, digital lighting tools provide indispensable support for both quantitative evaluation and qualitative assessment, enabling designers to integrate scientific rigor with experiential judgment. The chapter establishes a theoretical framework for understanding digital lighting design as a multidisciplinary process that combines measurement, perception, and design intent.

Keywords:

Lighting design, Digital lighting simulation, Virtual prototyping, Photorealistic rendering, Visual perception

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1.1 Lighting Design as a Multidisciplinary Process

The journey of designing human spaces is a complex process, influenced by multiple parameters. One of them is definitely light. Different levels and distributions of lighting contribute to modify the perception of environments and the psychological predisposition to their use (Rossi, 2019). The design of a luminaire, understood as an interior or urban furnishing accessory, represents only one part of the "light" issue in an interior or exterior space. A decisive aspect is in fact the method of distribution of illuminance levels, which the experience of the designer knows how to size appropriately, according to the various visual tasks foreseeable based on the forms, the reflectance of the materials and the arrangement of the structures (Yu et al., 2023). These aspects are often treated in a generic way: as the relationship between direct or indirect lighting, natural light, chromaticity levels and the close relationship between light and matter/color that influence and shape each other to achieve the desired effect. The ability to manage all these parameters, for a quantitative and qualitative evaluation of the lighting project, requires multidisciplinary skills that are part of the cultural and technological background of the best designers. Other important aspects concern the ability to analyze and predict the differently bright situations to which an environment may be subject. The assessment of natural lighting and its variation in accordance with geographic location, climate, season, and day-to-day operations, in relation to supporting or replacement artificial lighting (Nabil and Mardaljevic, 2005). And again, the possibility of structuring reconfigurable lighting according to multi-purpose spaces.

Drawing a shape and a color acquires therefore also the meaning of managing the light information that they will produce. The last twenty years have seen the widespread introduction of automatic calculation tools to support the design and production of forms, the development of increasingly advanced Lighting CAD software systems, and more recently the attempted entry of Lighting Design into the BIM methodology (Ramhamdani, 2025). Today it is possible to produce quickly, and at low cost, the virtual prototypes of projects under development in accordance with the methodologies of industrial design (Zhou, Zhang and Gu, 2022). And Prototyping, rapid prototyping with 3D printing, allows us to include in the design process of a product a point of reflection and compare some of the aspects related to the initial specifications of the design process. The purpose is to enable the evaluation of compliance with functional, aesthetic and communicative parameters, expected for the final product. Lighting

Design unfortunately cannot take advantage of rapid prototyping tools and, in most cases, not even traditional prototyping.

1.2 Limits of Physical Prototyping in Lighting Design vs Photorealistic Rendering

It is rather nonsensical to think of making a prototype of a lighting system. A prototype of real dimensions corresponds in fact to the installation of the project, while a scale model, even in the unlikely hypothesis of having lighting sources in scale, would have no sense from the perceptual standpoint (Stevens, 1961). In fact, the perception of luminance levels is a phenomenon that depends on the magnitude of light fluxes, on the chromatic relations but also on the angles and areas of the observed surfaces (Boyce, 2014). For the design of luminaires, rapid prototyping can be assumed to support design evaluation and nowadays also partially, thanks to LED technologies, an evaluation of functional photometric lighting characteristics. Or we should resort to the creation of prototypes equal to the finished product with the consequent increase of costs and time in the design phase. The aspects of architectural design that relate to the use and management of natural light in interiors are equally difficult to assess accurately, because of the large number of parameters that can influence them. Scientific experiments that attempt to use scale models to evaluate natural lighting are quite puzzling. The problem is not so much related to technology, to the reproduction of the various possible conditions of natural lighting, but that related to the actual usefulness of the scale model with respect to the evaluation of the subjective perception of the illuminated environment.

The new frontier beyond rapid prototyping is that of perceptually reliable virtual prototyping, i.e., one achievable with the tools made available by virtual reality and computer graphics with image synthesis (Slater, 2009). However, these new programs have not completely solved the problem, and this is well known by the designers who have tried to use these computer tools to obtain summary images of their lighting project. In most cases, expectations were frustrated because, when the project was completed, the final real project did not correspond in terms of color and light distribution to what had been obtained with the virtual images.

First of all, it should be established that most of the programs available on the IT market, capable of creating synthetic images, do not aim at reproducing exactly an existing or hypothetical reality, but rather giving a beautiful representation of it, which we can define as communication-based. The most obvious example we can give is the fact that most of us are able to

distinguish a synthetic image, of a geometric model of an environment, from a photograph of the same environment in reality. Commercials and special effects in film productions are proof that these software tools still have significant communication capabilities but are inadequate for designing real environments in a digital design workflow. Another problem is that the lighting project must be developed based on the parameters and photometric and colorimetric quantities of lighting engineering and not based on the abstract quantities of computer graphics. This applies both to the definition of luminaires, in terms of the spectrums and shape of the emitted light, and to the materials that must interact with the light, from the reflector of an outdoor projector to the wood of a living room's floor. Ultimately, the reason that most of commercial rendering software is unable to produce photorealistic synthetic images is that it was designed and developed to produce beautiful images quickly, and not to make a physically correct calculation of the interaction between light and matter in an environment (Pharr, Jakob and Humphreys, 2017).

Figure 1.1 Non-photorealistic and photorealistic rendering of a lighting project.

In recent years, however, precisely because of the needs presented by the design of light, some software products have appeared aimed at a physically more correct calculation of light distribution, based on the parameters of

Lighting Design (Dial, 2025; OxyTech, 2025; Revalize, 2025). The value of these programs lies in the fact that the calculation is not only aimed at rendering, but also and primarily at the virtual measurement of quantities such as illuminance and luminance, which enable an objective quantitative evaluation of the project's requirements with respect to the standards and recommendations of the sector. Some of these systems are based on mathematical computational models aimed at describing the light-matter interaction in the real world, considering the laws of electromagnetism and optics. In our field, the purpose of rendering is also to virtually simulate the process of perception of a real image in the human brain in order to present a synthetic equivalent on the computer screen. The purpose of virtual photography is to try to reproduce in the observer the same visual perceptual stimulus corresponding to the reality of the project that is being prototyped virtually. This objective is called photorealism and its purpose, in the field of lighting and color design, is to enable a subjective qualitative evaluation of an environment that does not yet exist in reality, being still in the design phase (Ferwerda, 2003). Together with the evaluation of the quantitative aspects of Lighting Design, the result produced by these programs is therefore to constitute a tool for virtual prototyping.

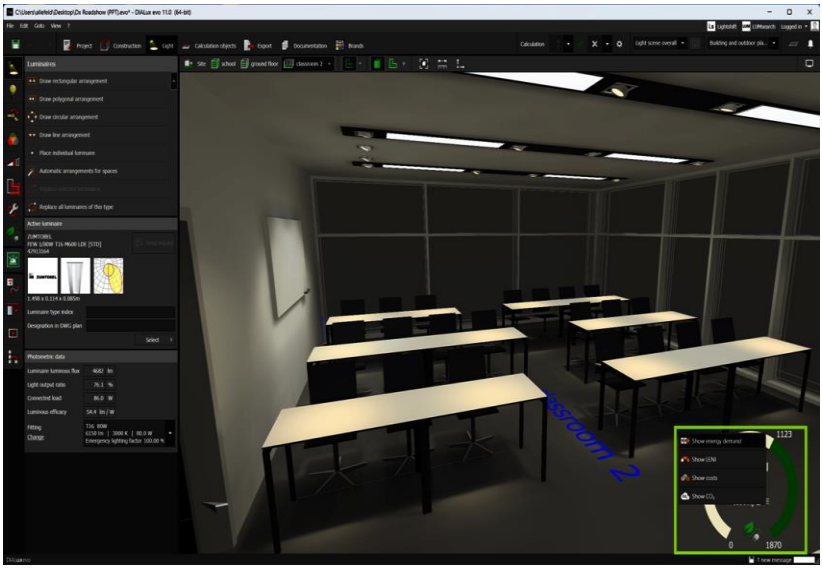

Figure 1.2 The Dialux EVO lighting CAD software.

1.3 Physically Based Simulation and Computational Constraints

Despite the rapid evolution of physically based rendering and global illumination algorithms since the formulation of the rendering equation (Kajiya, 1986), and the consolidation of open physically grounded simulation tools such as Radiance (Ward and Shakespeare, 2004), a persistent gap remains between image synthesis research and lighting design practice. While computer graphics has achieved high levels of physical accuracy (Pharr, Jakob and Humphreys, 2017), and daylight simulation research has significantly advanced predictive reliability (Mardaljevic, 2000), these developments are not always fully integrated into everyday lighting design workflows. At the same time, standard colorimetric models such as the CIE 1931 observer (CIE, 2018) remain insufficient to account for complex perceptual phenomena in real environments (Fairchild, 2013). Consequently, designers operate at the intersection of physically based computation, perceptual modeling, and project-driven constraints, often without a coherent theoretical framework that connects these domains. This chapter addresses this gap by clarifying the epistemological and methodological foundations of digital lighting design, distinguishing between communication-oriented rendering and quantitatively validated lighting simulation, and arguing for an integrated approach that combines physical accuracy with perceptual awareness. So, even the best Lighting CAD currently available has limitations and is susceptible to improvements that will hopefully be offered in the coming years in the wake of research in the areas of image synthesis and visual perception.

A first inevitable limitation is that their use is far from immediate. In fact, these programs are not magic boxes capable of accepting all design data as input and providing quantitative measurements of the project parameters and virtual photographs as output. In order for the calculation to be correct, the data provided must be extremely accurate and complete, both from the point of view of defining the three-dimensional geometry of the environment and the characteristics of the materials-colors and luminaires. In addition, the mathematical models used to calculate the light distribution must be controlled by a series of parameters useful for limiting calculation errors; the general rule that applies to this activity is that the greater the precision required to calculate a result, the greater the time required to obtain it (Ritschel et al., 2012). Depending on the complexity of the environment's model and the computational accuracy required, it may be

necessary to wait for results for more than a day on a modern personal computer.

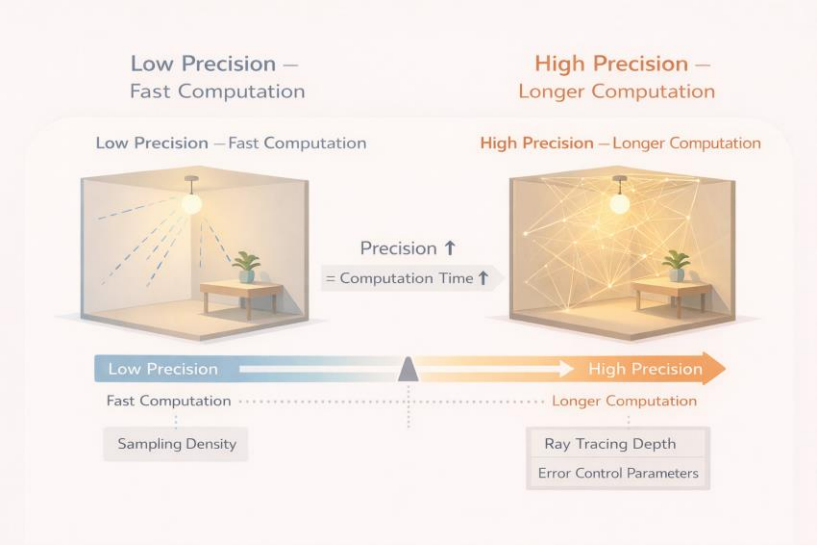

Figure 1.3 Quality vs. computation time.

1.4 Perceptual Models and Educational Implications

A further limitation is the fact that the more a software tools try to emulate the physical reality of light-matter interaction, the more it is necessary to have a model of virtual observer to transform the light spectrums that hit the retina of the human eye, into colors represented on the digital display (Tumblin and Rushmeier, 1993; Ferwerda, 2003; Marini, Rizzi and Rossi, 2004). At the current state of research, a human visual model capable of understanding all known perceptual phenomena has not yet been defined. In fact, even the standard colorimetric observer model defined by the CIE, which is the basis of colorimetry, is not able to correctly simulate the perceptual effects of the human visual system. The limitations of the CIE standard observer should be articulated at three distinct levels. First, physiological limits concern inter-observer variability, state of adaptation, field size, and contextual effects, which cannot be fully represented by the color-matching functions of the CIE 1931 standard observer (Fairchild, 2013). Second, computational limits derive from the necessary reduction of

spectral power distributions to tristimulus values and from subsequent processes such as tone mapping and gamut mapping, which introduce model-dependent transformations between physical stimulus and displayed image (Tumblin and Rushmeier, 1993). Third, epistemological limits arise from the normative nature of colorimetry itself: the CIE observer is a conventional reference model designed for measurement consistency rather than a comprehensive theory of visual experience (Rizzi, 2021). Consequently, while colorimetric standards provide a rigorous and indispensable quantitative framework, they do not exhaust the complexity of perceptual phenomena in real environments (Gregory, 2015). Recognizing these three levels of limitation does not weaken the scientific basis of lighting simulation; rather, it clarifies its domain of validity and supports a more coherent integration between physical measurement, perceptual modeling, and design interpretation. The problem is enormously complex because it involves a complete analysis and description of the psycho-physiological behavior of the human brain that science has not yet grasped; some scholars even doubt that we can get there in a short time.

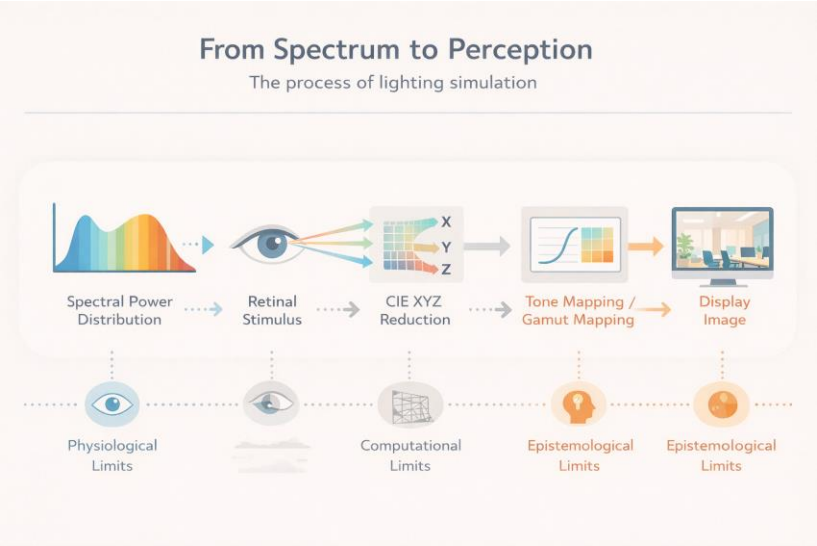

Figure 1.4 The workflow from spectral power distribution to perceived image in lighting simulation, highlighting the transformation from physical light data through CIE XYZ reduction and tone/gamut mapping to final display, while indicating physiological, computational, and epistemological limits across the process.

Based on this limitation, however, the use of software systems for Lighting-Color Design should not be abandoned. Twenty years ago, the computational accuracies achievable today were not conceivable, and scientific research concerning image synthesis is more advanced than the features found in commercial software products. As far as the aspects of quantitative evaluation of light are concerned, much has been done, and Lighting CAD today allows for a much more accurate and precise calculation than the manual one, thus enabling a more careful evaluation of the compliance of Lighting Design with industry standards. Regarding the qualitative and aesthetic evaluation of the lighting design, the production of virtual photographs is not an exact science, but can be controlled through manual parameters that are based on the experience of the designer in being able to recognize various types of environmental conditions, also with the help of quantitative evaluations. A good training path to develop this kind of experience consists in implementing in the Lighting CAD models of environments and illuminations already existing in reality and, based on objective data, try to produce virtual photographs as similar as possible to reality by controlling the calculation parameters of the images. It can also be observed that the use of software tools allows us to easily experience the application of the theory of lighting engineering to real cases, with a value of experimental and interactive teaching that goes hand in hand with the techniques that allow us to combine learning by reception with learning by discovery. This serves to induce the novice designer to apply the new knowledge with respect to the reality in which he or she lives, drawing attention to significant and interesting stimuli in the design process.

1.5 Digital Design Methods and the Management of Complexity

Digital design is not the same as using software; it is a structured method for managing technical, informational, and organizational complexity (Oxman, 2006). In the context of lighting design integrated with CAD and BIM workflows, the designer does not work with a simple object, but rather with a system composed of hardware, an operating system, application software, object libraries, plugins, graphics drivers, and network infrastructure. This ensemble constitutes the actual working tool, characterized by an extremely high level of complexity and intrinsically imperfect. Approaching digital design therefore means adopting a conscious approach to managing this complexity. The workstation is neither a neutral nor infallible entity: it can generate errors, unexpected behavior, slowdowns, or data loss (Lu et al., 2008). The first methodological skill

consists in recognizing that the technical-IT infrastructure is a fallible system and that responsibility for controlling the design process rests with the designer. In this sense, the methodological dimension precedes the operational one.
A second aspect concerns the distinction between personal use of digital devices and professional use. Daily experience with digital devices does not automatically guarantee adequate skills for managing complex projects (Trinkunaite, 2015; Kirschner and De Bruyckere, 2017). Digital design requires mastery of file structure, directory organization, version management, format compatibility, and the ability to diagnose hardware and software malfunctions (Margaryan, Littlejohn and Vojt, 2011). Without this understanding, the reliability of the design process is compromised.

Figure 1.5 The contrast between everyday digital device use and professional computational infrastructure: while personal devices are designed for intuitive interaction, complex digital design workflows require structured hardware systems and technical expertise to ensure reliability and control.

Managing complexity also requires explicit planning of activities. A digital project cannot be conducted in an improvised manner: it is necessary to identify the various operational phases, establish priorities and dependencies, predict processing times, including computational times, and identify critical activities. In collaborative BIM environments, the sequence of operations and the consistency of software versions directly influence data consistency and team and workflow efficiency (Succar, 2009; Kerzner, 2017). The time dimension therefore becomes a structural constraint of the design process. Another methodological element concerns data security and preservation. Digital production results in files that can be damaged,

overwritten, or made incompatible by software updates (Azhar, 2011). Conscious management of backup copies, versioning, and historical archiving is not a technical detail, but an essential component of the design method. Data loss is not just a technical inconvenience: it entails financial, time, and professional costs (Langlois et al., 2023).

Figure 1.6 The Centennial Light, installed in 1901 at the Livermore Fire Department in California, is one of the longest-lasting incandescent lamps ever recorded. Its extraordinary longevity—over a century of nearly continuous operation—contrasts sharply with the planned obsolescence introduced in 1924 by the Phoebus cartel, which standardized and deliberately limited the lifespan of incandescent bulbs to approximately 1,000 hours. Image credit: Rjaerial, Own work, via Wikimedia Commons. Licensed under CC BY-SA 4.0.

Finally, managing digital complexity requires a proactive approach to technological obsolescence. Hardware and software are subject to rapid update cycles, sometimes driven by market forces rather than actual functional needs (Poppe et al., 2021). Designers must critically evaluate when to update and when to maintain a stable configuration, balancing

innovation, compatibility, and operational continuity (Gussek, Schned and Wiesche, 2021). In short, digital design methods aren't just a sequence of software commands; they define a set of strategies for governing a complex and unstable technical ecosystem. Project quality doesn't depend solely on formal design skills, but on the ability to integrate those skills with rigorous management of the digital infrastructure that enables them.

1.6 Digital Skills, Professional Responsibility and Problem Solving

In the context of digital design, technical skills cannot be reduced to the mere ability to use software. The demands of digital skills in a professional context encompass a complex set of operational knowledge, critical thinking, and professional attitudes that directly impact the reliability of the design process (Oberländer, Beinicke and Bipp, 2020; Audrin, Audrin and Salamin, 2024). The distinction between personal and professional use of digital technologies is a crucial step: daily familiarity with devices and platforms does not automatically guarantee the mastery required to manage complex tools such as CAD, BIM, or lighting design software. Digital design requires the careful management of files, directories, extensions, interoperable formats, export and import procedures, as well as an understanding of the differences between software versions and their impact on data compatibility. In collaborative environments, the improper use of such tools can compromise the consistency of the digital model, lead to information loss, or produce difficult-to-detect inconsistencies and significant financial losses. Digital skills, therefore, are not an ancillary aspect of the project, but rather a structural condition.

Alongside technical skills, the dimension of professional responsibility is also important. A designer's reliability is measured not only by the formal or functional quality of the proposal, but also by the ability to meet deadlines, ensure operational continuity, and prevent critical issues related to the tools used. In a complex digital system, hardware or software errors, unexpected malfunctions, or version conflicts are not exceptional events, but rather real possibilities that must be anticipated and managed. The designer is required to adopt a proactive approach, avoiding blaming technology exclusively for inefficiencies and instead developing control and mitigation strategies. In this context, problem solving becomes a key skill (Giang et al., 2024). Addressing a system error, a corrupt file, or a software crash requires not only technical knowledge, but also analytical skills, self-control, and stress management. An individual's emotional response to an unexpected event directly impacts the effectiveness of the solution. A methodical approach,

focused on identifying the causes and finding viable alternatives, allows errors to be transformed into learning opportunities (Karla et al., 2022). Conversely, a passive or fatalistic attitude can amplify the consequences of the critical event. Another aspect concerns awareness of the limitations of the tools. Software for lighting design is not an "intelligent" product capable of automatically compensating for conceptual errors or methodological shortcomings. It operates according to specific logics that must be understood and managed. Giving the system autonomous decision-making capacity is tantamount to improperly delegating responsibility, which should remain with the designer. Technology is a powerful tool, but it is neutral with respect to objectives; it is human intelligence that gives it direction and meaning.

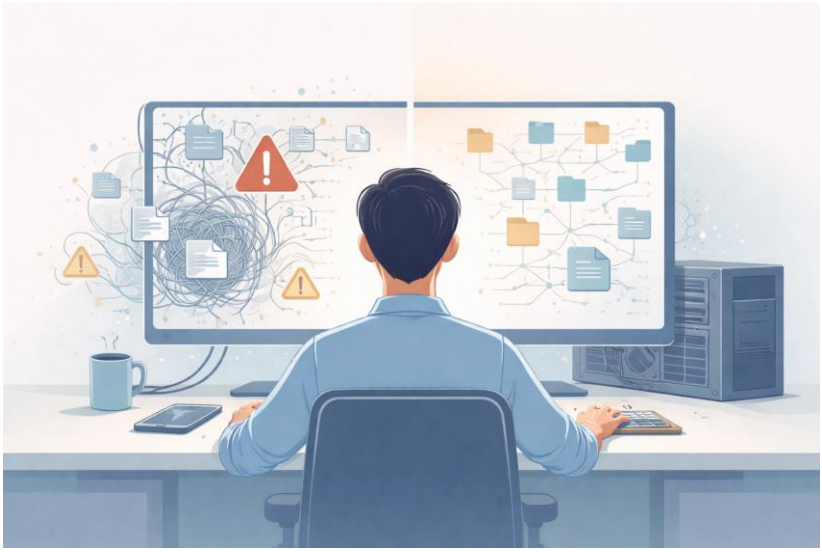

Figure 1.7 Problem solving in digital design: technical errors and system failures require not only operational knowledge, but also analytical reasoning, emotional control, and a structured approach capable of transforming disruption into organized and effective solutions.

Digital skills also include the ability to find, evaluate, and organize technical information (Alavi and Leidner, 2001; Cross and Sproull, 2004). Manuals, online help, specialized forums, and official documentation are essential resources for problem-solving. However, access to information is

not enough: it is necessary to develop a critical sense in selecting sources and precision in defining search keywords to identify reliable solutions. Knowledge management thus becomes an integral part of the design method.
Ultimately, digital skills in lighting design and BIM workflows are not limited to instrumental expertise, but are configured as an integrated set of technical knowledge, professional responsibility, and problem-solving skills. The quality of a digital project depends on the maturity with which the designer governs the technological system in which they operate, transforming complexity into opportunities and unexpected events into opportunities for methodological growth.

1.7 Reliability, Obsolescence, Data Consistency and Computational Infrastructure in BIM-Based Workflows

The integration of lighting design into digital design workflows entails a substantial shift in design information management. The digital model is no longer a simple representational medium, but becomes the central repository of the building's geometric, technical, and performance data. In this scenario, process reliability depends not only on the accuracy of design choices, but also on the stability of the hardware and software infrastructure that enables their processing, sharing, and archiving.
Reliability in digital design workflows primarily concerns the consistency of the information model over time. Different versions of the same software, uncoordinated updates between team members, or the use of incompatible plug-ins can generate conflicts, lost parameters, unintentional alterations to objects, or, in the most critical cases, file corruption and financial loss. Data consistency is therefore not a given, but the result of methodical version control procedures, authorization management, and cross-checking of changes (Howard and Björk, 2008).
Another critical factor is technological obsolescence. Digital design software is subject to rapid, often annual, update cycles that introduce new features but can compromise backward file compatibility. In collaborative environments, unsynchronized upgrades can disrupt business continuity and generate unexpected costs (Volk, Stengel and Schultmann, 2014). Obsolescence affects not only software, but also hardware: underpowered workstations, insufficient memory, or slow storage systems can drastically slow down computation times, impacting productivity and the quality of design control. Computational capacity therefore plays a strategic role. Complex projects, integrated with lighting data, photometric simulations, or advanced rendering, require significant computing resources (Ritschel et al.,

2012). The choice of infrastructure—processor, amount of RAM, dedicated graphics card, backup systems, and cloud storage—is not merely a technical decision, but an integral part of the working method. An inadequate configuration can result in excessive wait times, system instability, or data loss, with direct repercussions on project deadlines.

Figure 1.8 Interoperability in Open BIM workflows: during data exchange through IFC formats, semantic and parametric information—particularly for specialized objects such as lighting fixtures and photometric data—may be partially simplified, fragmented, or lost in translation between different platforms.

For example, within Open BIM workflows, based on interoperable formats like IFC, the complexity of translating data between different platforms is added. Every export and import carries the risk of losing semantic or parametric information, especially when dealing with specialized objects such as lighting fixtures or photometric data (Venugopal et al., 2012). Data resilience depends on the quality of the original modeling and an understanding of the limitations of exchange formats. In this context, conscious management of file security and preservation becomes essential. Multiple backups, historical version archiving, and clear policies for naming and organizing folders are tools for preventing errors and malfunctions. Data loss or inconsistency is not only a technical problem, but also a financial and professional risk factor. Reliability, obsolescence, data consistency, and computational infrastructure are therefore interconnected dimensions of digital design. Managing them requires technical skills, organizational discipline, and a critical awareness of tool limitations. Only through this approach can operational continuity and information quality be guaranteed in advanced digital design processes.

1.8 Conclusions

Digital lighting design cannot be reduced to the mere use of software tools, nor can it be interpreted as a simple technological evolution of traditional design practices. As discussed throughout this chapter, it represents a methodological transformation in which physical measurement, perceptual modeling, and computational simulation converge within an integrated design framework. The impossibility of relying on full-scale physical prototypes makes virtual prototyping not an optional aid, but a structural condition of contemporary lighting practice. The distinction between communication-oriented rendering and quantitatively validated lighting simulation is therefore not a technical nuance, but a disciplinary clarification. Rendering tools support perceptual anticipation and visual interpretation, yet they cannot substitute the photometric and colorimetric rigor required for compliance with standards and performance verification. Conversely, Lighting CAD systems provide measurable data and normative control, but they operate within computational constraints and within the epistemological boundaries of existing perceptual models. Recognizing this complementarity prevents both technological determinism and naïve trust in visual realism. The chapter has also highlighted that the limits of digital tools are not exclusively technical. They concern the physiological variability of human observers, the computational reduction of complex spectral phenomena, and the normative assumptions embedded in colorimetric standards. Such limits do not invalidate digital simulation; rather, they define its domain of reliability and call for informed interpretation. Scientific accuracy and experiential judgment must therefore coexist within the design process.

At the same time, digital lighting design unfolds within a broader ecosystem characterized by infrastructural complexity, interoperability challenges, data fragility, and rapid technological obsolescence. Reliability is not guaranteed by software itself but by the designer's capacity to manage versions, formats, computational resources, and collaborative workflows. Digital competence thus emerges as a structural dimension of professional responsibility. The quality of the project depends not only on formal creativity or technical calculation, but on the maturity with which complexity is governed. Ultimately, digital lighting design should be understood as a critical practice. It requires the ability to interpret numerical outputs, to evaluate perceptual plausibility, to control computational parameters, and to anticipate systemic risks. It also demands awareness that every model—physical, perceptual, or informational—is a selective

representation of reality. Within this awareness lies the epistemological foundation of responsible design.

The integration of measurement, simulation, perception, and method defines the contemporary frontier of lighting design. Digital tools do not replace the designer's intelligence; they extend it. Their effective use depends on theoretical clarity, methodological rigor, and critical judgment. Only under these conditions can digital simulation become not merely a technical instrument, but a coherent medium through which design intent, scientific knowledge, and experiential quality are meaningfully connected.

1.9 Conflict of interest declaration

The author declares that there are no actual or potential conflicts of interest related to this chapter. Specifically, no financial, personal, or professional relationships with individuals or organizations have influenced, or could be perceived to have influenced, the content, analysis, or conclusions presented herein. The research and writing of this chapter were conducted independently and objectively. The author confirms that no competing interests exist within the meaning of the RCASB guidelines.

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2. Lighting Design and verification with CAD systems

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Abstract

This chapter examines computer-based tools for lighting design and verification, framing them as elements of a virtual design workshop that supports both quantitative evaluation and qualitative assessment of light in built environments. After outlining the skills required to operate within this digital framework, the chapter analyzes software systems for artificial lighting calculation, focusing on space modeling, luminaire and photometric data management, and the evaluation of illuminance, luminance and visual comfort through established metrics. Particular attention is given to the limitations of rendering as a perceptual aid and to the need for technically grounded representations when assessing lighting performance. Through applied interior design case studies, the chapter illustrates how virtual measurement tools support the balance between functional requirements, visual comfort and design intent. The discussion then extends to optical simulation software used in luminaire design, highlighting the role of ray-tracing and Monte Carlo methods in virtual prototyping and photometric analysis. Overall, the chapter emphasizes the methodological value of digital tools in integrating environmental lighting design and product-level optical analysis within a coherent design process.

Keywords:

Lighting design, lighting verification, virtual design workshop, illuminance and luminance analysis, visual comfort.

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2.1 The virtual design workshop

Let's enter the virtual laboratory. The tools we have at our disposal are software programs to support lighting design and also tools for the management of luminaire and lamp data, which can be used and tested during the design phase.

However, who is interested in entering the virtual laboratory? Mainly lighting and interior designers, whether experts or university students still in their training phase. Some professionals interested in learning more about the aspects of multimedia communication related to lighting management could also pass through here, and perhaps even some set designers dealing with real or virtual environments and wanting to experience the effect of their designs on the computer screen. Indeed, the communicative impact of a photorealistic rendering can improve all aspects related to multimedia communication and virtual prototyping of environments.

What are the skills required to be able to use the tools of the Virtual Lighting design Workshop?

Lighting design is one of the most complex aspects of interior and exterior design. The difficulties encountered in introducing this topic to designers and students are generally of two types: the first is of a scientific and technological nature and the second is curricular. The use of natural and artificial light generally requires a wealth of skills that can only be acquired through an appropriate multi-year course of study followed by an apprenticeship with a strong experimental value (Turan *et al.*, 2020).

While it is inconceivable to approach lighting design without technical and scientific foundations, the availability of new software tools enables a more dynamic approach to the training of the lighting designer, so much so that it can be assumed that the very use of the virtual laboratory can simplify the training process. The tried and tested methodology consists of the acquisition of introductory elements of the fundamental principles of photometry and lighting engineering, combined with basic computer and computer graphics skills (Dewey, 1938; Shivaramu, Aveen and Ullal, 2025). Based on these premises, one can then begin a phase of experimentation in the virtual laboratory trying to tackle the analysis of environments that already exist in reality. While the aspects of Lighting design can of course be further developed and explored in a subsequent training course, it is equally true that the results show how the development of an awareness of the existence of the "light problem" in comparison with the known reality, leads the student to a more conscious approach of the geometric aspects and problems related to illuminance and its variation according to a variety of parameters.

Good lighting is one of the essential elements of a "human-friendly" environment. Since humans perceive a large part of their information about the environment through the organ of sight, it becomes indispensable for the designer to create the conditions for good vision, not only through natural light, by arranging openings and appropriate orientation, but also through rational and conscious choices related to artificial light (Boyce, 2014).
The dimensional characteristics of the environment, the human activities that take place there, the furnishings, the colors, the finishing materials and their reflection factor (Bellia, Pedace and Fragliasso, 2017), the luminaires and light sources, are all essential elements for correctly assessing the lighting issue (Siniscalco, 2021).
A lighting design that does not take these interactions into account risks generating overlit environments, or undesirable contrast and color rendering effects, also altering the physiological and psychological relationships of users with their environment (Rossi, 2019). In this respect, it is clear that the simultaneous use of architectural and lighting design is the best approach to ensure optimal results.
While artificial light is used to support natural light during daylight hours, to soften excessive contrast effects or to increase illuminance levels in very deep rooms, there is an increasing number of circumstances in which the illumination of an environment is entrusted to artificial light alone, such as in certain types of work and commercial environments, offices, classrooms and so on (Bellia, Pedace and Barbato, 2013; Denk, Jimenez and Schulz, 2015; Figueiro *et al.*, 2019). This is the motivation that prompts us to directly involve the interior designer in the lighting project, a project that, in our opinion, has too often been delegated to other professionals, who are not necessarily attentive and sensitive to the issues mentioned above.
We believe that the biggest stumbling block in professional practice is the complexity of the calculations and the general lack of information on the photometric characteristics of lamps and luminaires. In order to be able to determine the dimensions and characteristics of a lighting system in a short time, it is necessary to have available a quick calculation tool that allows the results to be compared with one or more design hypotheses and can, albeit with limitations, relate to the aesthetic/functional choices of an architectural project (Ochoa, Aries and Hensen, 2012).
The remainder of the chapter will analyze three types of virtual laboratory software tools:

- a first type of software that primarily enable the quantitative evaluation of light and the management of both databases containing photometric characteristics and luminaire catalogs;

- a second type of software, which use rendering calculation techniques to analyze the issue of luminaire design;
- a third type of software that, in addition to more limited aspects for quantitative evaluation, have considerable outlets for qualitative analysis, as well as the possibility of producing animations and interactive virtual environments.

While the first and the last type have, in various respects, common functionalities, but different purposes of use in the field of lighting design, the second deals with a totally different topic centered on the design of luminaires for artificial lighting.

The purpose of this chapter is not to provide a guide to the use of a particular software but to highlight the functionalities that are integrated into the design process and methods, by mentioning examples and case studies from a variety of software. In this context, we would like to present the reader with the advantages and limitations of computer tools in approaching the complexity of the issues involved in a lighting project, proposing examples with graphics and images.

2.2 Measurement and evaluation of environments

In the field of computer-assisted artificial lighting design, there are particularly interesting computer tools that make it possible to verify, during the design phase, illuminance values and luminance distribution, in relation to as many interacting elements in the environment as possible, by providing the designer with various types of luminaires and light sources. This latter aspect makes it possible to orient choices not only according to the visual task, but also to the possibilities of energy saving, the control of dispersion and thus of light pollution and, no less important, the reduction of operating costs (Davoodi, Johansson and Enger, 2014; Azmi Muslimin *et al.*, 2025).

For these purposes, it is therefore advisable to use software that enables the calculation of lighting parameters of artificial lighting systems for indoor and outdoor environments, with functions for displaying result tables, graphs and images of the created environment (Maamari and Fontoynont, 2003; Shikder, 2009; Azmi Muslimin *et al.*, 2025). Typically, these instruments are equipped with a photometric archive containing various categories of luminaires, with their associated measurements and lamps, and a catalog of lighting products, subdivided by manufacturers and types, also providing technical data sheets, commercial data and electrical data.

Illuminance and luminance values can be calculated on all surfaces in the room, including furniture, also considering the shadows they generate

(Davoodi, Johansson and Enger, 2014; Králiková *et al.*, 2022). These programs can consider regular and irregular shaped environments and evaluate local reflections according to the Lambert model and/or by means of calculation models with which surface reflection modes such as mirroring and glossy can be defined. Lambert's local lighting model states that a perfectly diffuse surface reflects light uniformly in all directions. The intensity of the reflected light therefore does not depend on the angle of reflection but on the angle from which the light hits the surface. Therefore, diffusive surfaces that enjoy this property are also called "Lambertian". A classic example of a Lambertian surface is chalk. It is important to note that the vast majority of surfaces we encounter in everyday life have a diffusive behavior, with the exception of mirrors and metals or other highly polished materials.

An important consideration to be made with regard to these CAD software programs for lighting calculation is that they have not been developed for architectural design, therefore it is always suggested to simplify, whenever possible, the modeling of rooms and furniture, so as not to considerably burden calculation with details that would be irrelevant for the results of the lighting design.

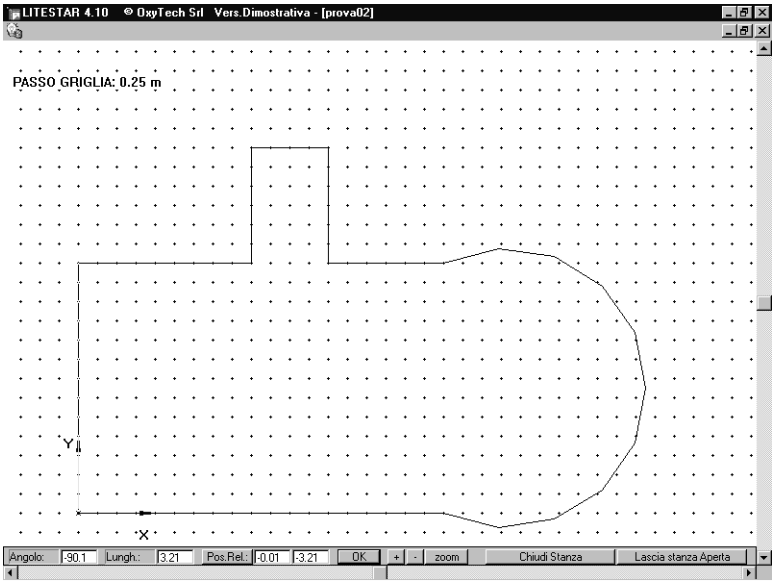


Figure 2.1 Example - Defining the perimeter of an environment.

2.2.1 Definition of the environment

Almost always these programs provide elementary modeling functions for the environment, while furniture can be conveniently chosen from a library of standard elements or modeled. The aim is to allow 3D models to be produced very quickly in order to be able to concentrate on the design aspects of lighting. It is possible to enter the room into the program using two different procedures: defining the room plan and then the height of the area. Alternatively, it is possible to choose a predefined room or area from the program's library.

All calculation methods used are based on surfaces being flat. Curved surfaces can still be modeled, which the program approximates with an operator-defined number of polygonal elements. It is advisable to approximate curved elements by using not too many polygons in order not to adversely affect calculation times (Besenthal, Maisch and Ropinski, 2019).

Alternatively, it is possible to import 3D models made with other software. While at first this may seem the easiest and most natural solution, particularly if the lighting design is part of a larger architectural project, this type of approach can cause many problems. Indeed, the demands of 3D drawing and modeling of architectural design require a level of detail an order of magnitude greater than that required for lighting calculations. Therefore, when using this type of approach, it is essential to control the polygonization parameters with which the 3D model is exported from the architectural CAD, and try to obtain a model that is characterized by surfaces that are as regular as possible. This goal is far from obvious because architectural CADs are not realized with the purpose of light calculation in mind and polygonization is generally badly handled. A 3D model with an irregular distribution of polygons and/or with the presence of very elongated isosceles or scalene triangles can increase the time required for the lighting calculation tenfold and also lead to incorrect results due to approximation problems in the numerical calculation. Another problem generated by this approach is that the architectural model also contains a large number of structural elements on which it makes no sense to calculate the light and whose surfaces would further slow down the calculations.

Whichever method is used to create the geometric model of the room, two basic rules apply for lighting calculations: limiting as much as possible the number of surfaces that are affected by a lighting or shading effect, e.g. it is perfectly useless to model the interior of a piece of furniture, and using polygonal models that are as homogeneous and regular as possible.

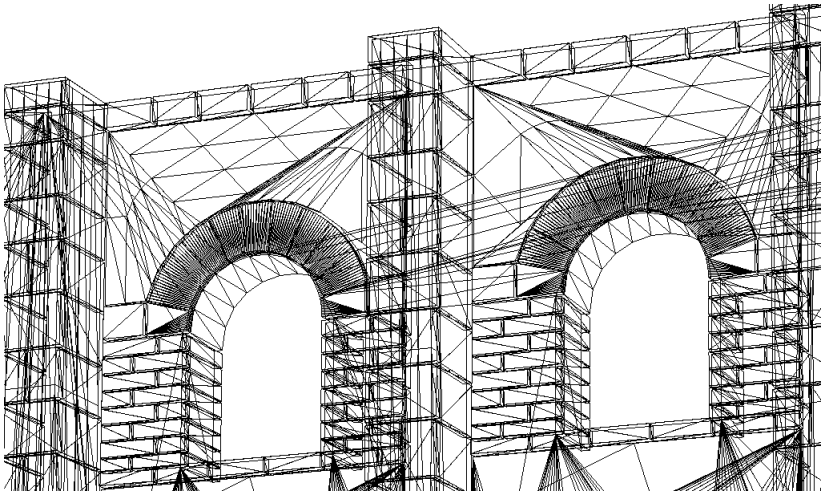


Figure 2.2 View of a part of a model portraying the façade of a historic exterior. The 3D polygonization carried out by the architectural CAD produced a chaotic set of very irregular triangular surfaces, this is especially true for the load-bearing structure underlying the brick and ashlar details. The model thus presents a mixture of flat faces of very different sizes relating to various details of the real structure.

Once the specification of the geometry is complete, it is possible to define certain parameters of the environment that are useful for calculation purposes, i.e. whether it is an interior or an exterior, as well as the colors and reflection factors of the geometries. Some software has useful libraries of materials to which it automatically associates a predefined reflectance value that can still be changed as required. From a physical standpoint, reflectance affects the amount of reflected light and thus the measurable luminance. This value can be expressed as a percentage or as a value between 0 and 1. It is to be considered as an average value of the surface and indicates, in any case, that the type of reflection is to be understood as diffuse.

The importance of correctly determining the reflection factors of surfaces should by no means be underestimated, as these make a decisive contribution to the calculation of indirect illuminance, particularly for interior spaces (Simm and Coley, 2011; Makaremi *et al.*, 2019). Underestimating reflection factors will lead to an over lit project, while overestimating reflection factors will lead to a poorly lit project.

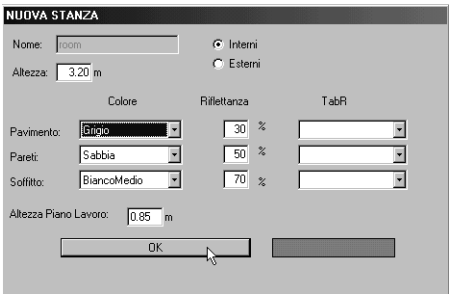


Figure 2.3 Example of the definition of reflection factors for the main surfaces of a room.

In this context, it is also important to recall the guidelines included in the standard (CEN, 2021) regarding the reflection factors of materials recommended for interior design, with particular reference to workplaces, remembering that this indication is in any case of a general nature for all interiors in which people reside for several hours. These guidelines basically try to reproduce in interiors the same decreasing clarity values, from top to bottom, that we have in the natural environments in which we evolved:

- Ceiling 0.6 ÷ 0.9
- Walls 0.3 ÷ 0.8
- Worktop 0.2 ÷ 0.6
- Floor 0.1 ÷ 0.5

If the lighting design is for an existing room, these reflection factors and colors should be measured with the aid of a portable colorimeter or spectrophotometer. If, on the other hand, the environment is just being designed, colors and reflections can be part of a joint design of light and color, as would be desirable even if not yet widely practised. A very interesting aspect is that during the design phase, the software can also allow you to assess how the illumination changes, in quantity and directionality, as the reflection factors of the surfaces change.

2.2.2 Luminaire Management

Luminaires are characterized by a photometric solid measured in the laboratory by means of a goniophotometer. The photometric solid is represented, in a three-dimensional polar diagram, by the closed surface whose points have a distance from the center of the diagram proportional to the light intensity emitted in that direction. Two polar coordinate systems are used.

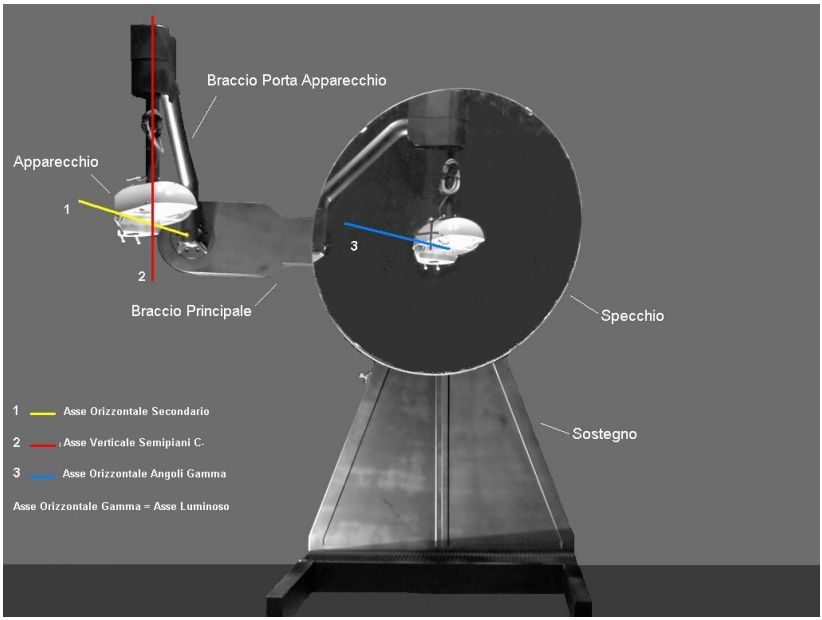


Figure 2.4 A mirror goniophotometer for measuring the photometric solid.

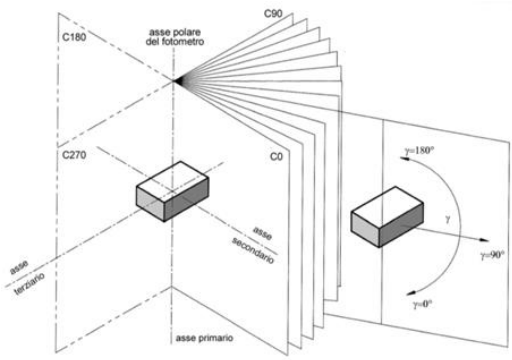


Figure 2.5 The C-gamma system defines the photometric solid of the luminaire by a series of half-planes that are sections that rotate by an angle C with respect to the reference axis. For each half-plane, the polar diagram of the light intensities emitted by the luminaire with respect to that section is shown with gamma angles ranging from 0° downwards to 180° upwards.

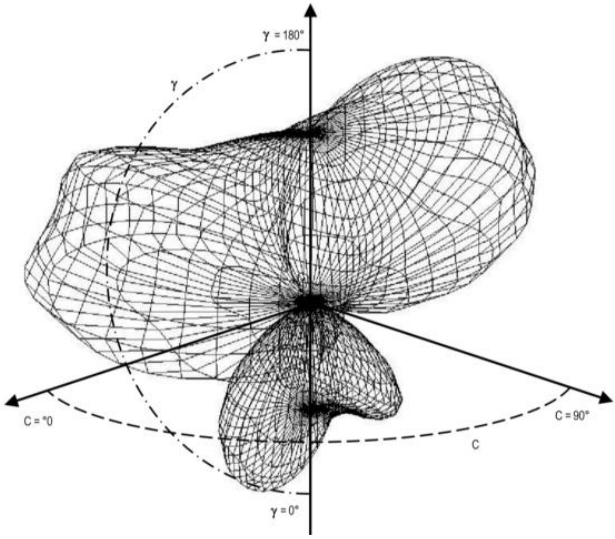


Figure 2.6 Example of a photometric solid of a luminaire, downloaded from a manufacturer's site in .ies format, emitting more light upwards, for indirect lighting, and less light downwards. This type of product generally generates very comfortable lighting with a low UGR because it makes great use of the indirect illuminance produced by the ceiling.

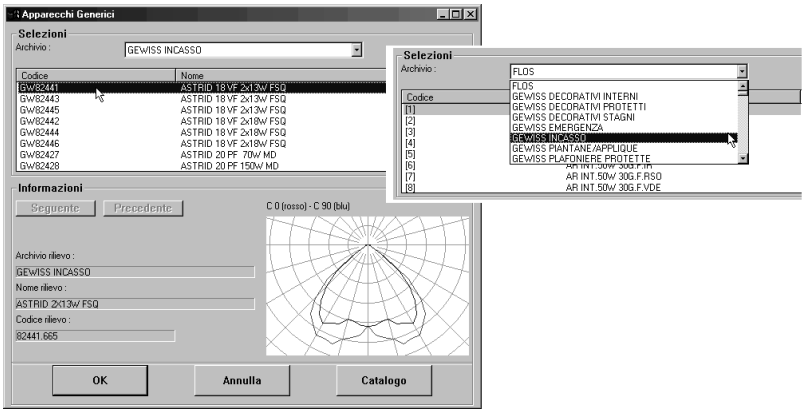


Figure 2.7 Example of the selection of a recessed luminaire with direct downward emission only, selected from the internal catalog of a lighting calculation software. The manufacturer, product code, and the two main sections of the photometric solid on the two planes C0-180 and C90-270 are given.

The C-gamma system for interiors and street luminaires and the V-H system for headlamps (ANSI/IES, 2019). Ultimately, it represents the directional shape of the light emitted by the luminaire. This is the fundamental datum that makes it possible to calculate the illumination produced by a luminaire. Some software requires you to manually enter this data, which is generally available on lighting manufacturers' websites on the product data sheet web page, in the form of a file in two possible formats: .ies ((ANSI/IES, 2023)) or .ldt ((Stockmar, 1998)). Many manufacturers make a file with the geometric model of the luminaire available in addition to this format.
Other software, on the other hand, integrates a catalog of manufacturers, with whom they have collaborative agreements, in which thousands of products divided into types are available (Dial, 2025; OxyTech, 2025; Relux, 2025). This catalog can also be periodically updated via the Internet by automatically accessing the software manufacturer's cloud server to add new manufacturers/products and remove discontinued luminaires. The presence of the integrated catalog is very useful because it saves a lot of time that can be more profitably used for the realization of the project. By selecting a product, the photometric archive window appears, including the data of the chosen luminaire and the type of lamp associated with it, in the case of traditional products where the lamp can be replaced within the luminaire.

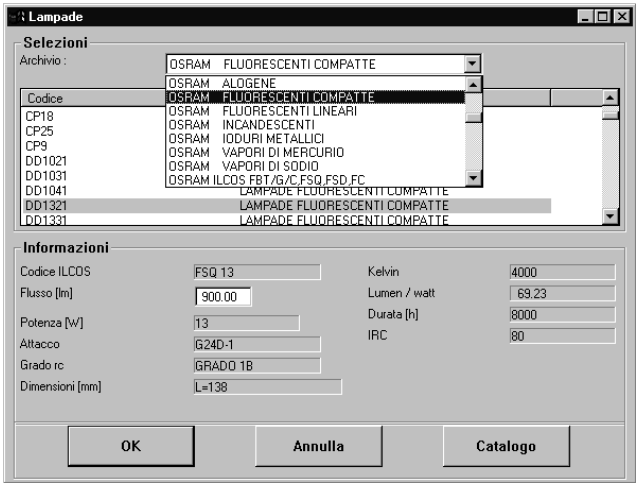
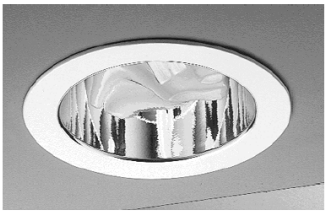
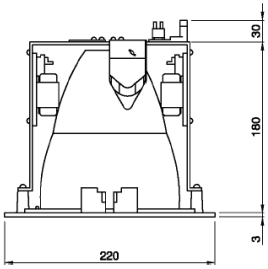


Figure 2.8 Example of a lamp management archive. The tab allows you to view the technical characteristics of the light source.

OxyTech

Tipologia Prodotto	DA INCASSO	Codice	GW82441
Modello	Astrid 18 VF	Codice E.A.N.	8011564069169
Prodotto	Astrid 18 VF - 2 x 13W FSQ G24d-2/3 230V-50Hz	Codice F.N.D.G.M.E.	





Dati Commerciali e Generali

Colori	Peso Netto [Kg]	Peso Lordo [Kg]	Volume [m3]
BIANCO	1,30017	1,31062	0,0124

Disponibilità di Magazz.	Num. Listino	Prezzo Unitario [LIT]	Dimensioni

Specifiche Elettriche

Tipo Lampade	Tipo Attacco	Tensione [V]	Potenza [W]
FSQ	G24d-3	230	13

Cl. Isolamento	Grado IP
I	20

Parametri Fotometrici

Classe BZ	Classe UTE	Classe DIN	Codice CIE
-	-	-	0, 0, 0, 0, 0

VDT	CIE Lumin	DIN Lumin	SLI	TRO	SPREAD

Norme e Marchi di Conformità

Norme	Marchi di Conf.
CEI EN 60598-1, CEI EN 60598-2-2	IMQ, HNR

Figure 2.9 Example of a product data sheet.

From the luminaire selection it is possible to access the lamp catalog should you wish to replace it with one having a different performance. Lamps can be chosen according to the type and technical data provided in the catalog: electrical data, lifetime, power, type of connection and dimensions, luminous flux emitted, color temperature, color rendering index CRI and efficiency. This data obviously cannot be changed. The lamp initially

associated with the luminaire can be replaced with a different one, chosen from the lamp archive. Beware that some programs do not make a correctness check on the replacement of the lamp with a different and possibly non-compatible one, which can lead to results that do not make any sense from a technical standpoint. Any changes to this data can only be made based on knowledge of the characteristics of the luminaire and its possible ability to accommodate different models and lamp types. This type of functionality is obviously not available for LED products in which the light source is integrated in a non-replaceable whole with the luminaire.

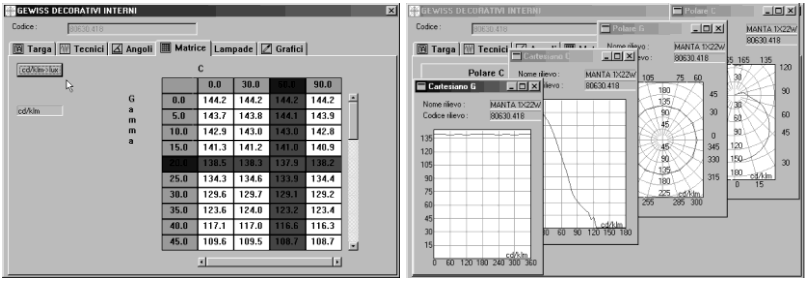


Figure 2.10 Example of displaying C-gamma planes of the photometric solid in various formats.

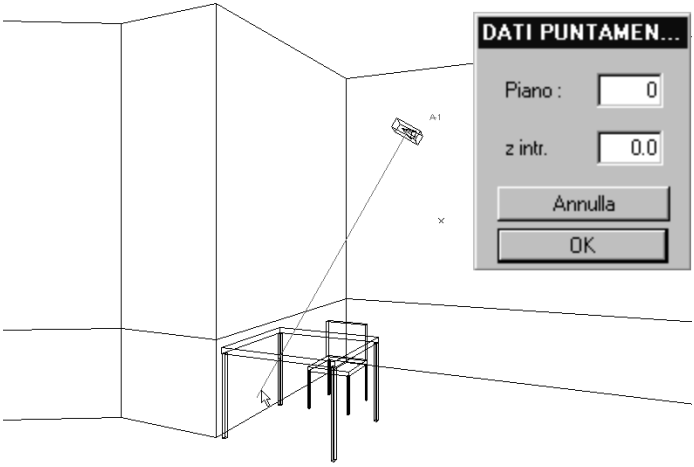


Figure 2.11 3D schematic view of the positioning and pointing of a device.

Each product in the catalog is generally associated with a data sheet displaying its data and images, which can be printed or exported in pdf format. From the product sheet, the photometric data of the luminaire can also be displayed in various different formats.
Once a luminaire has been chosen from the catalog, it can be inserted into the geometry of the room, positioning it where it is considered most appropriate in relation to the design idea. In addition to the position, the orientation of the primary axis with respect to which the photometric solid is associated with the luminaire's geometry must also be defined.
The three-dimensional pointing function, i.e. the possibility of defining the orientation of the luminaire's intrinsic co-ordinate system with respect to the environment's Cartesian axis system, is fundamental to the correctness of the design. Indeed, having established the fact that in lighting design, luminaires cannot, as a rule, be placed in any random position but are subject to constraints, the control of illuminance is also and primarily done by pointing the photometric solid of individual luminaires.
Once the luminaires have been added to the room, it is always possible to view their complete list. Actually, it is not simply a list but a table with editable fields for entering and modifying certain parameters. A tick in the box next to the device number indicates that it is selected and switched on. The ON-OFF function allows an appliance to be switched on or off and therefore to be taken into account or not in the calculation. This is a very useful feature in the design refinement phase, as it makes it possible to perform separate calculations in order to assess the contribution to the overall lighting made by the various products included in the design.

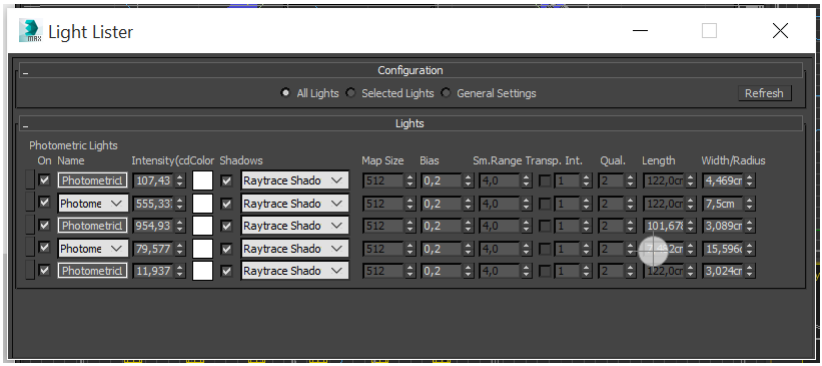


Figure 2.12 Example of a luminaire list included in a project.

2.2.3 Management of lighting calculations

Once the geometry of the room has been defined and the luminaires have been chosen and positioned, the lighting in the room can be calculated. Different software presents different calculation methods that can be based on lighting standards, the radiosity method or the more recent photon mapping. The latter two methods are preferable because they take into account both the direct component and the diffuse inter-reflections between walls and furnishings, i.e. indirect illuminance. A fundamental parameter to be chosen is the number of inter-reflections of light to be considered in the calculation, bearing in mind that as this value increases, so does the accuracy but also the calculation time. With modern computers, it is best to always maintain at least a factor of 10 inter-reflections.

There are three main calculable quantities that can be taken into account by the program: illuminance, luminance and glare assessment using the UGR index (CIE, 2010). It is important to bear in mind that any change in the characteristics of the environment or devices requires the calculations to be repeated.

The calculation of illuminance on surfaces only depends on the relative position between these and the light sources, while the calculation of luminance and the UGR factor always also depends on the possible positions of the observer, in the environment considered, which must therefore be accurately defined according to the human activities that are assumed to be carried out by the occupants in that environment (Son *et al.*, 2015). The software allows various observers to be inserted, using a dialogue box to determine their position in the environment and the direction of observation. Another parameter that can be considered, should the calculation refer to outdoor areas, is light pollution, evaluated according to the UNI 10819:2021 standard on the requirements of lighting systems in order to limit the upward light flux dispersion. There are generally no functions to assess light pollution with respect to the many different regional laws in Italy.

The calculation grid automatically provided by the software adapts itself according to the dimensions of the surfaces in the environment, but its pitch can be changed manually by the operator. When using the manual grid it should be remembered that, in the presence of furniture, a grid that is too wide would only consider one point for each piece of furniture, especially if it is small, limiting the rendered result. On the other hand, the use of a very fine grid enables accurate calculations, but greatly increases the time required to compute the results, even up to many hours or days in the case of very large and complex projects (CIE, 1982).

The calculation times change according to the complexity of the project, in all its aspects: the size of the room, the number of luminaires and furnishings, the number of inter reflections to be considered and the type of calculation selected (Ritschel *et al.*, 2012). It is therefore to be expected that the program will also take many minutes or even few hours to perform the calculations. A good method, which the designer can use in order not to wait for hours in front of the computer, is to use a simplified calculation to make initial approximate but quick evaluations during the development of the project, and then refine the calculations during the night hours when the computer can work autonomously to solve the more complex calculations.

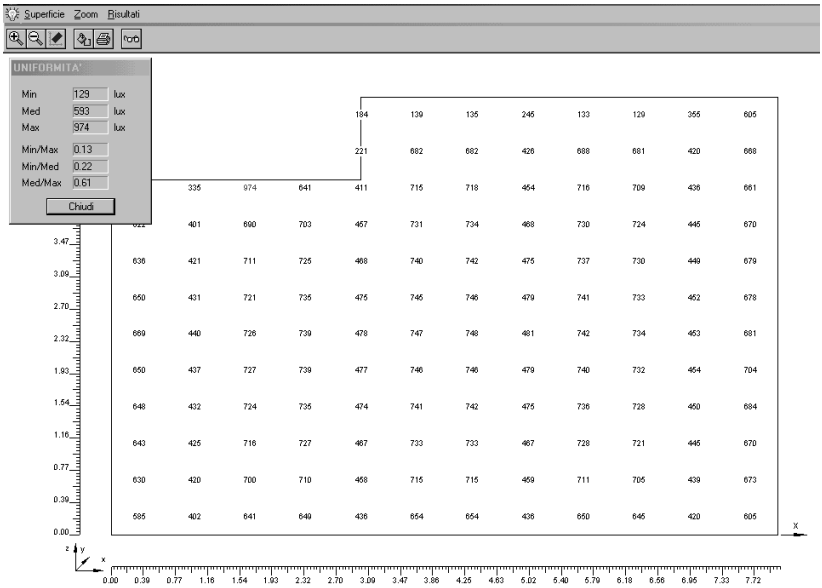


Figure 2.13 Technical representation of illuminance on the work surface with numerical values.

Once the calculations have been completed, the results can then be visualized and analyzed for any surface in the environment by means of technical representations. There are various functions that allow the results to be represented in numerical or graphical form. The first choice you have to make is to decide whether you want to see the results for individual surfaces or on the three-dimensional model of the environment. Depending

on this choice, different representations can be obtained, since different functionalities are provided by the program.

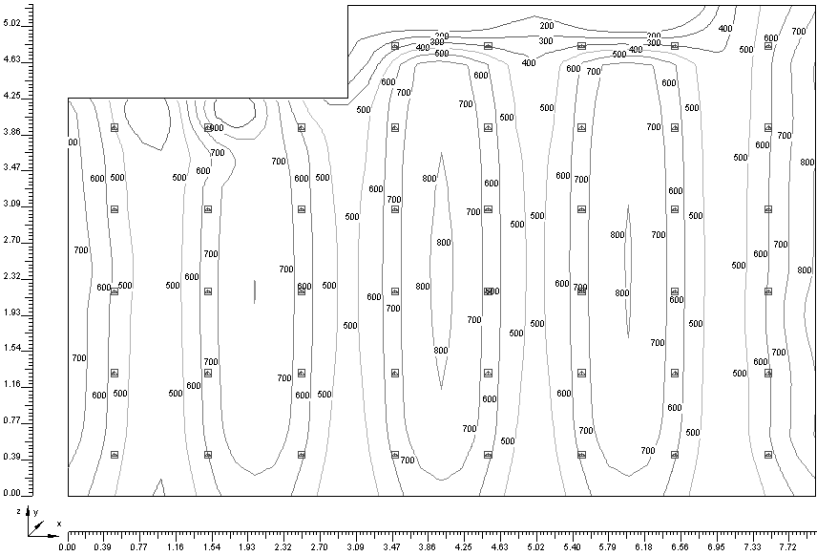


Figure 2.14 Technical representation of illuminance using iso-value curves (Isolux).

The first mode is to display results for individual surfaces. These are the surfaces of the room, such as the floor, individual walls, ceiling or individual pieces of furniture, and read, for each of them, their respective illuminance or luminance values in relation to a position. In the illuminance analysis, the point values on the defined grid, the maximum value, the minimum value, the mean value and the uniformity ratios between the illuminance are always reported. In addition to grids with numerical values, the following representations are possible (Ward and Shakespeare, 2004):

- By means of iso-value curves (called Isolux) representing the level variations of the quantity considered. It is also possible to manually determine which levels to represent.
- By means of false colors (spots) representing levels of the selected size.
- By a 3D surface whose height represents the level of the selected size.

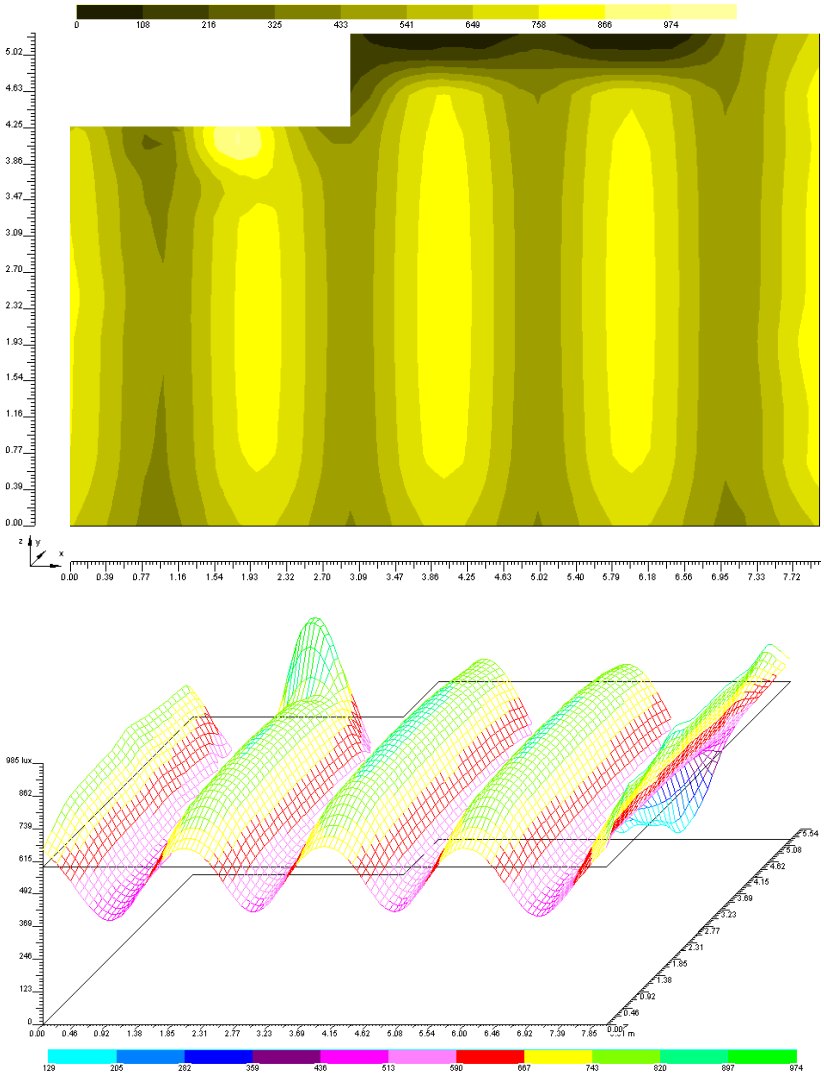


Figure 2.15 Technical representation of the illuminance on the work surface by means of false colors (top) and by means of a three-dimensional graph (bottom).

Another method of representing the results is based on a three-dimensional rendering of the environment (Pharr, Jakob and Humphreys, 2017). The quality of rendering that can be achieved in this context cannot be considered photorealistic, as it is mainly a tool for calculation. However, the 3D representation can in some cases be more complete and informative than the two-dimensional one. The 3D view is represented in wire-frame format and, via a window with framing controls, the position of the virtual observer, the direction of observation and the angle of view can be determined. Once these parameters have been established, it is then possible to switch to 3D visualization.

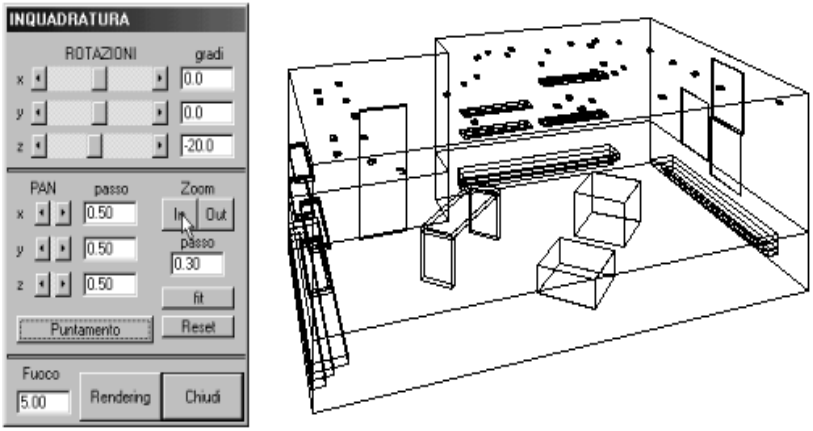


Figure 2.16 Example of a 3D view with the framing control window.

Through the rendering, the technical three-dimensional representation of illuminance levels and luminance can be obtained. For both of these parameters, the representation can be realized in different ways. The damped method generally consists of a surface display with a brightness on the screen that is proportional to the intensity of the selected magnitude. The problem with this type of representation is that the dynamics of the computer screen cannot reproduce the dynamics of the calculated real light at all. In fact, in a real scene, luminance can vary by more than eight orders of magnitude, whereas the computer screen in the best cases can only reproduce three. To overcome this problem, the program defines a maximum saturation level that can be controlled automatically or manually.

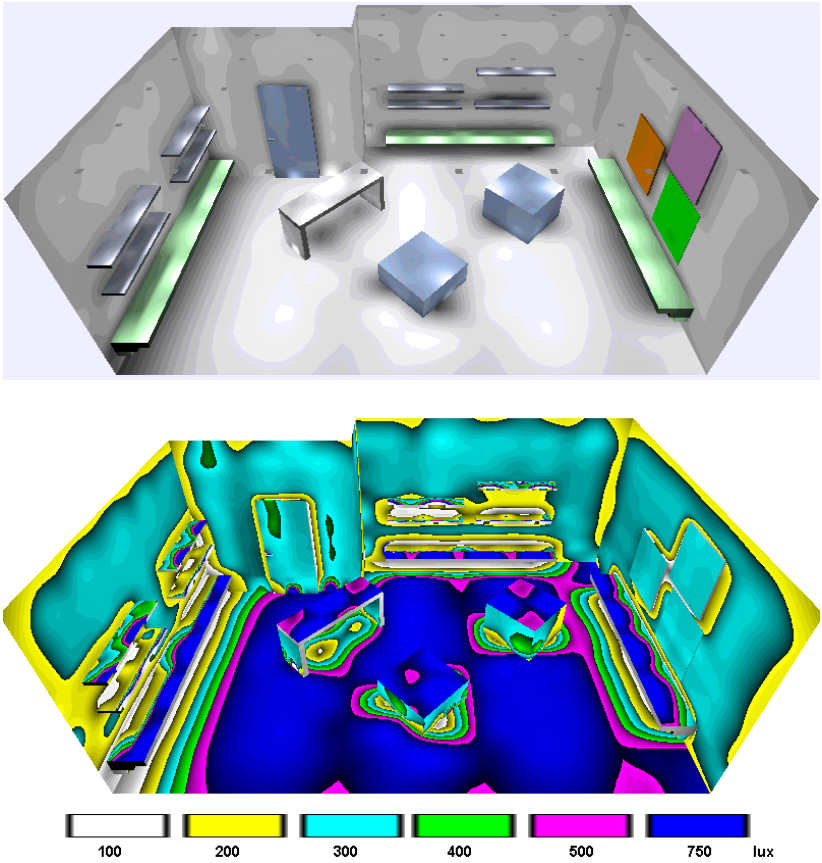


Figure 2.17 Technical representation of illuminance. Through non-photorealistic three-dimensional rendering (top) and through false color scaling (bottom).

Another method consists of a false-color representation of the chosen size. This is very useful in the development of the lighting design because it provides an overview of the illuminance or luminance levels, which are useful for evaluating the variations of the two quantities on the scene's surfaces, according to the visual tasks set during the specification phase. However, the assignment of the mapping between colors and light levels must be done manually by the operator, and this requires a previous analysis of the illuminance and luminance levels of the virtual environment carried

out by means of the two-dimensional surface analysis, in order to establish the most appropriate levels. Some programs also provide a representation by means of iso-value curves, but these are not as effective in 3D as in the two-dimensional case (Akyüz and Kaya, 2016; Fernandez-Prieto and Hagen, 2017).

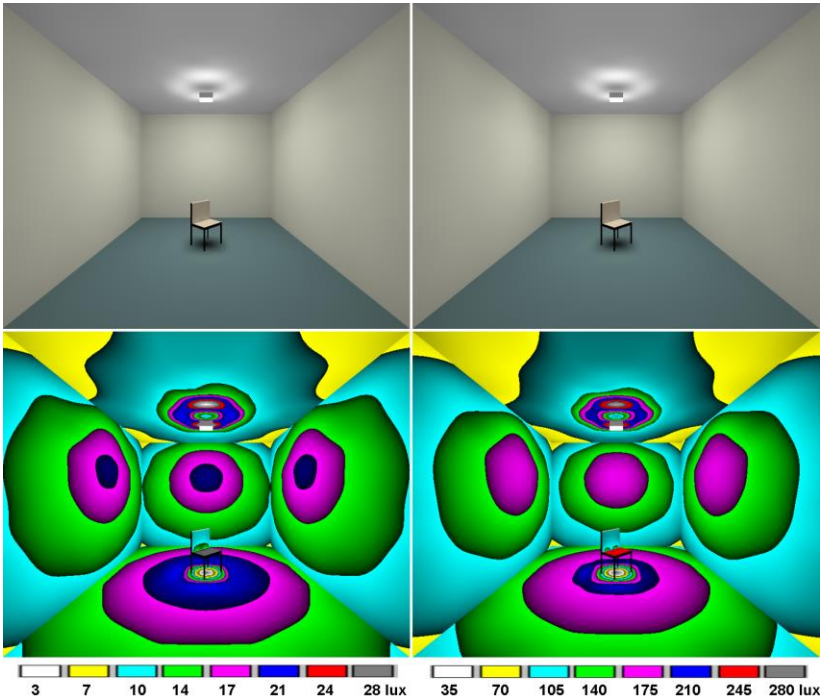


Figure 2.18 Comparison of two renderings with automatic saturation switched on. The room on the left is lit by a lamp producing a flux of 1000 lm, while the one on the right by a 9500 lm lamp. The rooms, however, appear the same. It is evident from the false-color comparison that in reality the illuminance due to the 9500 lm lamp is almost an order of magnitude higher than the other.

The designer always has the opportunity to determine the image size in pixels. Images created through the rendering function can be deleted or saved. A very critical aspect of rendering images in dampened mode is the saturation or exposure factor used to adapt the light dynamics calculated in the virtual scene to the screen. Both are commonly used in

different software, although the more correct one is definitely exposure, as it recalls the concept of camera exposure. When automatic mode is selected for the saturation level, the program analyzes the maximum illuminance or luminance level in the scene and maps that value to the maximum brightness of the screen.
While this procedure is useful for clearly representing the image, it can also generate renderings that in some cases can lead the designer to make inaccurate assessments. In fact, if the scene is very dark and the maximum illuminance level is only 20 lux, all the dynamics of the computer screen will be mapped in the range between 0 and 20 lux, and surfaces illuminated at 20 lux will appear bright white. For the same reason, if the environment has very high illuminance levels, these will be scaled to match the light dynamics of the screen, appearing darker than they are in reality.

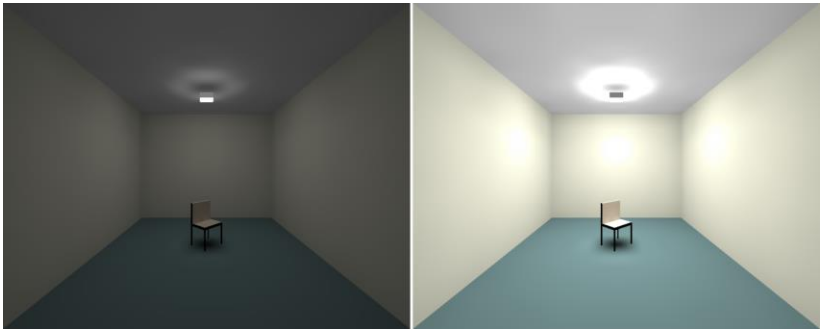


Figure 2.19 The same comparison as in Fig. 2.18 with manual saturation level = 150 lux shows that there are considerable illumination differences in the room, but the correct quantitative assessment is not made from these renderings, but rather from the technical representations.

The problem is even more pronounced if one wants to make comparisons between renderings in damped mode, of the same room, subjected to completely different illuminance levels. Automatic saturation would bring them back to similar luminance-screen levels, thus making the comparison impossible.
Because of what we have already mentioned about visual perception in the context of lighting CAD (Rossi, 2021), we can say that the most correct method to solve this problem is to set the saturation level manually, by entering a value that is slightly higher than the maximum

illuminance levels that the lighting designer intends to set in the room design. The designer can obtain this information from the reference standard for the type of environment and visual task considered. Obviously, in the case of comparing two or more renderings, the saturation level must be set the same for all images produced. A general rule therefore applies, which can be stated as follows: the rendering of an environment, photorealistic or not, can never be considered as a correct tool for assessing the amount of light in the lighting design.
Furthermore, it is important to note that the assessment of illuminance is a requirement to verify the design against the standards but does not make it possible to assess the perceived clarity in the environment. In fact, the latter is best described by luminance, which also depends on the chromatic and reflectance characteristics of surfaces, and the position of the observer.

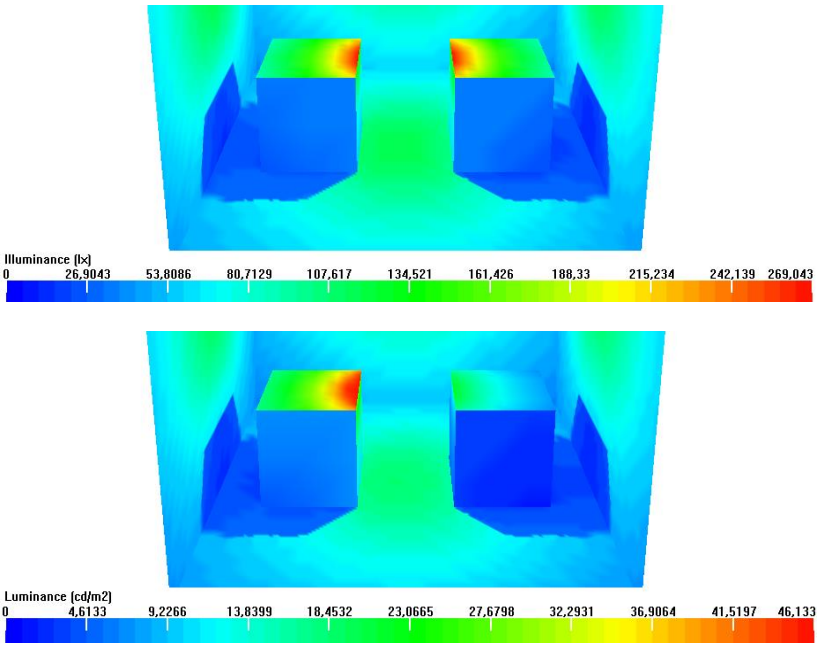


Figure 2.20 In this scene we have two objects that are illuminated with the same amount of light, but the one on the left has a high reflection factor (light gray) while the one on the right has a low reflection factor (dark gray). Above: illuminance is identical; below: luminance are different.

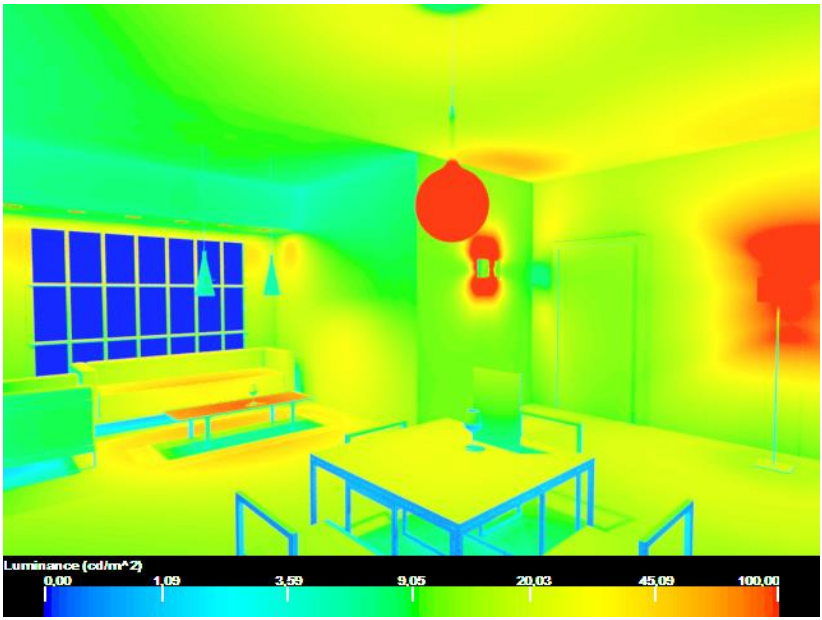


Figure 2.21 3D luminance assessment of a project using false-color scaling. Please note the red zones at luminaires that may be a source of disturbing glare.

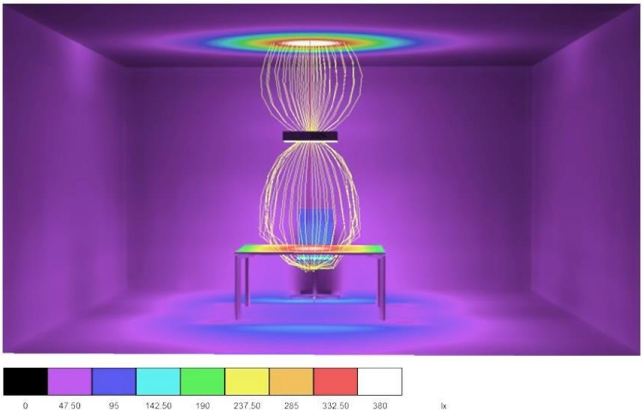
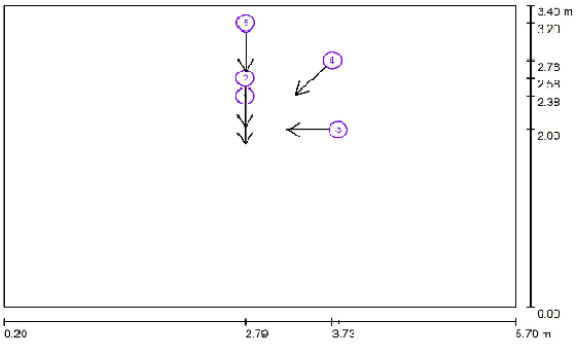


Figure 2.22 Calculation example for an office-type environment in which a luminaire with direct and indirect emission was used in order to increase visual comfort.



Elenco punti di calcolo UGR

No.	Denominazione	Posizione [m] X	Y	Z	Linea di mira [°]	Valore
1	N2	2.794	2.377	1.250	-90.0	18
2	N3	2.794	2.578	1.620	-90.0	15
3	N4	3.794	1.997	1.620	-180.0	17
4	N5	3.731	2.777	1.620	-136.0	17
5	N7	2.800	3.200	1.620	-90.0	<10

Figure 2.23 Calculation of the UGR with respect to 5 possible positions and orientations of the user's gaze in the previous figure. In the last column on the right, very low UGR values can be appreciated, confirming the high comfort level of the lighting solution.

For an accurate control of glare, in addition to luminance analysis, for a more complete assessment of the visual comfort of a project, the calculation of the UGR index can be used (Son *et al.*, 2015). This will be lower the greater the visual comfort of the environment. In order to calculate the UGR, all possible eye positions of the room users must always be defined in the design phase.
Today, the UGR is the best tool for the quantitative analysis of the comfort of a lighting design and, in fact, is only calculated using software tools, as manual calculation for any real design environment is extremely complex. The quantitative technical evaluation provided to us by the UGR calculation, with its ability to provide us with a metric for evaluating the comfort of the lighting design, is a first step towards the qualitative evaluation of the design as well.

2.3 Case studies

2.3.1 Two indoor case studies

To analyze the virtual measurement tools presented in the previous paragraphs, we used the software to develop real projects. What we wanted to test is the program's potential in fairly complex design circumstances, both in terms of furniture and space distribution. For this purpose, we have chosen two types of environments as examples: a small flat and a jewelry shop in a shopping center. Both contexts do not require installations aimed at a specific visual task, but rather the distribution of luminance in order to achieve the desired visual atmosphere.

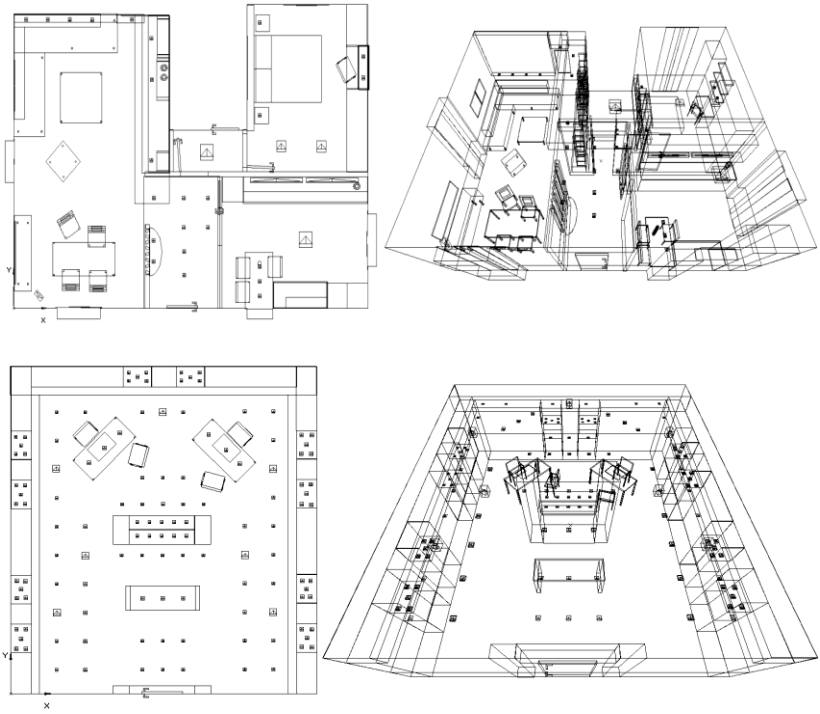


Figure 2.24 Floor plan and 3D wire-frame of the flat and shop with the arrangement of all lighting points.

The two projects required a different design process, as the characteristics of the installations are different. The installation of the house, has contemplated, during the calculation phase, the differentiation of the

illuminations within the environment, in order to verify the distribution of luminance in function of them; the installation related to the shop, on the other hand, being characterized by a high level of illumination of the shop window elements, has required the verification of a condition of balance of the luminance in the environment; although considering the installation with differentiated illuminations, it has been calculated in the condition of full regime, as usually happens in commercial contexts.

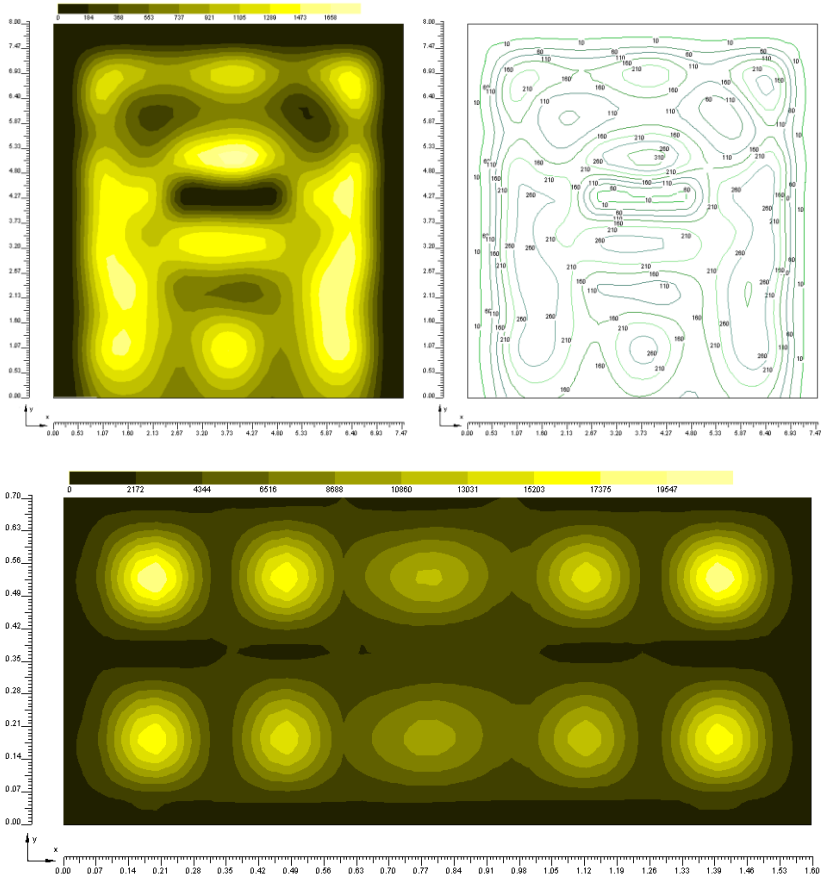


Figure 2.25 Top: lighting on the shop floor. Below the accent lighting on the jewellery display case top. The analysis shows that, since it is a jewellery exhibition, it is deliberately very high and is not the same in the ten planned exhibition areas.

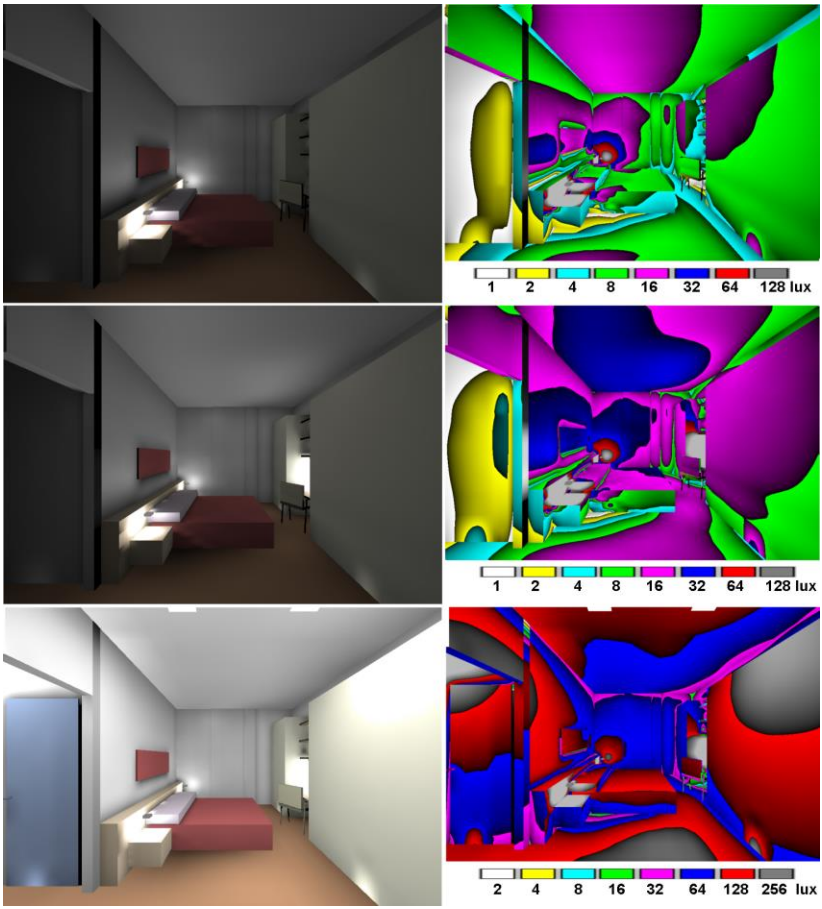


Figure 2.26 Differentiated switching on of lights in the bedroom of the flat, with the related illuminance levels shown in false colors.

With this in mind, we tested various functions of the software intended for modeling the space and furniture, in order to reproduce the correct calculation with the luminaires. In the room modeling phase, we had to resort to several "box" elements to reproduce floorboards, doorways and false ceilings; this operation, which is indispensable in such a context, requires great care in positioning the elements, especially when they are placed next to each other in order to obtain a planar surface.

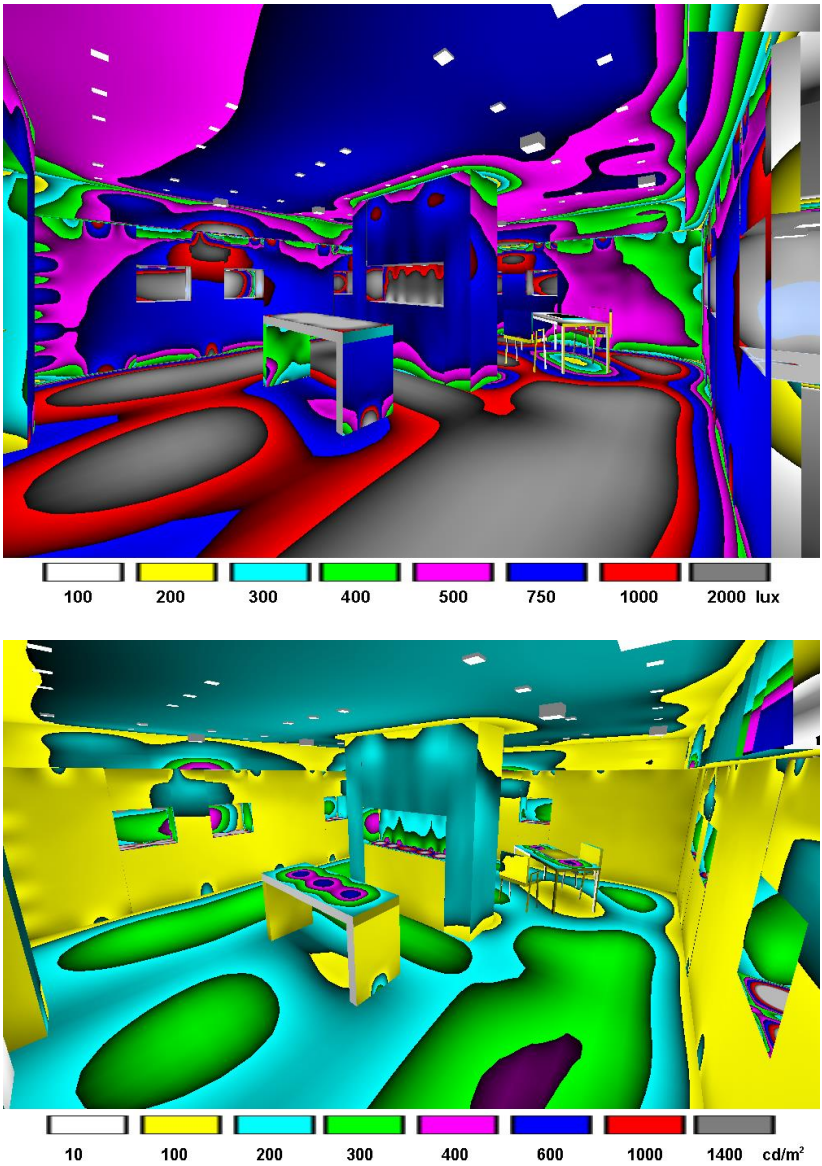


Figure 2.27 False-color representation of illuminance (top) and luminance levels for the shop design.

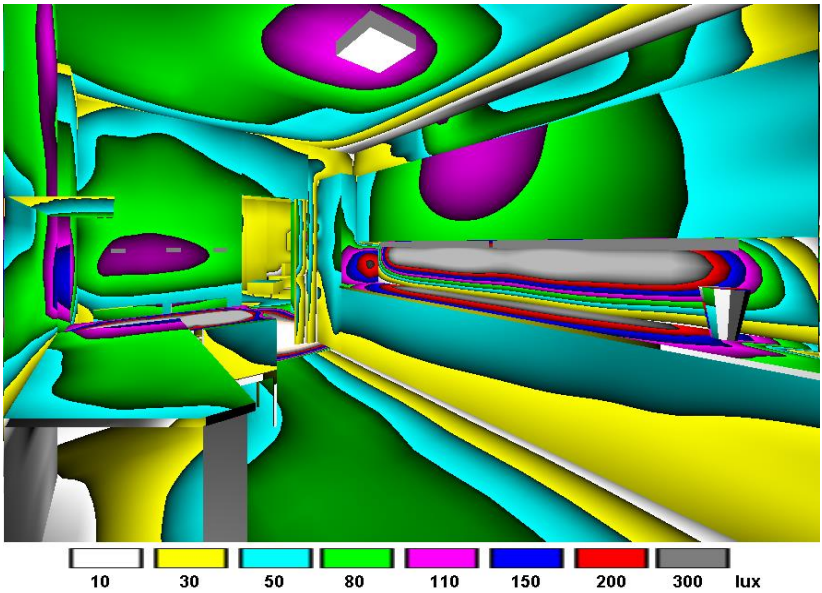


Figure 2.28 The flat's kitchen, evaluation of false-color illuminance.

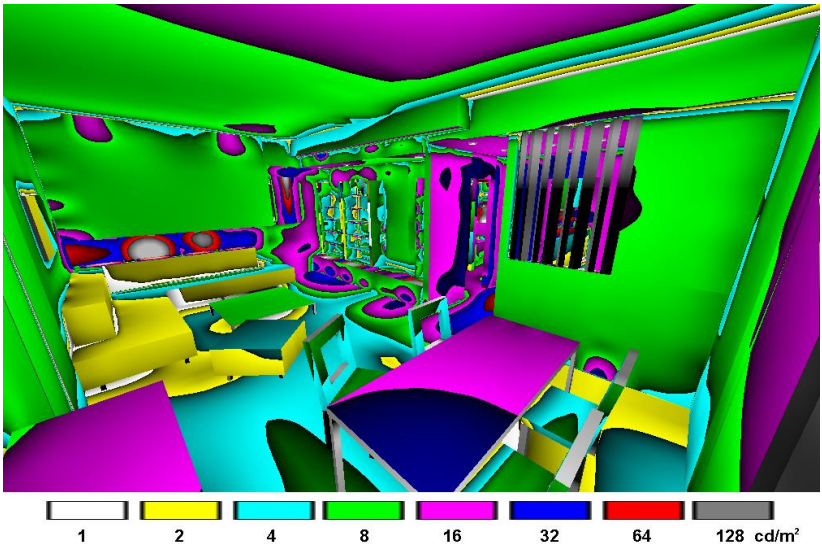


Figure 2.29 The living room of the flat, evaluation of false-color luminance.

The purpose of precisely juxtaposing the elements is to control reflections, avoiding dispersion of light flow through gaps that would not exist in reality and which could considerably burden the calculations by prolonging them for several hours.
The insertion of the remaining furniture elements was quick and overall sufficient for the reconstruction of the pathways within the environment. It was essential to accept a certain simplification of the furnishings, however this did not compromise the result aimed at the quantitative evaluation of light, especially in the living context.
One limitation is that reflections of specular surfaces are not calculated at this stage, and consequently materials such as crystal in display cabinets or the polished lacquer of furniture and polished marble floors are not considered. It is therefore impossible to rely on the program to calculate the reflected glare of the luminaires.
Moreover, the presence of the integrated catalog provided us with different types of luminaires and lamps, allowing us to differentiate between light sources, especially in the home, and to establish their degree of direct glare; the program allows us to evaluate the rotation of the photometric solid of the luminaires according to their aiming. The positioning of the luminaires in the environment was also very quick, especially in the case of their arrangement at regular inter-distances.
The shop's lighting system was entrusted to low-voltage recessed luminaires, with LED luminaires differentiated by power. It turned out to be advantageous to be able to check, through a single calculation session, the illuminance levels on the surfaces of greatest interest, such as sales tables and window tops, and the luminance distribution. The luminance value of the showcases was particularly interesting for us to verify, as they are elements intended for the display of small precious objects, which need to be appreciated in their details and colors, and which impose on the observer a very close distance to the objects at a defined height.
The calculation times were highly influenced by the number of furniture elements in the room and its articulation, as well as the number of luminaires in the design. In the case of the shop, the area covered is 60 square meters with an average height of 2.70 meters and a total number of 125 luminaires. The program was asked to carry out a complete calculation of illuminance and luminance values with seven levels of inter-reflection and took about one hour with a medium-performance computer. The calculation time for the flat is longer. Despite the fact that the area of the flat is almost equal to that of the shop (about 70 square meters with a height of 2.90 meters) and the number of devices significantly lower, the number

of elements used for the distribution of the space and its furnishing (108 elements, as opposed to 54 used for the shop) had a great influence. In this case, two hours of calculation were required.
One of the often tedious aspects of project activity is the editing and paper presentation of project data useful for the client's evaluation and descriptive data for the installer's work. The following pages provide a presentation of some of the main elements of the lighting design for the jewellery shop, showing the extract of a very interesting functionality for the automatic printing of data and results of design calculations, which saves a lot of time when writing the presentation. Next to this there is also the "Calculations/Economic Calculation" function, which allows you to make an economic calculation of the installation and operating costs of the system. The presentation is only an extract of some of the information that can be included in the executive project, which consists of more than 50 pages including product sheets, luminance evaluation and UGR factors, profit and loss account of the products used (excluding installation) and various rendering views.

2.3.2 From the environment to the lighting product

Many Italian designers have tackled the design of lighting products over the years, creating some of the most beautiful lamps still on the market today and contributing to the prestige of the Italian school of design. However, the design of luminaires, and the management in this context of the technical aspects of lighting, presents a considerable degree of difficulty that usually requires collaboration between several professionals. In fact, alongside the design of the form there is the problem of the functional design of the light, as well as a number of other aspects concerning the safety, quality and certification of the products. Referring for these latter aspects to the many publications in the field of electrical engineering, we would instead like to investigate here the possibilities that software tools present in analyzing the functional characteristics of light emitted by luminaires.
There are currently software products on the market that use mathematical calculation models for analyzing the photometric characteristics of luminaires. The purpose of these software products is to establish a point of contact between the worlds of research and industrial production or, at the very least, to facilitate the interchange between the two. Indeed, these optical analysis programs are based on the ACIS system, for the creation, management, manipulation and visualization of three-dimensional models, which is a key tool for solid modeling, commonly adopted in industry. ACIS is an object-oriented geometric modeling system designed to be used

as a calculation engine in 3D applications. It is used by many CAD systems and is produced by Spatial Technology Inc .

The simulation of light is realized using the global Ray-Tracing Monte Carlo global lighting model (Arvo *et al.*, 2001). The Monte Carlo variant of Ray-Tracing is based on mathematical statistical models for tracking light rays. This allows the designer to calculate the flux and light output propagated in lighting products. Users of the software can perform stray light analysis, illumination analysis and optical system analysis. Therefore, this software allows the effects of scattering, diffraction, absorption, reflection and refraction to be studied in any geometric model. The models used can be imported from any CAD program via files in SAT, STP, or IGS formats. However, solid geometries can also be created directly in them.

The model includes not only surface geometry and optical material data, but also the radiometric properties of the surfaces themselves such as absorption factor, reflectance, transmittance and diffusion coefficients. The rays propagate through the pattern and, by absorption, reflection, transmission and diffusion, are reduced to smaller and smaller fractions of the initial flux each time they intercept a surface. This propagation process generates a "tree" of beams that ends when the fraction of the propagated flux falls below a certain user-defined minimum threshold.

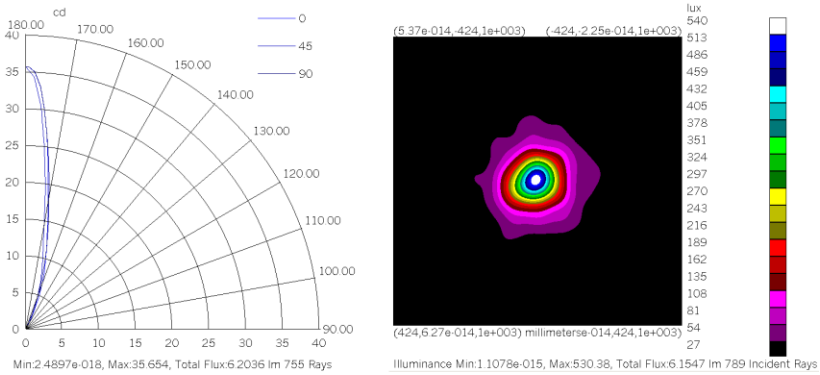


Figure 2.30 - Two examples of measurements that can be simulated in the software. On the left is the polar diagram of light intensity (photometry). On the right is a false-color map of the illuminance produced by a luminaire on a sample plane.

At the end of the calculations, the software is able to provide various types of results. These include:

- The spatial diagrams of irradiance and illuminance.
- Angular radiance and luminance diagrams.
- IESNA or Eulumdat format files for the definition of photometric solids.
- The absorption of mass through a volume.
- The computation of the flux absorbed and incident on each surface of the model.
- The incident ray table shows the co-ordinates (x, y, z) and flux of each ray meeting the selected surface.
- The recording of ray traces that, through the system expressed in x, y, z coordinates, are absorbed by a surface, indicating the type and amount of flux.
- The sorting of the beams, displayed by type, provides a precise overview of the optical system.

Moreover, these software products generally have two modes of operation: analysis and simulation. In analysis mode, the entire tree structure of the rays produced by the initial ray propagation are saved in memory. This shows the illuminance incident on each surface of the model. When the number of traces considered increases greatly, the analysis mode requires the use of too much computer memory, so it is more practical to use the simulation mode. In this mode it is possible to specify a particular surface and have only the radii outgoing and incoming from it stored. This drastically reduces the need for memory compared to analysis mode.

2.3.3 A reflection on the calculation models used

In computer graphics, the simulation of light transport is a tool that helps to create convincing images of an artificial world, with the aim of giving a description of the environment, including geometry and surface properties. A description of the light source and the points of view of the virtual observer from which the images are generated are also offered. Light transport algorithms then simulate the physical laws of optics in order to generate realistic and accurate images (Kajiya, 1986).

One of the main goals of light propagation calculation methods is to increase human efficiency in realizing virtual environments that are hopefully indistinguishable from reality. However, sometimes it is not enough to place lights in the scene, because most of the time software tools fail to simulate indirect lighting. In some cases it is therefore necessary to supplement the scene with the addition of lights that do not exist in the real environment to be simulated; these will have the purpose of enriching the rendering of the luminaires with the effect of indirect lighting diffusion.

Another application of light transport is modeling, the purpose of which is to have a preview of how an object will look or, in the case of optical devices, how it will behave before it is built, and this is the primary purpose of virtual prototyping techniques. In this context, the simulation of global light behavior is carried out by an algorithm called Ray-Tracing Monte Carlo, in which each ray is subject to probabilistic sampling. The samples are chosen randomly and not according to a deterministic model, based on widely established criteria for the physical systems in question. Randomness is achieved by choosing arbitrary locations and directions for emitted beams, and also by choosing random directions for diffused and diffracted beams. The Monte Carlo sampling method is thus a form of ray tracing that allows a statistical sample of all possible directions to be extracted from the system. The effectiveness of this method lies in being able to solve various types of calculation problems with a single computation technique.

A simulation using the Monte Carlo method can be manually refined by increasing the number of samples, i.e. the radii plotted. Software products that uses this method include methods that improve the effectiveness of the Monte Carlo, such as beam splitting and selective sampling. Through ray decomposition, the ray can be split into various components when it strikes a surface. In addition, rays can be split or decomposed within an object by specifying its mass scattering (bulk scattering), generally used for the analysis of biological tissues. In selective sampling, the diffuse components are again divided into others that go in both expected and random directions. During all these decompositions, energy is stored to ensure an accurate result in order to provide a correct prediction of irradiance and illuminance trends (Arvo *et al.*, 2001).

With the ray decomposition technique, the luminous flux of the incident ray is also decomposed, assigning a fraction to each component based on the properties of the surface or material. The decomposition process is repeated at each interception to form a tree structure. This procedure, by adding various levels of detail, greatly improves the efficiency of sample processing but unfortunately increases the required calculation time.

Selective sampling is a technique applied in the Monte Carlo method to improve the sampling of diffuse light. It is essential in the stray light analysis, where only a very small fraction of incident light reaches the detector or output surface. In the less refined version of the Monte Carlo method, the rays find their way out through random scattering alone. It is therefore necessary to draw a large number of rays so that a small part passes through the optical device. In software, selective sampling is a

technique by which scattered beams are sent in very precise directions, thus saving time and calculations. The redirection thus carried out brings the probability of the rays reaching the exit surface to unity, so the relative flux must be reduced by the probability of random exit from the surface. Ultimately, the aim is to conserve energy, i.e. to ensure that there is no double attenuation: this is a calculation that the software easily performs during processing in ray tracing.

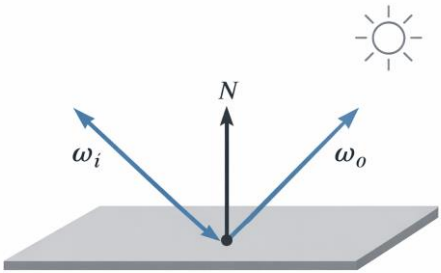


Figure 2.31 Interaction between light and matter, incident ray ω_i and reflected ray ω_o.

In the Monte Carlo method, light scattering is represented by discrete samples, i.e. rays of light, instead of continuous fields of light as in reality. Angular scattering distributions are used as probability functions to determine the directions of randomly scattered beams. Thus, for the selected beams, the direction is predetermined and the flux, sampled from them, is derived by integrating the probability density over the solid angle subtended by the considered flux.
This field appears highly promising, since Monte Carlo Ray Tracing methods can now be implemented using GPUs specifically dedicated to ray tracing computation, as well as Deep Learning algorithms to optimize calculations. However, these developments in fundamental research have not yet been implemented in the lighting CAD software currently available to lighting designers(R. Yan *et al.*, 2025; S. Yan *et al.*, 2025).
In addition to the aspects concerning the global calculation seen so far, attention must also be paid to the local aspects of the interaction between light and matter.

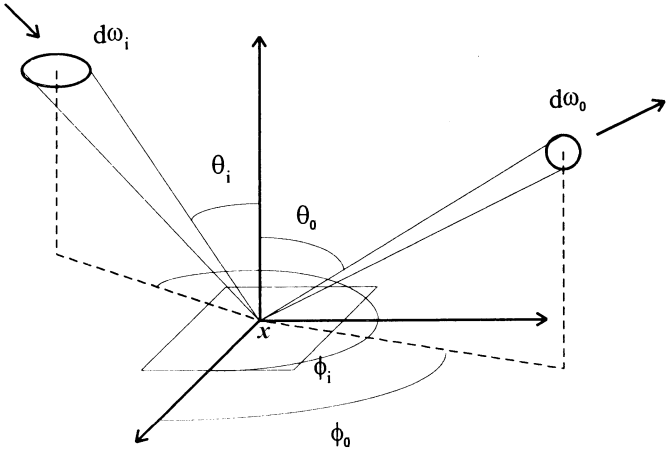


Figure 2.32 - Description of the BRDF. Light from a solid angle $d\omega_i$ is reflected at point x within another solid angle $d\omega 0$. The two directions, incidence and reflection, can be considered for each direction in the hemisphere above the surface sample x. The BTDF is described similarly, but with directions $d\omega_0$ passing below the surface.

The objects that can be modeled on the computer are mainly made up of elementary surfaces of infinitesimal thickness, so they are not to be considered as real objects. The local calculation model, used for opaque materials, describes the surface reflection phenomenon through the Bidirectional Reflectance Distribution Function (BRDF) (CDGF, 2021; Jurado *et al.*, 2022). For transparent materials that transmit light in a defined proportion, i.e. partly reflected and partly transmitted, it is necessary to model objects as solid elements in order to use the Bidirectional Transmission Distribution Function (BTDF) in the calculation. The combination of these two functions gives rise to the bi-directional scattering distribution function (BSDF), which fully describes the behavior of light when interacting with the surface of a material.

Optical simulation software programs are used by lighting manufacturers for luminaire design support. Thanks to their use, prototyping and photometric surveying of luminaires in the laboratory could be avoided, with obvious time and cost savings. The contraction of these two factors also makes it possible to expand research and experimentation of the best solutions from various points of view, from the technical aspects to the energy standpoint. The design aspects inherent in the shape design also

clearly benefit from this, thanks to the possibility of quickly experimenting with the relationship between light function and luminaire shape.
In this section we present the procedure followed to carry out the verification of a virtually recreated reflector. The linear fluorescent lamp luminaire in which this reflector is housed must meet a number of lighting requirements that are the input constraints to the design process. It is to be verified that the optical characteristics ensure a comfortable darklight distribution, with luminance control to be less than 200 cd/m² for angles of 60° ÷ 65° to the perpendicular, for glare control.
As previously mentioned, the software can import three-dimensional models in ACIS format, which is currently one of the most widely used industry standards for solid modeling (Corney and Lim, 2001). ACIS provides a wide range of possibilities for interchanging data between different programs, for creating, visualizing and editing designs, including NURBS surfaces (Rogers, 2001). Non-Uniform Rational B-Splines; they are parametric surfaces with which three-dimensional curved surfaces can be modeled and described. The ACIS format is therefore extremely important for describing and handling both mechanical elements such as reflectors and diffractors. It also offers a way to directly share data with other programs that support this format, such as CAM systems for industrial machining.

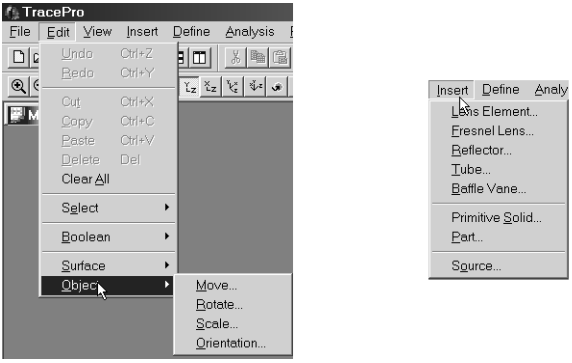


Figure 2.33 The editing menu and the menu for inserting solid primitives.

The three-dimensional model of the reflector shown below was drawn in 3D using a modeling program, there are many such software products available on the market: Pro-E, Alias, Rhinoceros and others. After opening the ACIS file, which contains the description of the luminaire model, the calculation

software has the task of assigning optical properties to the objects that make up the entire model. Every object must be considered as a set of surfaces.
In addition to importing models created with other systems, the program can still allow you to carry out certain operations to modify the imported solid and define further objects by working in editing mode. It is possible to insert the predefined elements required to recreate optical systems, such as lenses, reflectors, tubes and diaphragms, using geometric primitives such as spheres, circular and elliptical cylinders, cones, blocks and tori.
The luminaire we are about to analyze is composed of several elements that have been previously designed with a modeling program: optics, anti-glare louvres, main body of the luminaire, light source, each with different material finishes and radiometric characteristics.
In order to attribute the desired material characteristics to the object, it is always possible to draw on a database of materials in the calculation software, thanks to reference values provided by the manufacturers, such as the aluminium finish. However, it is also possible to recreate them by having two fundamental properties available: absorption and reflectance, specular or diffuse, which, based on a mathematical model, allow the program to approximate the real value of the BRDF (CDGF, 2021).

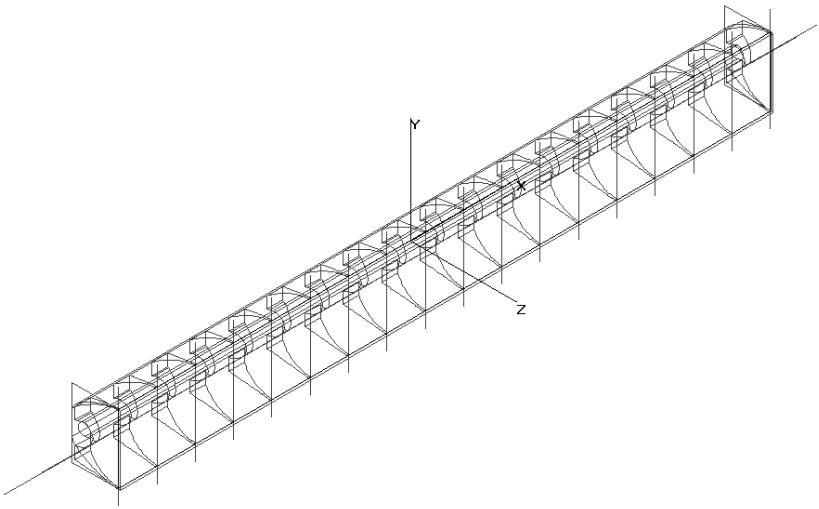


Figure 2.34 3D geometric model of the Ra Sistema luminaire. Courtesy Artemide.

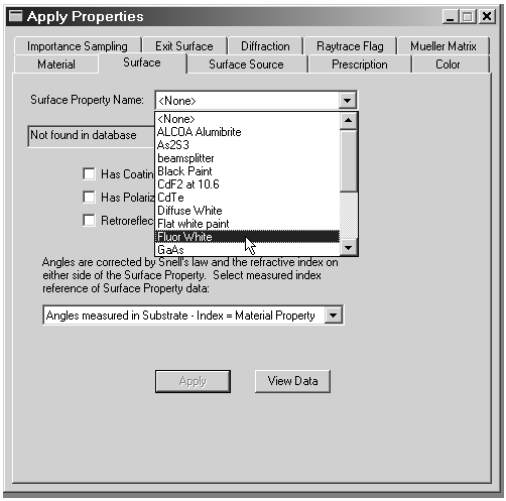


Figure 2.35 A window for assigning the characteristics of materials selectable from those available in the program library.

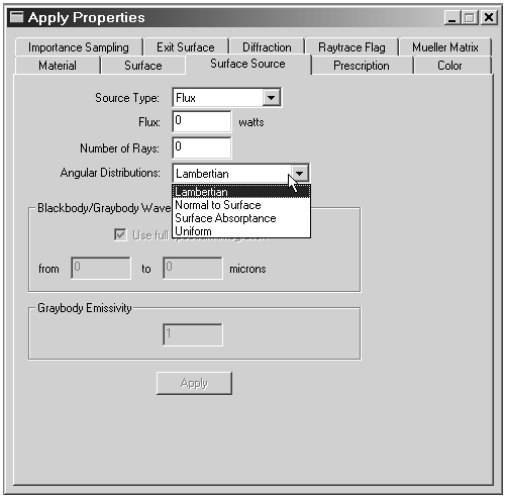


Figure 2.36 The window for defining the characteristics of light-emitting surfaces from light sources.

For opaque materials, the procedure for assigning values is simple. However, for emitting bodies, such as the linear fluorescent source, which is clearly visible in the 3D model as a cylinder, additional specifications must be introduced. The surface of the light source must be defined as a body emitting a luminous flux. This identification process is carried out by specifying the type of source, the luminous flux, the power, the amount of rays emitted and the angular distribution of the light, which in this case is assumed to be Lambertian as for all fluorescent sources.

Assuming that such a luminaire is equipped with a shielding glass, we should attribute to this object the property of transparency by defining two parameters: refractive index and absorption. In this case, the three-dimensional model cannot be defined by an infinitesimally thick surface and must therefore be realized as a solid volume.

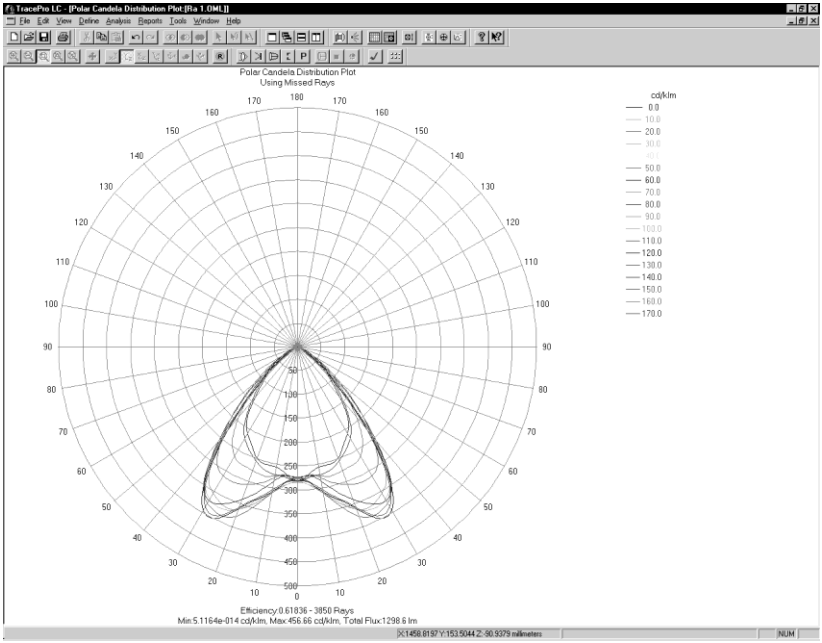


Figure 2.37 Result of the calculation of the light intensities emitted by the luminaire shown in a polar diagram, from which the set of C-gamma planes defining the photometric light solid characteristic of the luminaire is obtained. As can be seen, it is a luminaire with only direct light emission downwards.

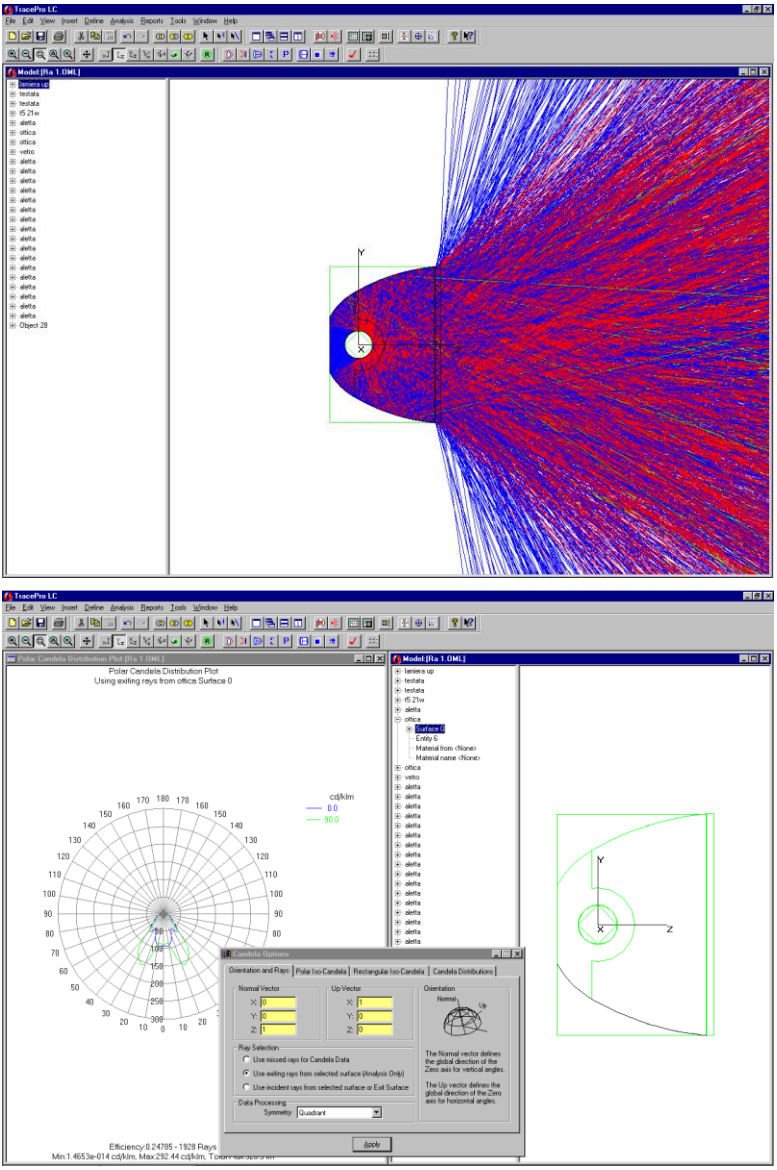


Figure 2.38 Top: Trace of the intensity levels of the luminous flux emitted by the luminaire. Below: Transformation of the reference coordinates.

Once all surface characteristics have been defined, the ray-tracing Monte Carlo calculation is started, at the end of which all useful results for the evaluation of the photometric properties of the luminaire can be obtained. In this example, it is possible to evaluate, in addition to the intensity diagrams, the iso-value curves of irradiance and illuminance calculated on the intended sample plane at an assigned distance from the luminaire.
In some cases, it is very useful to visualize the emitted flux as a ray tracing. Calculation software makes it possible to create diagrams in which the rays of greater luminous intensity are highlighted with the color red, and those of lesser intensity with the color blue. This representation makes it possible to immediately check the angle of the emitted intensities and to ascertain that the intensities emitted by the darklight reflector do not exceed 90° with respect to the primary axis of the luminaire. In addition, the software provides flexible handling of luminaire orientation; in the presented project, although the luminaire is positioned in an unconventional way, the calculation outputs, as well as the polar diagram of luminous intensities, can be reoriented by means of a Cartesian axis transformation.
With the most advanced software products, it is possible to use replicable modular geometric figures called RepTiles to simulate the behavior of BEF-type film. Brightness Enhancing Films are transparent films capable of increasing the luminance of a backlight source by focusing it in the desired direction. These are micro-structural elements that can be repeated thousands or even millions of times in order to improve the luminous performance of the object. With a classic CAD or Ray-Tracing program, it would be difficult, if not impossible, to model such structures. Using the RepTile functionality, the calculation software enables the modeling of these repetitive microstructures, of any size. The modeling approach used is also fully scalable, in the sense that the size of the series, i.e. the number of elements, does not affect the calculation time required at all.
The use of RepTiles finds useful applications in innovative lighting solutions for modern workplaces. Particular reference is made to channelled light systems, where the light source is remote, i.e. when the apparent source of light does not correspond to the actual location of the lamp. Luminaires using this technology allow for more flexible lighting management in offices. An application example of these technologies is the Aero luminaire designed by Sottsass Associati and produced by Zumtobel Staff. Recent developments in this device have been made possible by advances in adhesives that enable the perfect physical and optical bonding of a microprismatic film to an acrylic block that transmits light from the source.

Figure 2.39 - Example of the use of RepTiles. The Aero luminaire designed by Sottsass Associati contains two linear fluorescent sources closed at the sides, the light is channelled through a BEF-type film. Courtesy Zumtobel Staff.

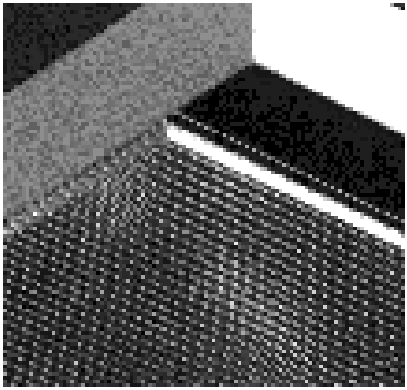


Figure 2.40 The Eldacon© optic consists of an acrylic block to which a BEF microprismatic film is applied. Courtesy Zumtobel Staff.

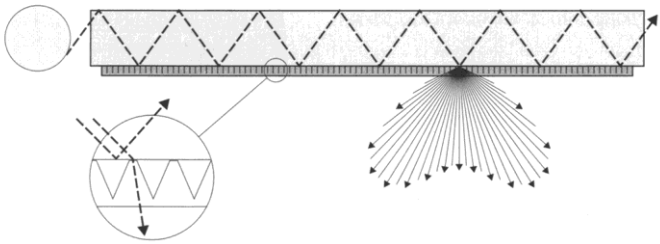


Figure 2.41 Functional principle of Eldacon© optics. Courtesy Zumtobel Staff.

The block transmits light from a linear fluorescent lamp solely by internal reflection, and the microprisms on the base distribute a controlled amount of light downwards in a classic batwing shape. Bat-wing. It is a form of the photometric solid that is widely used in a variety of lighting applications. Since the light is reflected and not refracted, there is no "fringing" of color, due to the phenomenon of chromatic dispersion, as in conventional prismatic luminaires. The result is a luminous surface in which the luminance is uniformly distributed over the microprismatic structure. The luminaire has no glaring effect as the light source is mounted on the side and is completely shielded from the observer. The same systems are widely used for all high-efficiency diffusing materials to conceal dazzling LED sources and direct the light in the product's intended directions of use.
These programs also provide the simulation of the operation of non-imaging sunlight concentrators such as CPCs (Compound Parabolic Concentrators). Such devices provide an efficient method of concentrating solar flux and harnessing its energy for a variety of uses. They are therefore advantageous when used to support applications requiring temperatures from 80 °C to over 300 °C. These are both domestic and industrial applications, such as water heating, power generation and desalination. The factors influencing the design of solar energy concentrators include:

- Cost and ease of manufacture on an appropriate scale.
- Large guides that make it possible to follow the movement of the sun.
- Duration and maintenance.
- Working temperatures required by the absorber.
- Better absorber geometries in relation to the type of energy utilisation.
- Susceptibility to contamination and durability of materials following ultraviolet irradiation.

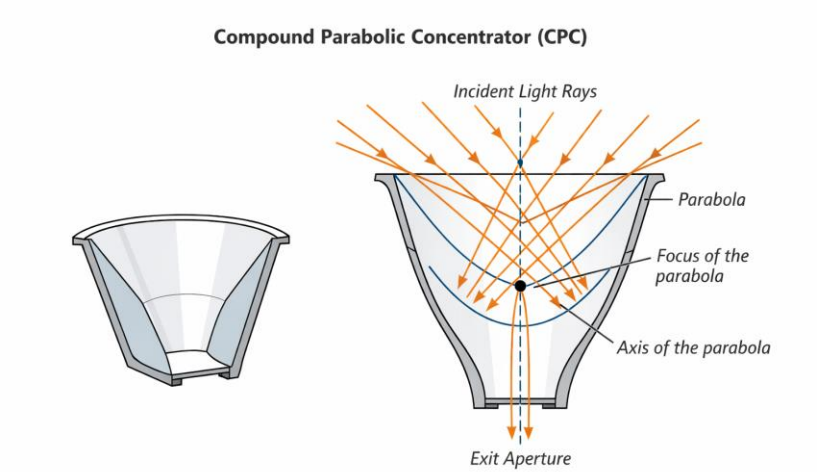


Figure 2.42 In the CPCs, the parabolic profile of the reflectors ensures maximum downward channeling of sunlight.

These programs have multiple applications in optical light management. Indeed, they have the ability to simulate not only all types of lighting systems, luminaires and light sources, but also all types of display systems, from backlit screens to liquid crystal displays as well as laser diodes, as visibility sources and for signaling purposes. The three most popular calculation software in this area are Optis, Photopia and TracePro.

2.4 Conclusions

The progressive integration of digital tools into lighting design has profoundly transformed both professional practice and educational methodologies. As discussed throughout this chapter, computer-based systems are not merely operational aids, but structured environments in which quantitative verification, qualitative assessment and design intent converge. Lighting CAD software enables the rigorous evaluation of illuminance, luminance, glare and energy-related parameters, supporting compliance with standards while reducing uncertainty in decision-making. At the same time, rendering tools—when used with methodological awareness—offer a perceptual complement to numerical analysis, helping

designers interpret spatial atmospheres without confusing visual plausibility with photometric accuracy.

The case studies presented demonstrate that virtual measurement tools can effectively support complex interior configurations, provided that geometric modeling is simplified and reflection parameters are carefully controlled. The balance between computational precision and manageable calculation times remains a critical aspect of workflow optimization. Moreover, the integration of luminaire databases and photometric archives reinforces the connection between design hypotheses and real industrial products, strengthening the link between concept and feasibility.

Optical simulation software extends this framework to the product scale, allowing designers and manufacturers to investigate light distribution, material behavior and photometric performance before physical prototyping. Ray-tracing Monte Carlo methods, BRDF/BTDF modeling and solid-based geometric systems such as ACIS establish a technically robust environment for analyzing the interaction between light and matter. Although recent advances in GPU computation and deep learning promise further improvements in efficiency and realism, current professional tools already provide a reliable platform for virtual prototyping.

Ultimately, digital lighting design should be understood not as a replacement for critical judgment, but as an amplification of it. The effectiveness of these technologies depends on the designer's ability to interpret results, understand their limits and integrate quantitative metrics with perceptual evaluation. When approached with scientific rigor and methodological clarity, digital tools become essential instruments for achieving lighting solutions that are technically sound, visually coherent and responsive to human experience.

2.5 Conflict of interest declaration

The author declares that there are no actual or potential conflicts of interest related to this chapter. Specifically, no financial, personal, or professional relationships with individuals or organizations have influenced, or could be perceived to have influenced, the content, analysis, or conclusions presented herein. The research and writing of this chapter were conducted independently and objectively. The author confirms that no competing interests exist within the meaning of the RCASB guidelines.

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The author declares that no specific funding, grant, or financial support was received for the study, research, or preparation of this chapter. No external sponsor had any role in the design, analysis, interpretation, writing, or decision to submit the manuscript. The work was carried out independently and without financial support from public, commercial, or non-profit funding agencies.

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3. Lighting Design and Building Information Modeling

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Abstract

This chapter explores the integration of lighting design within Building Information Modeling (BIM) workflows, focusing on the tools and methodologies currently available for lighting verification and performance evaluation. Although BIM is widely adopted for coordinating architectural and engineering disciplines, lighting design remains only partially integrated into BIM authoring environments and often relies on external software or proprietary add-ins. The chapter distinguishes between Closed BIM approaches, based on integrated plugins, and Open BIM workflows, which use standardized interoperability formats such as IFC. Through the analysis of representative tools — including ReluxCAD, ElumTools, LightStanza, V-Ray, DIALux evo, and IES Virtual Environment — the strengths and limitations of these approaches are discussed in terms of interoperability, analytical scope, workflow continuity, and data resilience. Particular attention is given to the disciplinary positioning of lighting design, the distinction between normative verification and visualization, and the limitations of digitally mediated simulations, especially regarding color reproduction. The chapter concludes that no single software solution currently satisfies all the requirements of BIM-based lighting design, highlighting the need for methodological awareness and informed tool selection.

Keywords:

BIM, Lighting design, Lighting verification, Open BIM, Closed BIM, Interoperability, Lighting simulation

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3.1 Introduction

For many years now, the field of building design has been talking about BIM and the transition from Computer Aided Design (CAD) to this new methodology. There is no doubt that the transition from traditional design with a drafting machine to CAD was a sort of epoch-making revolution in design methodology. Now the move from CAD to BIM represents a second and equally important revolution in this area. However, this change initially struggled to take place in Italy, while in the USA and other European countries it found greater development. Finally, in recent years, Italy too is seeing an increasing use of this design methodology, thanks also to regulatory obligations that were initially low, but are now becoming more and more present every year, especially in public procurement.

But what does BIM mean and why is it important that lighting design is part of it? The National Institutes of Building Science defines it as the digital representation of physical and functional characteristics of an object and, in a more specific sense, of a building (NIBS, 2021). Many people mistakenly think that it is a software or a particular technology. Instead, it is a process in which all information about the object/building/space to be created is organized. It is a platform in which it is possible to collect and enter both graphic data and technical documents such as specifications, schedules and bills of quantities, relating to the design and also the maintenance phase of the building, thus covering its entire life cycle.

All this information is gathered by combining the traditional graphic information of a given architectural element being designed, such as windows, walls, additional information such as volume, dimensions, materials used, shapes, thermal transmittance, acoustic insulation and other technical data of the building and its systems. This data collection constitutes the real and intrinsic innovation of the BIM methodology compared to the previous CAD. It does not stop with the finished project, but accompanies the completed building also in the subsequent phase of use of the asset, also managing and planning its various maintenance operations.

A further strength of the BIM methodology is its strong collaborative networking component. The information is available in a single template and is accessible, at any time, to professionals working together in the various design sectors. Architects, engineers, system designers, fitters, testers, construction companies, accountants and others can take full advantage of this continuous, up-to-date flow of data.

The project in the BIM process is therefore comparable to a virtual and dynamic prototype, is a database for the design, implementation and maintenance of the building (Alesi, 2021). Classic CAD software is no

longer sufficient to manage this information, but specific applications are required. In addition to modeling a virtual replica of the building being designed in 3D in a simple and intuitive way, this software can manage the project database, providing for phases, variants, management and revision/maintenance of the building to be constructed. One of the most popular applications supporting the BIM methodology is certainly Autodesk Revit (Stine, 2021). For Lighting Design applications this needs to be integrated with the V-Ray for Revit software plugin, which is dedicated to light calculation, rendering and technical representation of the lighting design (Sannino, 2019).

Within this application, there are a number of tools that make it possible to quickly and immediately assemble the project model by means of a virtual replica of the main architectural components such as walls, windows, doors, openings, floors, ceilings, roofs, pillars, railings and other details of the project.

If not all the components to be used in the project are natively present in the program or in its proprietary library, it is always possible to download the BIM model of the missing component from the sites of the various suppliers, if the company has made it available. These components, in the case of Revit, are called Families (Getuli, Bruttini and Rahimian, 2025). If, in the worst case, this is not available, there is an editor in the software with which we can create our own families from scratch. Once this model of the project has been created, access to the information collected there can be provided in different ways. By means of graphic tables such as plans, elevations, sections, axonometric views, perspective views and renderings, but also by means of technical reports such as metric calculations and schedules, or directly accessing the model and its components, depending on the level of interoperability achieved by the BIM methodology.

3.2 BIM and lighting

The lighting design process consists of numerous aspects that are not limited to criteria related to good lighting engineering practice, which ensure adequate levels of safety, performance, and energy efficiency. Factors such as the influence of light on human physiology and psychology have expanded the range of skills required to achieve an optimal lighting design (Rossi, 2019). Technologies are also becoming increasingly diverse, ranging from those related to light sources and their control to the prospective integration of technologies such as artificial intelligence.

This complexity inevitably affects the difficulty of achieving standardization in lighting design (or at least in its minimum requirements).

In Italy, the standard UNI 11630:2016 aims to define the criteria for the preparation of a lighting design project (UNI, 2016). It describes the various phases of the project, the operations to be carried out, and, of course, the required deliverables. Design software is mentioned only in very general terms, without reference to specific products; moreover, as a standard published in 2016, it does not integrate BIM methodologies, which were gradually introduced into public procurement with Legislative Decree 560 of 2017 (MIT, 2017). This highlights that, in Italy, the choice of the most suitable software tools for BIM-based lighting design is not yet subject to specific regulations. It is therefore up to designers to use the tools they consider most appropriate to integrate the various steps of the lighting design process within a methodology compatible with what is described in the various chapters of the European standard (UNI/EN, 2019) and further Italian implementation (UNI, 2025), which governs BIM.

In this growing adoption of the BIM methodology, lighting design is unfortunately still not considered on a par with other disciplines involved. It is still under development and is not natively envisaged within the various commercially available software. For example, in Revit there is no separate entry for lighting, which is generally covered by the Mechanical, Electric and Plumbing (MEP) section (Leite, 2019).

It is possible to insert appropriate families as luminaires. These may be present in the program's proprietary library or they may be found on the websites of the sector's manufacturers where available, like any other architectural component. The first case is actually of little interest, since the models present, although sometimes recalling models that really exist on the market, do not have verifiable information and can only be used in the meta-design phase or in the very first project hypothesis. The second case, i.e. the families of luminaires downloadable from the suppliers' websites, is certainly preferable but not always feasible, limiting the designer to the use of only the available luminaires or to 3D modeling of them. This operation implies a good knowledge of the family modeling environment and the need, absent in other types of architectural components, to also associate photometric data such as photometric solids and correct correlated color temperatures (CCT).

The inclusion of 3D models of luminaires in BIM software, however, does not solve the problem of lighting design. There is a lack of tools for calculating and verifying light. Lighting CAD software programs allow us to make rough calculations of how many luminaires to use in order to obtain a certain amount of light in a room, in compliance with the regulations in force. They can also produce false-color technical images or data grids

superimposed on rendered images, which are useful for checking how much illuminance and luminance can be expected in the environment of the lighting scheme assumed by the designer. None of this is possible today in BIM software. This can only be done with additional plugins.

Some of the main BIM authoring software packages, such as Revit (Autodesk, 2025), Archicad (Graphisoft, 2025), AllPlan (Allplan, 2025), Tekla Structures (Trimble, 2025b), and others, natively include the ability to calculate lighting in a realistic — though not always photometrically accurate — way, by importing the photometric data of lighting fixtures, mainly in the .ies format, promoted by the Illuminating Engineering Society (ANSI/IES, 2025).

The basic tools available within these software platforms are often insufficient to provide adequate information for a proper description of a lighting design project, generally offering at most illuminance values, the luminous flux incident on surfaces, in the form of false-color maps or numerical grids. Clearly, this does not allow for an effective evaluation of the parameters required to comply with standards such as the EU standard for indoor lighting, for the lighting of indoor workplaces (CEN, 2021) or outdoor workplaces (CEN, 2014). It is plausible that, over time, the digital tools available to lighting designers within BIM environments will become more refined, complete, and easier to use. At present, however, there is still no truly recognized approach for lighting verification within BIM, and multiple pathways are available from which the designer may choose.

Lighting verification of projects has traditionally relied on software tools that allow compliance with applicable standards to be assessed. To mention just a few of the most widely used: Dialux Evo by DIAL GmbH (DIAL GmbH, 2025a), Relux by RELUX Informatik AG (RELUX Informatik AG, 2025a), AGi32 by Lighting Analysts/Revalize (Lighting Analysts - Revalize, 2025a) and Litestar 4D Suite by Oxytech Srl (OxyTech, 2025). However, the software listed above was originally developed with the aim of performing comprehensive lighting calculations as standalone tools. They were not initially designed to be part of federated workflows and, as a result, their integration with BIM authoring software is relatively recent and, in some cases, not yet fully optimized.

Some software companies specializing in lighting verification tools have chosen to include options in their programs to open IFC (Industry Foundation Classes) files, allowing verification to be carried out in software external to BIM authoring platforms (ISO, 2024). This approach enables developers to focus their efforts almost exclusively on their own product, avoiding the constraints associated with developing add-ins for third-party

software such as Autodesk Revit. Another advantage is the ability to maintain a workflow with which users are already familiar, without the changes that would inevitably result from integration with another software platform. Another important aspect concerns the company's pricing strategy: integrating the functionalities of proprietary software into a third-party application would require rethinking how end users and all stakeholders in the supply chain pay for the product, since this would effectively create an additional product (the add-in), requiring developers to make decisions regarding licensing models.

Choosing to import a standard interoperability file from a BIM authoring software implies that the lighting verification program must be capable of reading the IFC format or, ideally, other open exchange formats such as COBie (buildingSMART International, 2025a). IFC is a data format developed by buildingSMART International (buildingSMART International, 2025c), a non-profit organization focused on the standardization of BIM processes, and its purpose is to promote data interoperability within the Architecture, Engineering, and Construction (AEC) sector, regardless of the BIM authoring software selected for a given project. IFC is an open format that contains numerous variables — such as dimensions, materials, location, and more — used to describe all the elements that make up a project, from walls and doors to windows and beyond. Moreover, the use of IFC files removes the dependency on specific software tools: should a program be discontinued in the future, the data contained in the IFC file can be read by another application, thereby increasing the longevity of project assets. This type of approach allows all the teams involved in the project to start from a common baseline (the IFC file) and to use specialized software — such as lighting verification tools — to include the results obtained within the Common Data Environment (CDE) and the project's BIM authoring software. This approach is often referred to as Open BIM.

As an alternative to the approach described above, other software companies have chosen to develop add-ins for specific programs used within the BIM process. This choice fits into a context in which all project teams are required to use the same proprietary software, which must therefore include all the functionalities needed to carry out the required activities. Alternatively, it is possible to rely on other specialized software, but through a direct connection with the BIM authoring platform, without using IFC files. These processes are commonly referred to as Closed BIM. Lighting verification is therefore carried out within the BIM authoring software selected for the project, or through an externally connected

program, without any export or import operations. In this way, interoperability formats such as IFC are not used, but data management among all project stakeholders can potentially be more uniform, since the results are returned directly to the BIM authoring software with a reduced risk of import or export errors.
The IFC interoperability format, in fact, contains a finite (albeit extensive) set of data, which does not include all the types of parameters generated by the BIM authoring software available on the market. This inevitably leads to the loss of some information when moving from one software environment to another. This does not occur when such transfers are avoided, because all operators use the same software or direct communication channels with the BIM authoring tool. Both approaches make it possible to achieve high levels of digital maturity, which are necessary for the application of BIM methodologies, and each presents both strengths and weaknesses. In the following sections, some tools for lighting verification of projects within the BIM context will be described.

3.3 Proprietary BIM solutions

The systems described in this section refer to what is commonly defined as Closed BIM or Proprietary BIM. In this approach, the various project teams interact with one another exclusively through the BIM authoring software. This software must be equipped with all the tools necessary to evaluate the required parameters, or it must provide a direct connection to external modules that supply verification data, without the need to use standard IFC files.
Project size, client requirements, applicable regulations, and certifications to be obtained clearly affect project complexity; however, even the simplest commissions involve numerous teams that must contribute: architects, engineers, designers, electrical distribution, lighting, HVAC, plumbing, fire protection, networks, construction, and so on. If all parties are required to work within the same BIM authoring software, it is evident that the platform must provide tools that allow each discipline to carry out the necessary verifications. It is known that software with such a high number of functions is also complex to learn and to use (Ho *et al.*, 2012; Ullah, Witt and Lill, 2023).
BIM authoring software provides numerous tools that can be used by the different project teams, and these tools may also vary across different versions of the same software, some being more oriented toward building design and others toward building services. However, no matter how many

parameters a software platform may offer, they are never sufficient to allow in-depth analysis across all disciplines.

Lighting design, for example, in software such as Autodesk Revit, can be verified — at least partially — in accordance with the EU standard (CEN, 2021). It is possible to import lighting fixtures, or families thereof, created by manufacturers or reconstructed by users using photometric files, in the *.ies format, and the geometric models of the fixtures. Evaluations related to building services, such as electrical load consumption, or to the total luminous flux produced by the fixtures can be performed, and by using Revit's online rendering engine it is possible to generate non-photorealistic images that provide information on the illuminance levels present in the scene. However useful these data may be, they are by no means sufficient to carry out a comprehensive assessment of compliance with the standard for lighting in workplaces.

When considering the advantages, it should be noted that the parameters stored in files generated by BIM authoring software do not suffer from information loss, since they do not need to pass through export and subsequent re-import using non-proprietary formats. During conversion to IFC, or during subsequent import into other software, in fact, some data generated by BIM authoring tools may be lost.

Some software vendors, in order to extend lighting verification capabilities within a Closed BIM context, have developed add-ins, that is, specialized modules integrated directly into BIM authoring software. In the following sections, the most widespread add-ins currently available on the market will be analyzed.

3.3.1 ReluxCAD for Revit

Developed by Relux Informatik AG, ReluxCAD is an add-in for Autodesk Revit and was released in 2018. It is presented as the first software in the world capable of bidirectional communication with the BIM environment (RELUX Informatik AG, 2025b). The module is installed directly within the Revit interface, in a dedicated ribbon, and is able to communicate with Relux Desktop, a separate specialized application dedicated to lighting verification. This communication takes place without data loss; however, it relies on proprietary software. Unlike IFC-based export, communication can occur exclusively between the two software products developed by Relux Informatik AG. For this reason, this bidirectional communication cannot be considered part of the Open BIM approach (Chatsuwan *et al.*, 2025). When the communication with Relux Desktop is used, the tools available to the designer allow for in-depth control. However, even when using only the

add-in installed in Revit, it is still possible to verify that the project complies with lighting standards. The tools are clearly more limited in this case, but they remain more advanced than Revit's default tools.

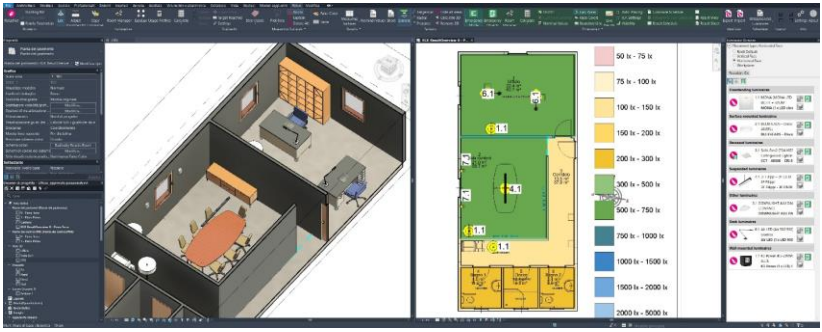

Figure 3.1 The ReluxCAD control ribbon interface for Revit.

The add-in is connected to an online luminaire database called ReluxNet, owned by Relux Informatik AG. After registering on the module's website which is required in order to use it, users can browse the database to find luminaires, or luminaire families, using search filters based on various parameters, such as emission type, application, location and mounting type, shape, and so on. When a luminaire is selected, its product data sheet is displayed, summarizing its main characteristics. At this point, the product can be compared with others available in the database or implemented in the working space. In addition to the proprietary ReluxNet database, the module allows communication with Building360, an online catalog of BIM families that also includes electrical, ventilation, architectural, and sanitary components (Building360, 2025). Once the luminaires have been imported into the model and carefully positioned on the appropriate surfaces floors, walls, or suspended ceilings, various operations can be performed on them; for example, showing or hiding the photometric solid, modifying the installation height, organizing elements, and so on.

Clearly, each space referred to as a "room" in Revit must be assigned a usage profile corresponding to those defined by the applicable standard (CEN, 2021) in this way, once the calculations have been performed, the module is able to verify compliance with the requirements set out by the standard. A luminaire layout suggestion tool, Easylux, based on the total flux calculation method, Zonal Cavity Method (Robinson, 1976), is also available. The module also includes a section dedicated to the control of

stairway lighting. It is also possible to set parameters related to the standard, such as the reflectance indices of floors, walls, and ceilings, to define an offset for the generation of calculation grids, and to set the maintenance factor.
To graphically represent the calculated results, ReluxCAD for Revit can generate surfaces, on the primary surfaces of rooms and on other surfaces selected by the user, that allow illuminance distributions to be visualized through false-color maps or numerical grids. All project data can then be displayed in Revit schedules and exported to technical drawings. Additional tools include the insertion of sensors into the project to define presence-detection areas and a dedicated section for the calculation and verification of emergency lighting.

3.3.2 Eulumtools for Revit

The Revit add-in developed by Lighting Analysts/Revalize, unlike ReluxCAD, is not intended for bidirectional communication with other software. Although the company also produces a specialized standalone application (Revalize, 2025), the add-in was designed to cover all the steps required for lighting design directly within Revit. In this case as well, no exports to external software using the IFC format are provided; the file is initialized within the module, which retrieves all the necessary information from the existing elements and requests any missing data.

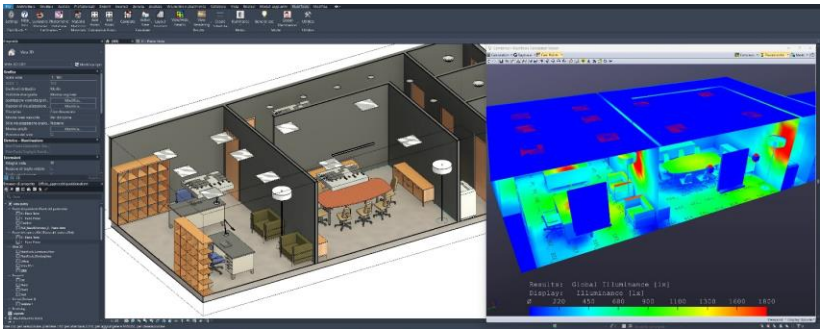

Figure 3.2 The control ribbon interface of ElumTools for Revit.

First, the module analyzes any lighting fixtures already present in the scene, which must necessarily include a photometric file, in the *.ies format, and other parameters such as the maintenance factor, the Light Loss Factor

(LLF) (Royer, 2014), the luminous flux, and so on. It is also possible to use the online database provided by Lighting Analysts/Revalize, called Instabase, to select luminaires from numerous manufacturers available on the market and send them directly to the module (Lighting Analysts - Revalize, 2025b).
The next step is the verification of the materials present in the model, a crucial phase for the correct calculation of light distribution. Unlike ReluxCAD, where it is possible to choose whether the main surfaces inherit materials from Revit or to assign them arbitrarily, ElumTools includes a dedicated editor View Project Materials, that allows users to verify that the materials listed in Revit's Graphics settings are correctly configured. In this section, it is in fact possible to modify color and reflection, transparency, and translucency properties, in order to create materials that respond correctly to light.
As regards calculation surfaces, ElumTools can also automatically generate calculation grids based on room selections or individual surfaces. The main difference compared to ReluxCAD is that, in addition to being displayed within Revit view windows, the results can be interactively explored in a separate window, the ElumTools Calculation Viewer, where different visualization styles can be selected: false colors or grayscale, for both illuminance and luminance, isolines, grid values, and even the visualization of the radiosity mesh used by the module for calculations (Greenberg, Cohen and Torrance, 1986).
All the commands necessary to verify the values required by workplace lighting standards are also available. Additional tools provided by the module include a Layout Assistant for suggesting luminaire placement using the total flux method, Zonal Cavity Method (Robinson, 1976), a tool for emergency lighting calculations, one dedicated to daylight calculations, and another for horticultural lighting design, where evaluations are expressed in Photosynthetic Photon Flux (PPF) (Ke *et al.*, 2022), in micromoles per second, typically provided by the manufacturer or in PPF Factor, micromoles per second per Kilo Lumen.

3.3.3 LightStanza

LightStanza is a web-based lighting analysis tool that operates through a bidirectional synchronization principle similar to that of ReluxCAD for Revit (LightStanza, 2025).
From the developer's website, it is possible to download dedicated plugins that can be installed in various software platforms such as Revit, making it directly applicable within a BIM workflow, as well as in modeling

environments such as Rhinoceros (Robert McNeel & Associates, 2025) and SketchUp (Trimble, 2025a). Once the plugin is installed in the host software, the model can be exported in a proprietary LightStanza format and uploaded to a browser-based environment, where lighting verification tasks are carried out remotely.

The platform is designed to support both daylight and electric lighting analyses through a cloud-based computational infrastructure. Calculations are performed online, allowing users to evaluate illuminance distributions, daylight availability, temporal variations of natural light, and lighting performance indicators without relying on local computing resources. This approach enables complex simulations to be executed efficiently, even for geometrically articulated models, while maintaining a relatively streamlined user experience compared to traditional desktop-based lighting simulation software. In addition to standard lighting verification tasks, LightStanza provides tools for editing luminaire families, for example to correct photometric data or resolve inconsistencies in lighting fixtures imported from BIM families. A sandbox mode is also available, allowing users to isolate limited portions of a project in order to test alternative lighting solutions or perform focused analyses without recalculating the entire model. When changes are introduced within the LightStanza environment, the updated data can be transferred back to the original BIM model through commands such as “Send changes to Revit,” enabling a form of iterative design feedback between the analysis environment and the authoring software.

From a disciplinary standpoint, LightStanza should be interpreted as a performance-based lighting analysis tool rather than a rendering engine or a generic visualization platform. Its primary purpose is the quantitative evaluation of lighting conditions, including daylight metrics, glare risk, and compliance-oriented performance indicators often associated with sustainability assessment frameworks. While the system is capable of producing visual outputs that support the interpretation of results, these visualizations are subordinate to analytical objectives and should not be confused with photorealistic rendering processes typical of visualization engines such as V-Ray. Similarly, although LightStanza overlaps functionally with established lighting CAD software such as DIALux, Relux or IES VE in terms of illuminance calculations and verification tasks, its operational logic differs significantly. The reliance on proprietary data formats and cloud-based computation places it outside open interoperability workflows. As a consequence, despite its tight integration with BIM authoring tools, LightStanza must be classified as a Closed BIM

methodology, where data exchange is optimized for efficiency and usability rather than for long-term openness or cross-platform standardization.

3.3.4 V-Ray Lighting analysis

Among proprietary BIM add-ins available for Autodesk Revit, V-Ray stands out as a particularly advanced tool for rendering that could be also used for lighting design visualization and analysis (Sannino, 2019). Its relevance within a BIM-based workflow lies primarily in two complementary areas: the generation of high-quality, photometrically reliable rendered images, and the support of lighting analysis through technical visualizations such as false-color maps and numerical grids for illuminance and luminance. From a methodological perspective, V-Ray does not replace dedicated lighting calculation software, nor does it aim to redefine the BIM authoring environment. Instead, it operates as a specialized extension that enhances Revit's native capabilities, addressing some of its intrinsic limitations in the simulation of light–material interactions and in the visual evaluation of lighting scenarios.

V-Ray integrates directly into the Revit interface, preserving the continuity of the BIM model and avoiding the need for external data exchange or interoperability files. This makes it a typical example of a Closed BIM approach, in which lighting verification and visualization are carried out within the same authoring environment used by the design team. The plugin leverages Revit's existing geometry, cameras, and lighting fixtures, while introducing a rendering and analysis engine capable of handling more advanced photometric and material behaviors. This integration allows designers to work on lighting evaluations without disrupting the collaborative structure of the BIM process or duplicating project data in external software.

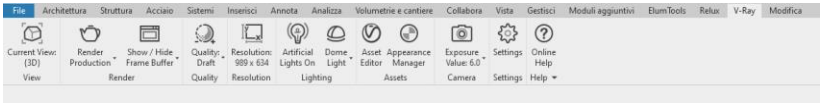

Figure 3.3 V-Ray tab integrated into the Autodesk Revit ribbon interface.

One of the main strengths of V-Ray is its ability to generate renderings that are not only visually convincing, but also based on physically meaningful light simulations. Unlike purely illustrative rendering engines, V-Ray is designed to support photometrically correct synthesis images, making it suitable for both communication purposes and technical assessment.

Lighting fixtures used in the model are those already defined in Revit; however, for correct results, it is essential that they include manufacturer-provided photometric data, typically in the form of *.ies files (ANSI/IES, 2025). These files define the real luminous intensity distribution of the luminaire and constitute the basis for both visual rendering and lighting analysis. By relying on these data, V-Ray enables simulations that are consistent with real-world lighting performance, especially in cases where Revit's native rendering engine proves insufficient. This aspect is particularly relevant for luminaires with complex emission patterns, such as direct–indirect or asymmetric fixtures. In such cases, the interaction between the photometric solid and the geometric model of the luminaire can significantly affect the accuracy of the simulation. V-Ray addresses this issue by providing material and rendering controls that allow the photometric distribution to be represented without being incorrectly obstructed by the luminaire geometry.

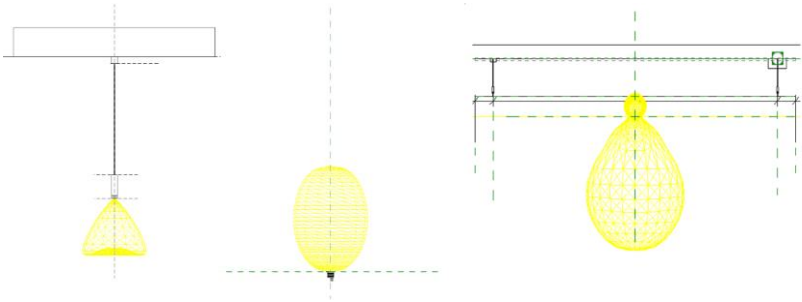

Figure 3.4 Examples of luminaires with direct, indirect, and direct–indirect light emission patterns.

V-Ray supports different lighting scenarios within the BIM model, including natural lighting, artificial lighting, or a combination of both. Daylight simulations are based on physically plausible models of sunlight and sky conditions, allowing the designer to evaluate lighting performance under specific geographic locations, dates, and times. Artificial lighting simulations rely on the accurate interpretation of luminaire photometric data and their interaction with the surrounding environment. In both cases, the rendering output is influenced not only by the characteristics of the light sources but also by the optical properties of the materials present in the scene. This highlights the importance of material management in achieving reliable results.

A key contribution of V-Ray to the lighting design workflow is its support for physically based materials. While Revit materials are fully compatible with the plugin, V-Ray provides its own material system optimized for realistic light interaction and efficient rendering. Importantly, this system does not alter the BIM data structure: Revit materials remain unchanged in the project database and are temporarily substituted by V-Ray materials only during the rendering and analysis phase. This approach ensures that the semantic and informational integrity of the BIM model is preserved, while allowing lighting simulations to benefit from more advanced optical properties. V-Ray materials are based on physically grounded principles, such as energy conservation, which governs the balance between reflected (Koppal, 2014; Tan, 2014), absorbed, and transmitted light (Ikeuchi, 2014a, 2014b). By enforcing these principles, the plugin reduces the risk of visually appealing but physically implausible results.

The correct definition of material properties is essential for lighting analysis, as surface reflectance has a direct impact on indirect illuminance levels and, consequently, on both visual comfort and energy performance. Materials with higher reflectance contribute more significantly to the distribution of indirect light, affecting the overall perception of brightness in an environment. V-Ray makes these interactions explicit and controllable, supporting a more informed evaluation of design choices.

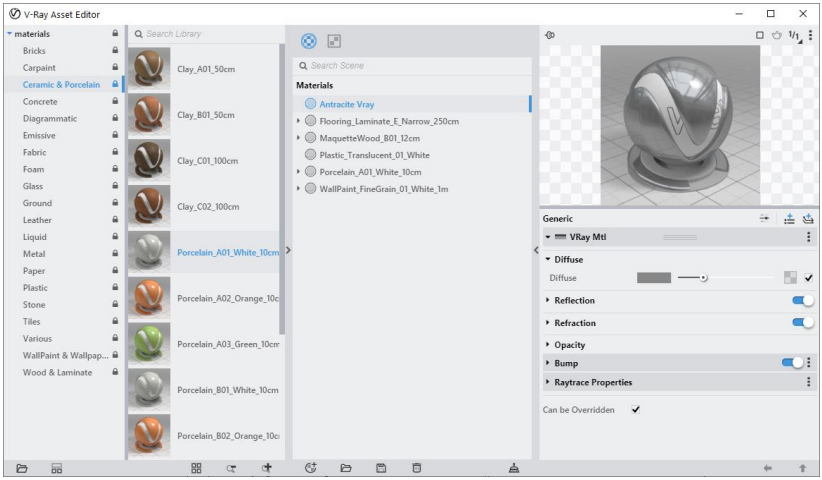

Figure 3.5 V-Ray Asset Editor, showing the organization of materials between library, project assets, and parameter editor.

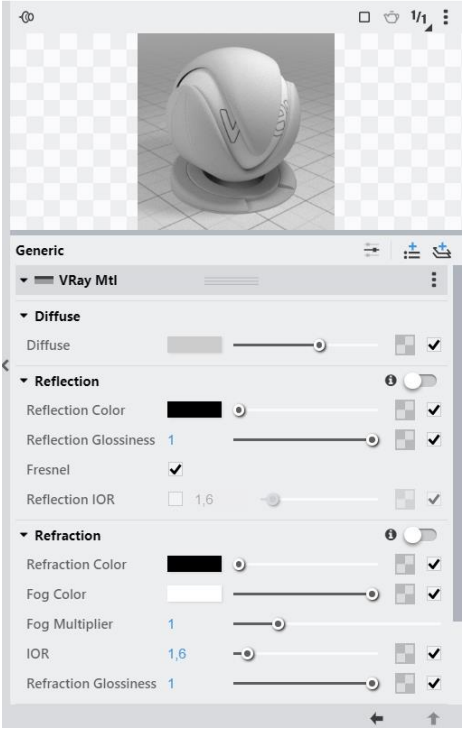

Figure 3.6 V-Ray Material Editor, used to define physically based material properties.

Despite the use of physically based rendering engines and photometrically accurate lighting data, the digital reproduction of color remains a critical and unresolved issue in lighting design. Color appearance is not determined solely by illuminance or luminance values, but emerges from the complex interaction between the spectral power distribution of light sources, the spectral reflectance of materials, and the perceptual mechanisms of human vision. Most rendering pipelines, including those used in advanced BIM-integrated tools, rely on simplified RGB-based models that cannot fully represent these interactions. As a result, rendered images — while physically plausible — inevitably introduce perceptual approximations that limit their reliability when supporting color-related design decisions. These limitations have been discussed in the literature on digital color reproduction in architectural and lighting visualization, highlighting the

need for critical interpretation of rendered outputs within the design process (Guarini and Rossi, 2021, 2024).

In addition to accuracy, V-Ray is known for the high visual quality of its renderings and for its efficient use of computational resources. The plugin offers different quality levels and rendering modes, allowing designers to balance calculation time and image fidelity according to the needs of the design phase. Low-quality settings can be used for rapid assessments and iterative checks, while higher-quality renderings are suitable for final evaluations and presentation purposes.

The rendering engine also accounts for global illumination effects, simulating multiple light bounces between surfaces. This capability is fundamental for realistic interior lighting simulations, where indirect light often represents a substantial portion of the total illuminance. By accurately modeling these effects, V-Ray provides a more reliable visual and quantitative representation of lighting conditions than standard BIM tools.

Within the broader landscape of BIM-based lighting tools, V-Ray occupies a specific position. It is neither a full-featured lighting calculation software nor a simple visualization add-on. Rather, it acts as an intermediate tool that bridges the gap between technical lighting analysis and high-quality visual representation, operating entirely within the BIM authoring environment. For this reason, V-Ray is particularly suited to workflows in which close integration between architectural modeling, material definition, and lighting evaluation is required. Its strengths lie in the combined management of geometry, photometric data, and physically based materials, enabling designers to assess lighting scenarios with a high degree of visual realism and technical consistency, without leaving the BIM platform.

In addition to high-quality visual renderings, V-Ray provides a set of tools specifically aimed at supporting lighting design verification within the BIM environment. These tools are grouped under the Lighting Analysis functions and allow designers to generate technical visualizations commonly used in lighting engineering practice, such as false-color maps and numerical grids for photometric quantities.

The analysis capabilities focus primarily on two fundamental quantities: illuminance, expressed in lux, and luminance, expressed in cd/m². These representations are not intended to replace full lighting calculation software, but rather to offer a qualitative and semi-quantitative assessment of lighting performance directly within the BIM authoring platform. In this sense, V-Ray occupies an intermediate position between purely visual rendering tools and specialized lighting CAD applications. False-color visualizations are particularly useful for understanding the spatial distribution of light on

relevant surfaces of the project. By mapping photometric values to a color scale, they allow the designer to quickly identify areas of under- or over-illumination and to evaluate whether the overall lighting concept is consistent with the intended visual tasks and applicable standards. The effectiveness of these representations depends on the appropriate definition of the reference scale, which should be selected to avoid out-of-range values and to maximize the readability of the distribution. While these tools provide valuable quantitative feedback on lighting performance, they do not address issues related to color appearance and perceptual fidelity, which remain critical aspects of digitally mediated lighting design (Guarini and Rossi, 2024).

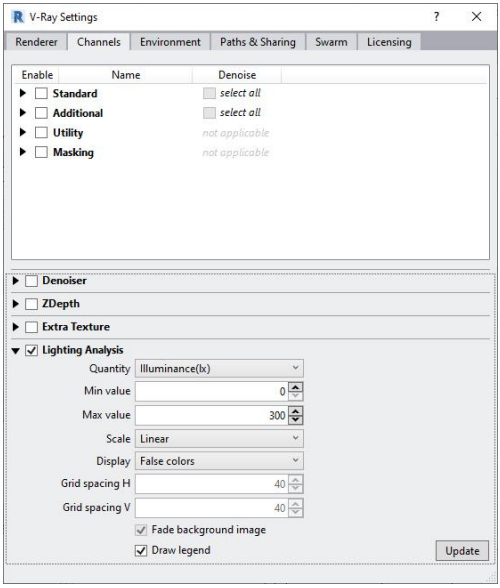

Figure 3.7 V-Ray Lighting Analysis settings used to generate false-color maps and numerical grids for photometric quantities.

When applied to illuminance, false-color maps are typically used to assess task areas such as work surfaces, circulation zones, or architectural elements that play a functional or perceptual role in the space. The goal is not only to verify compliance with target values, but also to understand the uniformity and balance of light distribution across the environment.

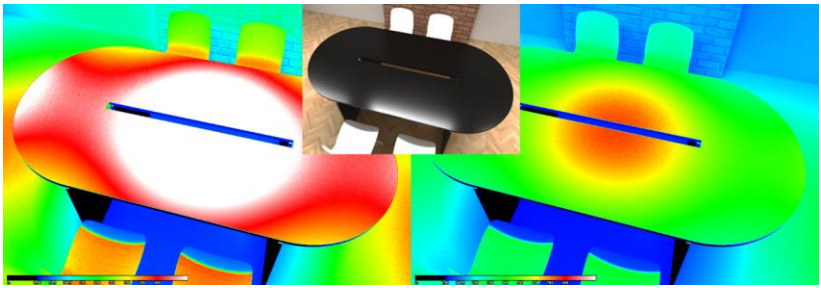

Figure 3.8 False-color representation of illuminance, showing the effect of different reference scales on the readability of the results.

Luminance analysis, on the other hand, is more closely related to visual perception and comfort. By visualizing the brightness of surfaces as perceived by an observer, these representations are particularly useful for evaluating situations where high contrast or glare may occur, for example in the presence of direct daylight or bright openings. Due to the often wide dynamic range of luminance values, the choice between linear and logarithmic scales plays a significant role in the interpretation of results.

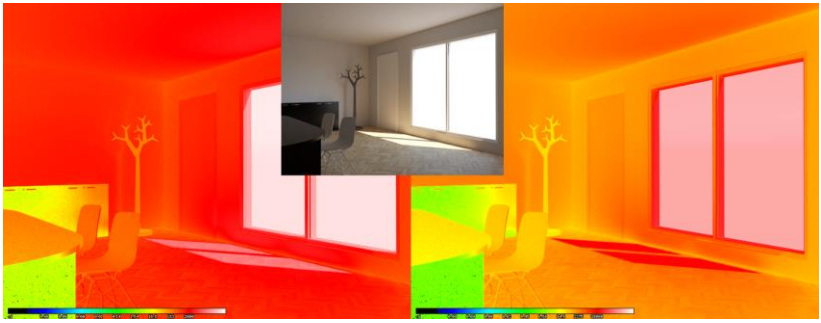

Figure 3.9 False-color representation of luminance, illustrating the importance of scale selection for perceptual analysis.

In addition to false-color maps, V-Ray allows the superimposition of numerical grids directly onto rendered images. This hybrid representation combines the visual context of the rendering with localized photometric values, facilitating a more detailed reading of lighting conditions at specific points of interest.

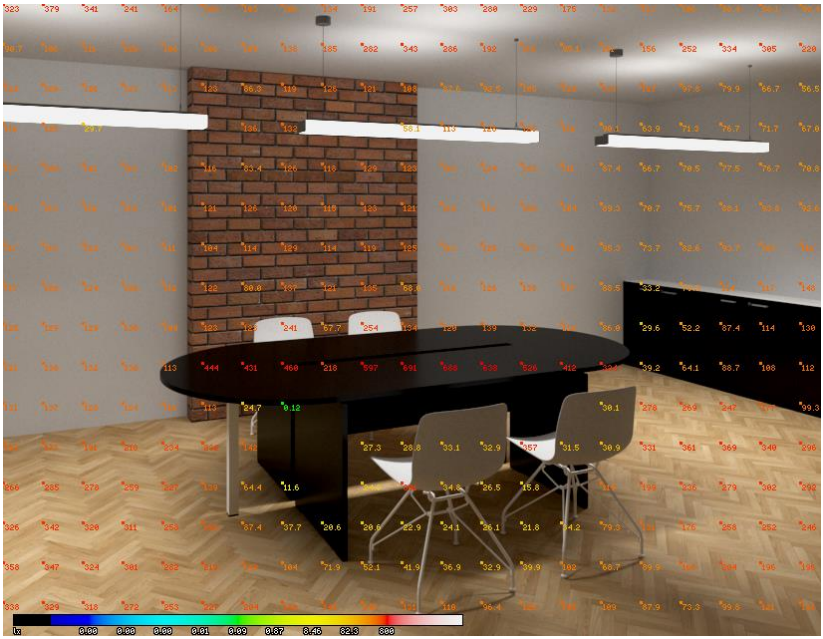

Figure 3.10 Rendering with superimposed grid of illuminance or luminance values for localized evaluation.

3.4 Open BIM solutions

As already mentioned, the Open BIM approach involves the use of standard, non-proprietary, files whose purpose is to ensure interoperability within a project; the goal is therefore to exchange data securely, avoiding information loss, between platforms developed using different technologies. The use of this approach had already been envisioned by Mark Bew of buildingSMART and Mervyn Richards (CPIC, 2015) when they formulated their well-known diagram "The Wedge," which described the maturity levels of BIM processes (Snook, 2013). As early as 2008, the use of files such as IFC was classified at Level 3, the highest, of the maturity diagram, where work was envisaged with integrated and interoperable data.

While the use of a closed system can ensure that no project team adopts approaches that could compromise the process, at the cost of reduced system flexibility, the Open BIM model allows each team to use different tools, provided that these can communicate with one another without loss of

information or incompatibility issues. This flexibility, as anticipated, comes at the cost of not being able to rely on all the variables available in BIM authoring software; only those provided by the interoperability file can be exchanged. Some parameters may not be taken into account during import or export from other software, but the data contained in the exchange file remain secure and unaltered.

Unlike Closed BIM, which relies exclusively on proprietary software, Open BIM does not follow a standardized workflow. The various exchange tools do not all need to be used simultaneously. Below is a list of some of the tools, in addition to the IFC format, developed by buildingSMART International to promote flexibility in collaboration:

- Information Delivery Specification (IDS): a standard that defines information requirements in a machine-readable form. It specifies what must be exchanged, enabling automated checking of IFC files and reducing data inconsistencies.
- BIM Collaboration Format (BCF): a standard that allows the exchange of information in the form of notes and comments related to various aspects of the project (for example, clash detection). Each stakeholder in the process can share information with others, improving communication among teams; this system can be implemented through files or via a web service.
- buildingSMART Data Dictionary (bSDD): a collection of dictionaries that provide definitions and terminology specific to each discipline involved in BIM processes for the built environment. Content is uploaded in a standardized manner by various entities, such as standardization bodies and professional organizations.
- openCDE Initiative: a collection of standard APIs (Application Programming Interfaces), documents, and tools for customizing processes, making workflows more flexible without compromising asset interoperability.
- IFC Validation Service: a free online platform for validating IFC files. Users can upload interoperability files to verify that they meet all the requirements defined by the standard.
- Use Case Management Service (UCM): a portal containing a database of case studies and best practices, intended to provide insight into typical BIM processes and to improve awareness and communication among the various stakeholders involved.

The key aspect of the Open BIM approach is data exchange through standard formats such as IFC. For this reason, some software companies have chosen to follow this approach by adapting their specialized

applications to read the IFC format, allowing users to import the model generated by the BIM authoring software selected for the project and to carry out all the lighting verification required by applicable standards, while retaining all the typical tools of the specialized software.
Once all the necessary verifications have been completed, these programs can in turn export an IFC file, rather than modifying the imported IFC as this would go against the very concept of interoperability, which can then be used to integrate the verified data back into the BIM authoring software.

3.4.1 Dialux EVO

This specialized software, developed by DIAL GmbH, is the most widely used lighting verification tool in Europe. It provides a wide range of tools for inserting lighting fixtures into a geometry (organized hierarchically) and for verifying projects in compliance with various European, American, and Japanese standards. These luminaires can be downloaded from the websites of manufacturers participating in DIAL GmbH's initiative, either as individual products or as plugins for DIALux evo. Another way to find luminaires is through the DIALux Luminaire Finder (DIAL GmbH, 2025b), the largest database available online, with more than two and a half million products; this portal hosts only manufacturers that have agreements with DIAL GmbH.

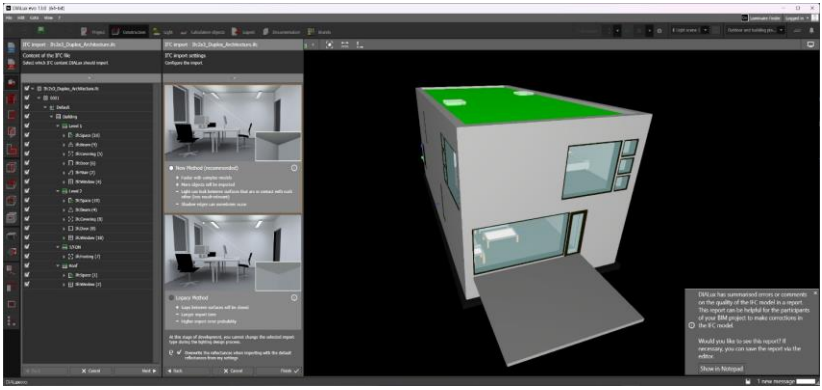

Figure 3.11 Guided procedure for importing IFC files into DIALux evo. If the guided process detects any issues, an error message allows the user to identify which elements caused the error, for what reason, and whether they were excluded from the import.

It is possible to manage materials and create lighting calculation surfaces to evaluate various photometric quantities; renderings can be produced and project reports generated. A full description of all the functionalities of this software clearly goes beyond the scope of this chapter; however, it should be emphasized that the large number of available tools makes model management particularly specialized. As already mentioned, spaces are organized hierarchically, which implies that importing models from other software is not possible without adopting specific precautions. In the case of IFC files, it is necessary to verify that certain conditions are met in order to ensure correct import.

First of all, it should be noted that there is more than one version of the IFC format (buildingSMART International, 2025b). Currently, DIALux evo is able to import the IFC 2x3 TC1 format and, partially, IFC 4 versions. When an IFC file is exported from a very large, complex, or geometry-rich project, the resulting file can be considerable in size. As the weight and complexity of the model increase, so does the difficulty of successfully managing the lighting verification workflow. Excessively complex geometries lead to longer calculation times; even report generation can require very long processing times.

Fortunately, when importing an IFC file, DIALux evo allows elements to be excluded through a guided procedure: a list of all components contained in the file is presented, with checkboxes that allow them to be deselected. In this way, it is possible to import only the portions of the geometry that are relevant to lighting verification and exclude components that could slow down the process. At this stage, it is clearly important for the lighting designer to prioritize the import of elements that influence light distribution within the space and to exclude the rest, thereby reducing the overall complexity and size of the model on which the verification will be carried out.

Once the model has been imported, the lighting fixtures inserted, and the necessary checks performed, everything can be exported to a new IFC file. By ensuring that the insertion point of this new file is correctly oriented, it will be possible to import it into the BIM authoring software and retrieve all the lighting fixtures correctly positioned.

3.4.2 Virtual Environment (VE)

Virtual Environment is a specialized software suite developed by IES, a global climate technology company, which brings together several integrated modules (IES, 2025). The platform is designed as a comprehensive environment for building performance simulation,

addressing multiple aspects of environmental analysis across the entire building life cycle. In its advanced configurations, VE includes tools for the evaluation of both daylight and artificial lighting (LightPro), with particular attention to supporting the achievement of sustainability and performance certifications such as BREEAM (BRE, 2025), LEED (USGBC, 2025), WELL (IWBI, 2025), and other assessment frameworks commonly adopted in international practice.

Within this software suite, it is possible to import BIM-related files, such as IFC models describing built spaces, and GPX files (Topografix, 2025) for the exchange of geographic and contextual data, including points of interest, routes, and site-related information. Once lighting and environmental analyses have been completed, results can be exported back to BIM authoring software, allowing verified data to be reintegrated into the broader project workflow. A key component supporting this exchange is the Quarantine window, which allows users to preview imported files before full integration and to resolve common issues that frequently arise during interoperability processes. Typical operations include the correction of gaps or inconsistencies in geometry through the Heal geometry command, as well as the identification and resolution of missing or improperly defined spaces.

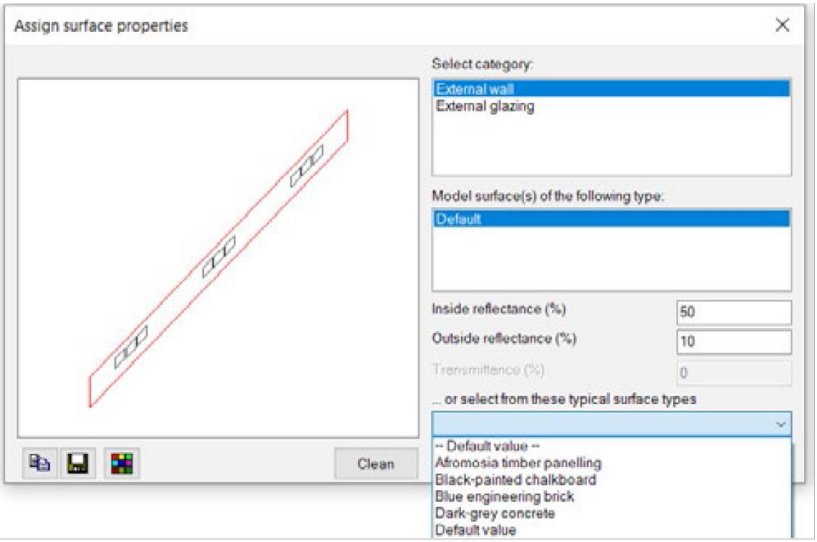

Figure 3.12 IESVE surface properties editor: assignment of internal and external surface reflectance values through predefined surface types or custom parameters, prior to illumination analysis.

Within this framework, the lighting-related functionalities of Virtual Environment — commonly referred to as IESVE in professional practice — are implemented through a set of dedicated modules specifically designed for the analysis of both daylight and electric lighting within a performance-based simulation environment.

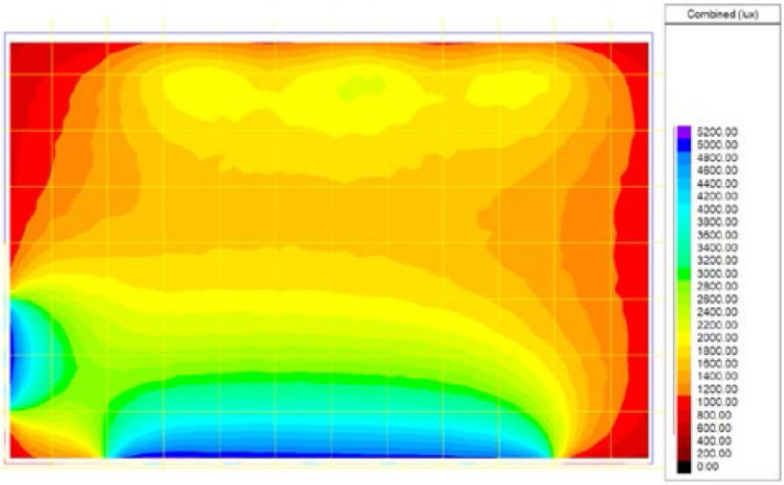

Figure 3.13 Combined daylight and electric lighting analysis in IESVE: false-color map showing illuminance distribution on the working plane.

The VE platform enables detailed evaluations of illuminance and luminance levels, glare risk, and lighting-related costs, supporting both artificial and natural lighting assessments. A distinctive characteristic of the software is its ability to integrate lighting simulations with broader building performance analyses, such as thermal behavior and energy consumption. This integration allows lighting design decisions to be evaluated not in isolation, but as part of a holistic performance-based design approach. In this context, lighting becomes one of several interdependent variables influencing occupant comfort, energy efficiency, and regulatory compliance. Daylight and electric lighting calculations within VE are performed using the Radiance calculation engine (Ward and Shakespeare,

2004), a physically based and widely validated simulation framework. The use of Radiance allows VE to support advanced analyses such as glare evaluation, daylight availability, and the interaction between artificial and natural light under different temporal and climatic conditions. This capability is particularly relevant for projects aiming to meet performance-oriented certification criteria, where dynamic simulations and annual metrics are often required rather than static point-in-time calculations. An internal luminaire database (FlucsLDB) is also available within the VE environment, containing a wide range of luminaires described using the most common photometric formats, including IESNA, EULUMDAT, and CIBSE (CIBSE, 1988). In addition to selecting luminaires from this database, users can edit photometric data through a dedicated editor, enabling the correction or adaptation of manufacturer-provided information when necessary. This feature supports a higher level of control over simulation inputs, which is essential for achieving reliable and reproducible results in performance assessments.

From a methodological standpoint, Virtual Environment should be interpreted not as a traditional lighting CAD application, but as a performance simulation platform capable of incorporating lighting analysis within a broader environmental framework. Its primary strength lies in the integration of multiple analytical domains within a single environment, allowing lighting performance to be evaluated alongside energy use, comfort, and environmental impact. This distinguishes VE from software focused exclusively on lighting verification and positions it as a tool particularly suited to complex projects where interdisciplinary coordination and certification-driven workflows play a central role.

Within the Open BIM paradigm, VE operates as a specialized analysis environment that relies on standardized data exchange rather than direct, proprietary integration with BIM authoring tools. The use of interoperability formats enables different project stakeholders to employ dedicated software suited to their disciplinary needs, while maintaining a coherent and traceable flow of information. Although this approach may involve a more articulated workflow compared to closed, plugin-based solutions, it supports greater flexibility, long-term data accessibility, and alignment with internationally recognized BIM standards.

3.5 Conclusions

This chapter has explored the current state of lighting design tools within the context of Building Information Modeling, highlighting both the opportunities and the unresolved challenges associated with integrating

lighting verification into BIM-based workflows. Rather than proposing a single "optimal" solution, the analysis has deliberately examined a spectrum of approaches — ranging from proprietary BIM add-ins to Open BIM interoperability workflows — in order to reflect the fragmented yet evolving landscape in which lighting designers currently operate.

A first, fundamental observation is that lighting design, despite its technical and regulatory relevance, is still not natively embedded within BIM authoring software. Platforms such as Autodesk Revit, while highly advanced in terms of geometric modeling, data management, and interdisciplinary coordination, do not yet provide lighting verification tools that are fully comparable to those available in specialized lighting CAD software. As a consequence, lighting designers must rely either on external applications or on add-ins that extend BIM authoring environments with additional analytical capabilities. Within this framework, Closed BIM solutions based on proprietary plugins — such as ReluxCAD for Revit, ElumTools, LightStanza, and V-Ray — offer a clear advantage in terms of workflow continuity. By operating directly within the BIM authoring environment, these tools reduce the need for data export and re-import, minimize the risk of information loss, and preserve the integrity of the shared project database. This approach is particularly effective in collaborative contexts where all stakeholders are required to work within the same software ecosystem and where iterative design feedback must occur rapidly.

However, the analysis has also shown that these proprietary solutions vary significantly in scope and intent. Tools such as ReluxCAD and ElumTools are explicitly designed for lighting verification and compliance checking, extending established lighting CAD methodologies into the BIM environment. LightStanza, while similarly focused on performance evaluation, introduces a cloud-based computational paradigm that prioritizes efficiency and accessibility over open interoperability. V-Ray, on the other hand, occupies a distinct and more ambiguous position: it is neither a full-fledged lighting calculation software nor a purely illustrative rendering engine. Instead, it acts as a bridge between visual realism and technical analysis, offering physically based renderings and semi-quantitative lighting evaluations that support design decision-making but do not replace normative verification tools.

Despite their strengths, Closed BIM approaches are intrinsically constrained by their reliance on proprietary ecosystems. Bidirectional data exchange is typically limited to products developed by the same software vendor, and long-term accessibility of project data remains dependent on commercial

strategies, licensing models, and software continuity. From a methodological perspective, this raises questions about the durability and neutrality of such workflows, especially in projects with long life cycles or public-sector requirements. In contrast, Open BIM workflows based on standard interoperability formats such as IFC offer a higher degree of technological independence and long-term data resilience. By allowing lighting verification to be carried out in specialized software — such as DIALux evo or IES Virtual Environment — these workflows enable designers to take advantage of mature, discipline-specific tools that have been refined over decades of professional practice. Moreover, Open BIM aligns more closely with international standards governing information management, such as the UNI EN ISO 19650 series, and supports heterogeneous project teams in which different stakeholders may adopt different software platforms (UNI/EN, 2019).

Nevertheless, the Open BIM approach is not without limitations. The exchange of data through interoperability files inevitably implies a reduction of informational richness, since only parameters supported by the exchange format can be transferred. This often necessitates simplification of geometry, selective import of model components, and manual verification of materials, spaces, and calculation surfaces. Furthermore, although lighting verification results can be reintegrated into the BIM environment, this process is rarely seamless and often requires additional coordination efforts to ensure consistency and traceability. From this perspective, the chapter has shown that the apparent opposition between Closed BIM and Open BIM is, in practice, a trade-off rather than a binary choice. Closed BIM workflows prioritize efficiency, immediacy, and tight integration at the cost of openness and long-term independence. Open BIM workflows prioritize interoperability, flexibility, and data longevity at the cost of workflow complexity and potential information loss. Both approaches can support high levels of digital maturity when applied consciously and within a clearly defined project strategy.

A key issue that emerges from this analysis is the disciplinary positioning of lighting design within the BIM process. While other building systems — such as structural, thermal, or mechanical components — are increasingly embedded into BIM authoring tools through native functions or standardized data structures, lighting design remains partially external, both conceptually and technologically. This condition has been highlighted in recent studies addressing the integration of lighting design and BIM for sustainable interior environments, where lighting performance is shown to be strongly interconnected with spatial quality, energy efficiency, and

occupant well-being, yet still insufficiently supported by integrated BIM workflows (Ramhamdani, 2025). This risks reducing lighting design to a downstream verification task, rather than recognizing it as an integral component of performance-driven architectural design. It is precisely here that the methodological rationale for software integration in lighting design becomes critical. This marginal position becomes even more critical when lighting design is considered in relation to advanced control systems, daylight-responsive strategies, and data-driven building management. Recent studies on the integration of BIM, lighting controls, and IoT technologies highlight how lighting performance increasingly depends on dynamic, interconnected systems that extend beyond static geometric and photometric representations, further exposing the limitations of current BIM-centered workflows (Zocchi et al., 2024). As emphasized throughout this book, the purpose of digital tools in lighting design is not merely the production of visually appealing images, but the ability to evaluate, test, and refine design decisions throughout the design process. This includes modifying luminaire types, distributions, material properties, and spatial configurations in response to quantitative feedback. When lighting analysis tools operate in isolation from the BIM database, this iterative and collaborative dimension is weakened, and one of the core promises of BIM — namely, the integration of all disciplines within a shared information environment — is compromised.

Recent empirical research shows that technical barriers — particularly interoperability between BIM and lighting design tools — remain a significant obstacle to the full integration of lighting design processes into established BIM workflows, requiring the coexistence of numerous specialized software programs and heterogeneous procedures (Hammes et al., 2025) Others have highlighted the need to develop interfaces and design approaches that facilitate the integration of lighting simulations within BIM models, as currently available tools alone do not meet all the requirements of an integrated design and verification process (Ribeiro de Andrade Scatrut and de Oliveira Gomes, 2025). At present, no single software solution fully satisfies all these requirements. Instead, lighting designers must navigate a heterogeneous ecosystem of tools, selecting workflows that best align with project scale, regulatory context, team organization, and available expertise. The examples discussed in this chapter demonstrate that meaningful integration is already possible, but it remains partial, tool-dependent, and methodologically fragmented.

Looking forward, it is reasonable to expect that lighting design tools will continue to evolve toward greater integration with BIM methodologies. This

may occur through more sophisticated native BIM functions, improved interoperability standards, or hybrid solutions that combine proprietary efficiency with open data structures. Until such convergence is achieved, however, critical awareness and methodological clarity remain essential. Designers must understand not only how to use specific tools, but also the epistemological assumptions and limitations embedded in each workflow. In conclusion, the current state of BIM-based lighting design should be interpreted not as a failure of digital methodologies, but as a transitional phase. The diversity of tools and approaches reflects the complexity of lighting design itself, which operates at the intersection of engineering, perception, regulation, and architectural intent. Recognizing this complexity — and selecting software tools accordingly — is a prerequisite for ensuring that lighting design maintains its disciplinary autonomy while fully participating in the collaborative logic of the BIM process.

3.5 Conflict of interest declaration

The author declares that there are no actual or potential conflicts of interest related to this chapter. Specifically, no financial, personal, or professional relationships with individuals or organizations have influenced, or could be perceived to have influenced, the content, analysis, or conclusions presented herein. The research and writing of this chapter were conducted independently and objectively. The author confirms that no competing interests exist within the meaning of the RCASB guidelines.

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4. Rendering and verification of lighting design

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Abstract

This chapter examines photorealistic rendering as a complementary tool in lighting design, focusing on its role in perceptual evaluation rather than normative verification. Starting from the limits of photographic representation and human visual perception, the text clarifies why perfectly photorealistic images remain unattainable and discusses the implications of this constraint for digital lighting simulation. The chapter introduces global illumination models highlighting their theoretical foundations, computational trade-offs, and relevance to lighting design workflows. Particular attention is given to the management of geometry, materials, artificial and natural light sources, and calculation parameters, emphasizing the distinction between quantitative lighting calculation and qualitative visual synthesis. Through applied examples, including architectural façades, interior spaces, and the illumination of artworks, the chapter demonstrates how rendering supports design decision-making by integrating measurable lighting data with perceptual assessment. Ultimately, photorealistic rendering is framed as a virtual prototyping instrument that bridges theory and practice, enhancing both professional design processes and educational approaches in lighting design.

Keywords:

Photorealistic rendering, lighting design, global illumination models, visual perception, virtual prototyping, lighting simulation

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4.1 Introduction to photorealistic rendering

The term photorealistic was introduced in computer graphics to describe synthetic images, virtually and hopefully indistinguishable from an existing or realizable perceptual reality, analogous to classic printed photographs (Brunet and Jansen, 1994).

The simplest example we can produce to express the concept is the classic photograph or slide of a real environment. The purpose of photography is to reproduce a visual perceptual stimulus equal to the reality that this technique was able to capture and store on printed paper. In the case of the slide, the method used to reproduce the perceptual stimulus changes, but the purpose is the same. However, experienced photographers know that, in many cases, in order to produce excellent photographs that can accurately depict the various aspects of the reality you want to capture, the main problem is the management of light in the environment where photographing takes place. Indeed, the color temperature and color rendition of the light source illuminating the environment, but also the distribution of luminance that are captured by the camera, can produce photographs that are chromatically incorrect or have levels of brightness and contrast that differ from perceived reality, so much so that, quite simply, that photograph is considered wrong. One wonders, however, how it is possible that a scene that we are able to correctly perceive in reality can become a bad photograph. Where can the error be? In human subjective perception or in the objective perception of the camera? In reality, the issue concerns the high dynamic range of the light signal, which can either be computed for a virtual environment or captured from a real environment using sensors with limited dynamic range, and must then be reproduced by output devices—such as monitors—that also have limited dynamic range (Reinhard *et al.*, 2010).

A classic example of the limits of the camera's capabilities is as follows: imagine we are in a room, with a window facing south on a slightly cloudy day, about noon. We look around the room toward the wall where the window is and through it we can see the buildings adjacent to ours. The illuminance levels of the surfaces we see are extremely different. From the outside we perceive luminance levels that can be as much as four or five orders of magnitude greater than those of the inside, yet we are able to see the details both inside and outside. If we take a photograph from our vantage point, two types of images can be obtained: in the first case, the photo shows the exterior correctly, while the interior is very dark; in the second case, the interior is correct, but the window appears as a white spot in the center of the wall, and the exterior details cannot be seen. This is

because the camera can adjust the exposure time according to either the external luminance or the internal luminance, but not at the same time. In reality, the camera is nothing more than an instrument for measuring the luminance levels of a scene, which are imprinted on the photosensitive film or digital sensor. Possibly an automatic camera can also automatically adjust exposure times according to the total luminance received from the environment, but, in its objectivity, it still cannot make a perceptual interpretation of colors and contrasts, as it occurs in the human visual system (Ward, 1994).

In the case of image synthesis, the actual environment may not even exist, but in any case the image is constructed from a three-dimensional geometric description of the environment, materials, lights, and observer. All this data together constitutes the descriptive model of the scene. The rendering image, presented on the computer screen, must ultimately produce in the observer a perceptual visual stimulus similar to the reality that the model is intended to represent (Kolivand *et al.*, 2018).

Today's designer can have extremely advanced 3D geometric modeling CAD tools with which very complex shapes can be created. Although these tools have already entered a stage of maturity for many years and are widely used by designers, the same cannot be said for rendering programs. For the sake of scientific fairness, a fundamental point must be clarified: despite the remarkable progress of rendering technologies, it is still difficult to produce images that can be considered perfectly photorealistic in all conditions (McNamara, 2001). This limitation arises not only from approximations in the calculation of light distribution, but also from the extreme complexity of the human visual system, as discussed in (McCann and Rizzi, 2011; Rossi, 2021).

Many rendering programs available on the market provide very beautiful and realistic animations and images, but not photorealistic ones. The difference lies mainly in the fact that a realistic image may be a good representation of reality, but an observer, not even too experienced, is able to say with certainty that what he or she is observing is not a photograph or film shot, but a computer product. The problem is even more pronounced when trying to reproduce an existing environment; the synthesis images that can be obtained will be immediately recognized with respect to photographs of the scene under consideration.

The main reasons why no rendering software has yet been able to achieve the result of perfect photorealism can be summarized as follows:

- The local computational model used to describe the behavior of the interaction between light and matter is often drastically simplified for

reasons of limiting computational time. A radiometrically correct treatment of light presupposes describing the interaction, between light and matter, by means of the BSDF seen in the previous chapter. Unfortunately, this function is not analytically known, and its complete measurement is very difficult for materials commonly used in construction, so instead of the correct BSDF, approximations are used to describe materials, affecting the accuracy of the calculation model. The perceptual optical effects of surface treatments of materials are also included in this problem area. For example, everyday experience teaches us that the same material, aluminum, can appear in substantially different ways depending on the surface treatments to which it may be subjected.

- The global calculation model is often simplified, at the expense of accuracy, to describe all the light in a scene. In fact, in an environment, light can come directly from lighting sources but also indirectly because it is reflected by other objects. A percentage of indirect lighting is always present in real scenes, while direct lighting may also be absent. Instead, many rendering systems consider only direct lighting and approximate indirect lighting by a constant factor, thus making a big mistake in describing real scenes. A mathematical description of the global illumination problem has been formulated by multiple researchers with the integral rendering equation, the solution of which, however, depends on the geometric complexity of the scene and lighting sources. Ray Tracing, Radiosity, and Photon Mapping are three approximate solutions to the rendering equation to address the various aspects of global illumination.
- The descriptions of lighting sources used in classical rendering systems bear no dimensional relation to the radiometric and photometric reality of light sources described in the field of lighting engineering. Again, simplification is done for the purpose of reducing computation time, resulting in making such tools absolutely useless for the lighting designer.
- Light is treated not as a spectral function but as a triplet of RGB color values. In fact, the description of light as a spectral function between 380 and 780 nm, and sampled every 5 nm, would require the treatment of at least 80 values for each calculated ray of light, as opposed to three for the simple colorimetric description of tristimulus theory.
- The luminance dynamics perceivable by a human observer in real scenes can vary up to eight orders of magnitude, while those representable on a computer monitor reach at most the lowest three

orders of magnitude. Fortunately, the human visual system can adapt to a good extent to the reduced luminance levels that can be represented on the monitor, thus allowing a wide range of luminance levels to be perceived. To do this, however, the observer must not be distracted by other, stronger sources of light, such as a reflected source on the monitor glass or sunlight coming in through a window, because then the perception of the digital image will fade and much of its information content will no longer be detected.

Years ago some rendering software developers, stimulated precisely by the demands of virtual prototyping and photorealism, have begun to address some of the problems mentioned above. One of the most interesting examples, from a research standpoint, which addresses at various levels all the issues mentioned, is the Radiance software developed at an American university and distributed free of charge on the Web. Born out of research by Greg Ward Larson in the late 1980s, it subsequently evolved, similar to the Linux operating system, through spontaneous and free contributions from other researchers and programmers (Ward and Shakespeare, 2004). In the past, experimental interfaces between Radiance and AutoCAD were developed, mainly to export CAD geometry for lighting simulations (e.g. Desktop Radiance, torad, and radout utilities). However, these tools never became widely adopted and were often difficult to use in practical design workflows. Today, Radiance is more commonly integrated into contemporary environmental simulation workflows through tools such as Honeybee and Ladybug for Grasshopper–Rhino (Sadeghipour Roudsari, Pak and Viola, 2013), DIVA for Rhino (Jakubiec and Reinhart, 2011), and ClimateStudio (Jakubiec and Reinhart, 2012), which provide user-friendly interfaces and tighter connections with parametric modeling environments.

Historically the first commercial alternative to Radiance was the Lightscape software (Lischinski, Tampieri and Greenberg, 1992), which started as a stand-alone project and later became an Autodesk product, then partially integrated into 3DSMax.

This program treats and solves the first three problems mentioned above, while with various tricks it circumvents the last two. The main advantage of its use lies in its graphical interface for project management, which certainly makes it more accessible for use by the general lighting and interior designer. The software has some illuminance and luminance calculation features similar to those of AGI32, Dialux, Litestar and Relux software we have seen in Chapter 3, but it completely lacks the product catalog part, as does the 3DSMax software that included it. Having established that the ideal system for photorealistic rendering does not yet being fully obtained, it

is however incumbent on us to question what level of photorealism can be achieved and which procedure is best.
The answer to this question is extremely complex because we enter the realm of pure scientific research on the simulation of light and perception. Without going into the scientific methodology with which to answer the problem, however, we can note that the topic has already been addressed by various researchers (McNamara, 2001; Ferwerda, 2003; Reinhard *et al.*, 2010; Pharr, Jakob and Humphreys, 2017). In a lot of researches, real environments, whose geometric and lighting characteristics are known, are compared by measuring illuminance and luminance with the results obtainable from different software (Mardaljevic, 1995; Rushmeier *et al.*, 1995; Reinhart and Walkenhorst, 2001; Maamari, Fontoynont and Adra, 2006; Cai, 2016; Mangkuto, 2016; Skarżyński, 2020)

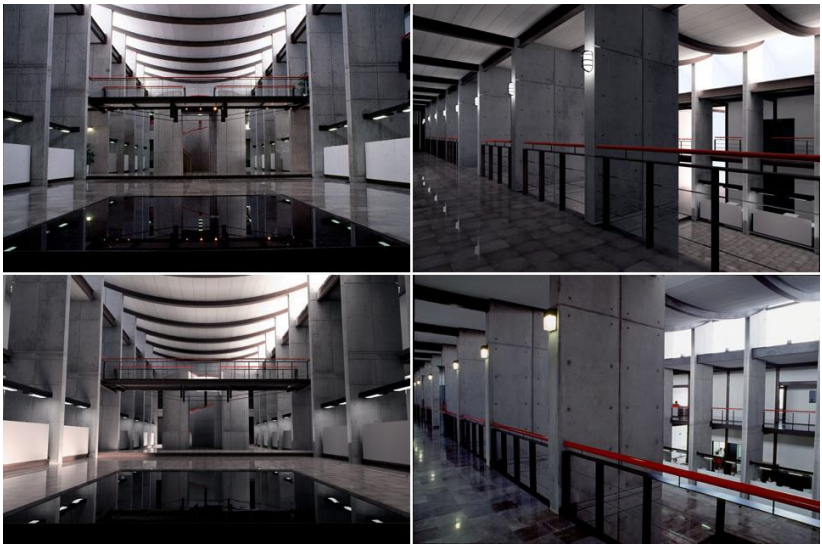


Figure 4.1 Comparison of two Lightscape renderings and two photographs of an interior. As an exercise, it is left to the reader to distinguish the photos from the renderings. Courtesy of Guillermo LLaguno.

With the same amount of calculation time required, which is actually a major factor for a designer, in the calculation of illuminance and luminance different software can give different results depending on multiple parameters, such as the geometry of the environment and the characteristics

of the materials and light sources. What is highlighted is that the result greatly depends on the correctness of the data inherent in the materials and light sources that are entered into the software.
In 1998, the Lightscape Corporation announced a contest among users of its software with the aim of rewarding the most photorealistic images. The winner, Guillermo LLaguno, a Mexican architectural rendering expert, stunned everyone with renderings of the natural and artificial lighting of an interior designed by architect Agustin Landa. Renderings of that project are distinguishable from photographs of the same only if the observer pays close attention to the details.

4.2 Global calculation models

By the term lighting calculation models, we denote the mathematical models that describe more or less accurately the behavior of light in its interaction with one or more media. In image synthesis, the use of illumination models is determined by the inherent difficulties of giving an exact analytical solution to problems such as reflection or refraction of electromagnetic waves in mutual interactions with objects in a very complex environment (Kajiya, 1986). Often these models are derived from analytical evaluations, on which simplifying constraints are imposed on both the type of electromagnetic wave and the nature of the materials.
In the case of photorealistic rendering, we are particularly interested in synthesizing images and thus ultimately learning about the light that arrives on the image plane simulating the retina of the human eye. This light radiation may come directly from lighting sources or from other objects in the scene being observed. Many objects, in our daily experience, appear to us as they reflect or transmit toward our eyes light coming from their surroundings and thus by indirect illumination. In fact, the light that illuminates an object does not come from light sources alone; although it is these that generate it, light is distributed in the environment through a myriad of reflections and refractions, changing color and energy until it hits the object concerned and finally the retina of our eyes. This component of lighting called indirect lighting, and its proper determination, is a first step toward photorealism through a correct physically based rendering computation (Pharr, Jakob and Humphreys, 2017).
Most rendering programs developed in the field of computer graphics assume that the appearance of an object is solely the result of the reflection and transmission of light coming directly from the illumination sources on the object itself, and this approximation does not allow a photo-realistically correct model to be formulated.

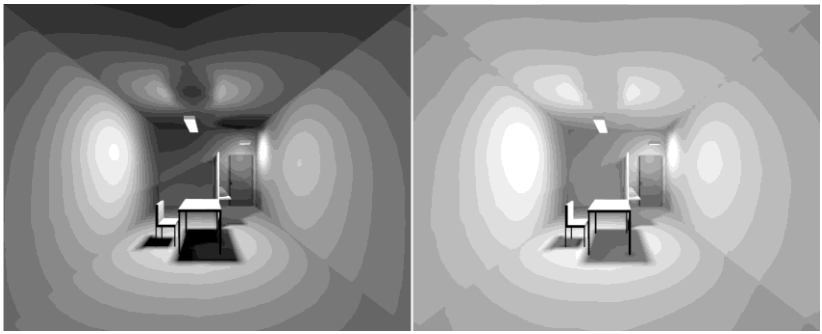


Figure 4.2 The environment shown is illuminated by two lighting sources. The image on the left shows the calculation of direct light only and therefore has absolute shadows and lower overall illuminance levels than the one on the right, where the calculation of also indirect illumination, distributing light energy more correctly, provides more realistic levels to the scene.

Ultimately, global computational models attempt to answer the question of where light incident on an object's surface comes from. The seemingly obvious answer would be from lighting sources. Light can certainly come from lighting sources through a direct path, but it can also come through an indirect path during which it is reflected and/or refracted and/or diffused by other objects. In the synthesis of images of real environments, in many cases, this indirect lighting component can be decisive, not only for the qualitative characteristics of the image but also for the quantitative ones that affect classical lighting design in determining illuminance levels.

During the `80s, two global illumination models known as backward Ray Tracing (Whitted, 1980) and Radiosity (Goral *et al.*, 1984) were formulated and developed, which start from different assumptions to calculate light distribution. The former is based on optical-geometric principles of light distribution, while the latter stems from energy balance considerations of radiance distribution between surfaces in an isolated system. Only after their introduction was it realized that actually both models are a simplified numerical solution of a much more complex analytical formulation describing the transport of light in a generic environment and known as the radiance integral equation (Kajiya, 1986).

In its original formulation, backward Ray Tracing is based on the recursive calculation of the specularly reflected ray and the refracted ray (if the object is transparent) according to Snell's law. The construction of the image takes

place in reverse to the propagation of light, beginning with the primary rays that start from the observer and pass through the points that make up the image plane, toward the scene and following the direction of light in the opposite direction. For this reason, the method is also called backward Ray Tracing. At each intersection with an object, the intensity of light at that point is computed as the sum of the four components:

- Light coming from other objects through diffuse inter-reflections (ambient light), approximated by an arbitrary constant.
- Light coming from other objects through specular reflections.
- Light coming from other objects through non-diffuse transparencies.
- Light coming directly from lighting sources.

To determine whether a point is in shadow relative to a source, a ray is geometrically drawn between the point under consideration and the respective source of illumination. The termination of the recursive process of generating reflected and refracted rays is generally ensured by two conditions: rays that do not hit anything and go to infinity carry no intensity contribution, and the program admits a finite maximum recursion level that must be chosen by the user.

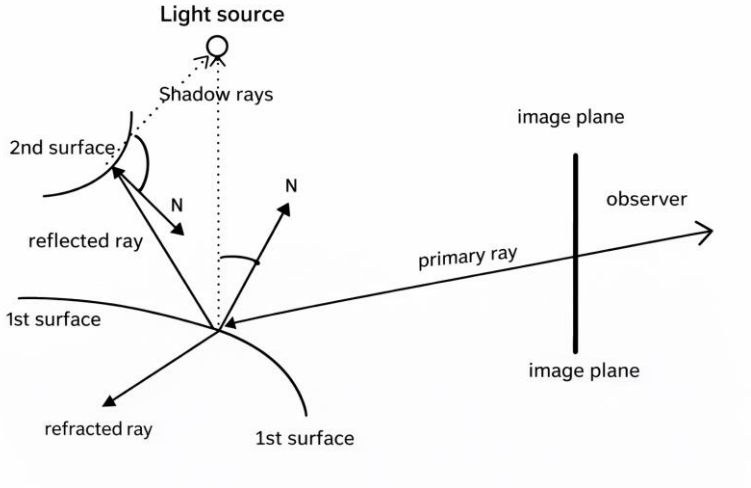


Figure 4.3 Principle of operation of backward Ray Tracing. N is the normal to the surface.

The basis of Ray Tracing is the calculation of the intersection between the surfaces that define the contours of objects and the lines that define the rays of light, in three-dimensional space. The determination of intersections can be obtained analytically, for simpler surfaces, or by numerical methods, for more complex surfaces. The basic problem is that you cannot know a priori which ray intersects some surface or even at what point this happens. To determine the first object intersected by a ray, it is necessary to look for any intersection with all surfaces in the scene; from those that are intersected, the one closest to the origin of the ray is then chosen. This procedure is extremely computationally intensive, so much so that it requires high computation times for each image. However, over the past two decades, research has discovered techniques to decrease computation time that are all based on a fundamental principle: try to compute only those intersections between rays and surfaces that are actually of interest for image determination.
The main limitation of backward Ray Tracing lies in its inability to calculate diffuse inter-reflections of light between objects, which in real scenes constitute the main component of indirect lighting. It should be clarified that the original formulation of this global illumination model was later expanded to consider this aspect as well.

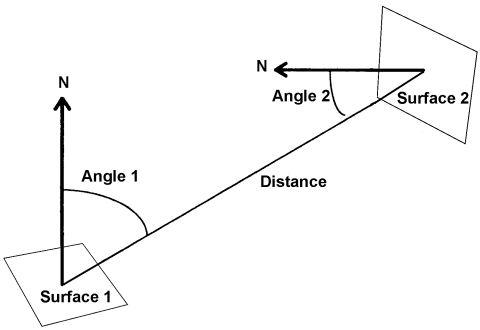


Figure 4.4 Determination of the form factor between two flat faces. This depends on the distance, angles and whether there are any obstacles between the two faces.

On the other hand, Radiosity is based on the principle of conservation of energy in closed systems. All surfaces in the scene are subdivided into three-dimensional surface polygons, also called faces, which are smaller in size than the geometry of the environment under consideration. For each of

these, the Lambertian hypothesis is applied, thus assuming that the energy leaving the 3D polygon is uniformly distributed throughout the hemisphere. The energy leaving a face is given by the sum of the energy emitted by that face plus the energy reaching the face from its surroundings and diffusely reflected from it. The energy from the surroundings is given by the sum of all the energies from the other faces of the scene that reach it.

Radiosity defined in this way is nothing more than the radiometric magnitude known as irradiance, hitting or leaving the flat face. Irradiance is the radiometric quantity from which illuminance is obtained. To determine the irradiance of all faces in the scene, it is necessary to determine the percentage, distance and angle at which all faces in the scene are seen with each other. This information is incorporated into a single parameter called the shape factor associated with all possible pairs of faces belonging to the environment, and whose computation time depends on the complexity and number of faces that make up the entire environment. The inherent limitations of this lighting model are:

- Transparencies are not considered.
- Surfaces can only be Lambertian, so even partial specular reflections cannot be simulated.
- The radiant output on one face is considered constant. Therefore, since the faces have a finite size, a calculation error is inevitably made, which grows with the increasing average size of the faces.
- Determination of the form factor requires calculation of two surface integrals. Analytically, this can be done only for elementary surfaces such as plane polygons, thus limiting the geometric complexity of describable surfaces.

One advantage of Radiosity is that, after calculating irradiance values, the solution is independent of the observation point, and thus, having sufficiently fast 3D graphics hardware capable of visualizing faces through the removal of hidden surfaces, one can interactively navigate the scene. Another interesting point is that the shape factors depend only on the geometry of the scene and therefore do not have to be recalculated if the reflectance characteristics of the materials or the spectra and intensities of the light sources are changed.

Backward Ray Tracing and Radiosity, however, cannot fully model the light transport phenomena described by the rendering equation (Kajiya, 1986). Unfortunately, an analytical solution of this integral equation, even for simple environments, is not possible. However, there are non-analytical solution methods based on numerical calculation that are well suited to be performed by a computer. Let's look at some of them:

- The two-step method used by Lightscape uses Radiosity in a first step to calculate diffuse inter-reflections and backward Ray Tracing in a second step to calculate specular components and the final viewpoint-dependent image.
- Two-way Ray Tracing used in other software proposes a simplified solution with low computational intensity (Chattopadhyay and Fujimoto, 1987). At an early stage, forward Ray Tracing is performed starting from the lights. In this way, all surfaces with more diffusive characteristics directly affected by light sources are determined. These surfaces are elevated to the rank of secondary light sources and used in a final backward Ray Tracing step. The intensity of secondary sources is given by the contribution of primary sources and also that of secondary sources. Again, the arbitrary ambient light component typical of Ray Tracing is eliminated.
- Radiance realizes a solution for diffuse inter-reflections by Ray Tracing, using a technique of calculating irradiance at a point, based on tracing the rays that pass through the entire hemisphere, looking for light components that come diffusely from all around. The advantage of this method is that the calculation of diffuse inter-reflections, based on an incremental technique, can be stopped after a certain number of steps, thus obtaining good results (Ward and Shakespeare, 2004).
- In Photon Mapping, available with Mentalray rendering in 3DSMax and also in Dialux, a two-step method is applied (Jensen, 1996). In the first step, photons emitted by light sources and reflected repeatedly from surfaces in the environment are statistically calculated, and this information is saved in a 3D data structure called a photon map. In the second step, the image is generated by applying the classical Ray Tracing method, generating transparencies, mirror effect and glossiness and deriving the information about the light present on all surfaces provided by the photon map.

In using numerical integration methods, the samples used are rays, which brings us back to more advanced Ray Tracing techniques than classical backward Ray Tracing. After all, Ray Tracing was also used in Radiosity to calculate form factors. In addition, over the years the calculation of radius-surface intersections has developed for a large number of different types of surfaces, and considerable optimizations have been introduced to reduce the computational costs of this process. Today, the term Statistical Ray Tracing also referred to as Monte Carlo Ray Tracing refers more generically to light ray sampling methods used to find a numerical solution to the radiance

integral equation (Cook, Porter and Carpenter, 1984; Lafortune and Willems, 1993; Veach and Guibas, 1995; Arvo *et al.*, 2001; Jensen, 2001; Pharr, Jakob and Humphreys, 2017).

4.3 The photorealism of advanced method

The advantages obtainable from using advanced global calculation models can be summarized as follows: the program uses the best of computational method to compensate for the respective shortcomings of the calculation models. Through this approach it is possible to achieve images in which correct calculation of indirect illumination, gradual shadows more similar to reality, and many other effects also including the mutual influence of colored light reflection between the surfaces of the environment. This phenomenon, well known in photography, is called color bleeding (Cohen and Wallace, 2012). We can summarize it with a very simple example: suppose we illuminate a room by indirect illumination from a spotlight pointed at the ceiling. The ceiling light, usually white, diffusely reflects the light from the spotlight, and thus illuminates the room. If we change the color of the ceiling to bright red, the reflected light will obviously be red, and it will illuminate the other surfaces in the room with red hues. In reality, humans perceive much less red than is actually detectable in the room with a spectrophotometer or photograph. This is because of the perceptual phenomenon explained, in the previous chapter, as color constancy.

When it was first presented to the public, Lightscape immediately differed from other rendering software in its ability to treat light in terms of photometric quantities and in its ability to use photometric solids from lighting companies to define luminaires, a feature that has long since been included in 3DSMax as well. An additional aspect, which is even more interesting for lighting designers and architects in general, is the ability of these programs to simulate the use of natural light, both in interior and exterior design, through a simple and intuitive but at the same time extremely flexible setup method.

For the purpose of calculation, two-step methods are based on dividing surfaces into plane faces (Bloomenthal, 1988), i.e., polygonal geometric patterns, which can also be done adaptively (Lischinski, Tampieri and Greenberg, 1992). All environment's surfaces are initially divided into rather large faces, which allows an initial calculation to be made very quickly. The initial faces can then be further subdivided into smaller elements if the first calculation shows that there are significant differences in illuminance between adjacent faces, as is the case, for example, near the edges of the shadows. The calculation begins by distributing the light

starting with the light sources, then moving on to the first levels of reflection, the second levels, and so on. At each step the program performs an iteration. The iterative calculation continues until all the energy leaving the sources has been absorbed by the surfaces or if it is interrupted by the user having to determine the maximum number of inter-reflections that can be calculated.

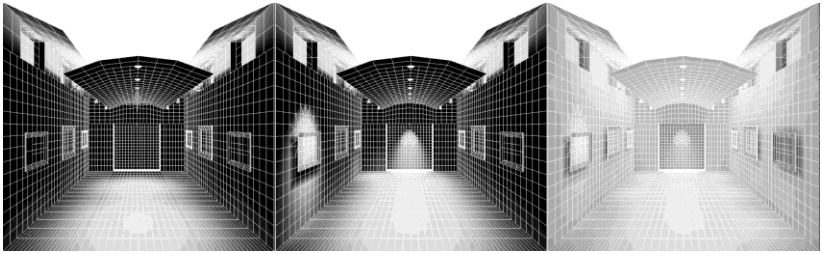


Figure 4.5 Calculation of surfaces with progressively refined subdivision.

This method offers many advantages; in a very short time, it is possible to obtain results that are already fairly accurate since in the first iterations the program is very fast. Later, as computational steps progress, the result is refined more slowly. It is generally not necessary to wait until 100% of the light energy of the sources has been distributed, as this can take a long time, but you can stop the calculation for slightly lower values between 95% and 100%.

Since both Radiosity and Photon Mapping determine the illuminance on surfaces, and since the illuminance does not depend on the position of the virtual observer but on the characteristics of the environment, the calculated 3D rendering can be navigated interactively, even before the calculations are finished, like a classical virtual reality model, with the advantage of showing a much more realistic representation of illuminance than the virtual environments usually used in computer graphics. For the same reason, digital video animations can also be made in a very short time. The limitations of this type of representation consist mainly of the fact that any changes to object geometry, materials, or lights result in the need to recalculate the first step from scratch. On the other hand, if only the position of the observer is changed, the calculated solution is still valid. In order to have a final rendering image, including visual effects such as transparencies and glosses, a second Ray Tracing computational step must be applied, which depends on the position of the observer and therefore its computation

can only be used for creating static images or animation frames, but these require a high computation time each.
At the model preparation stage, you have all those features typical of CAD systems for defining the geometric model, materials and lighting sources, discussed in the previous chapter. The basic steps can be described as follows:

1. definition of geometries;
2. definition of the virtual observer's viewpoints;
3. definition of real light sources;
4. definition of materials;
5. definition of the calculation parameters of the rendering steps;
6. performance of lighting calculation (first step: Radiosity or Photon Mapping);
7. calculating and saving the rendering image (second step: backward Ray Tracing).

A more accurate calculation will obviously require more computational resources, that is, more time and more available memory in the computer (Ochoa, Aries and Hensen, 2012; Ritschel *et al.*, 2012). The geometric model defined in the preparation phase is also modified in its polygonal subdivision, to make it suitable for calculation of the two rendering steps. Having two calculation steps can induce confusion in the lighting design development process. In fact, it is in the first step that the lighting calculation of the environment is done, which is independent of the presence and position of the virtual observer, while in the second calculation step only the synthesis image is produced, which obviously depends on the position of the observer. One working methodology, which can help the designer avoid errors and the loss of any changes made during design development, is to save the design calculation, for example, in a file that contains the photon map for possible later use. Keeping in mind, however, that any changes to the project will result in deleting the saved map and repeating the first calculation step.
The final stage of the work is the production of renderings as individual images, animations in digital video, interactively navigable virtual reality models, or even technical analyses of illuminance and luminance as discussed in the previous chapters.

4.4 The management of geometric data

It often happens to import geometric models from other modeling software, using exchange formats such as DXF, DWG, 3DS, OBJ, FBX, or IFC, depending on the interoperability requirements of the workflow. DWG is

the native format used by AutoCAD, while 3DS originates from 3D Studio. LWS is the format used by LightWave 3D. OBJ (Wavefront, 1990) and FBX (Autodesk, 2006) are widely adopted formats for transferring polygonal geometry and scene data between different modeling and rendering applications. In BIM-oriented workflows, IFC (ISO, 2024) may also be used to exchange building models between software platforms. Finally, DXF (Autodesk, 1982) is a file interchange format defined by Autodesk and adopted by many other geometric modeling software manufacturers.

Each of these formats has particular characteristics and capabilities for describing three-dimensional geometry. Some represent objects as polygonal meshes, while others rely on parametric or boundary representations (B-Rep), such as NURBS surfaces (Rogers, 2001). However, in order to perform lighting calculations and rendering operations, the software must convert all geometry into polygonal meshes composed of planar faces, a process commonly referred to as polygonal tessellation. This conversion is necessary because most computational algorithms used in physically based rendering, such as ray tracing and global illumination methods, operate on planar polygonal elements, typically triangles or quadrilaterals.

During this tessellation process, some geometric entities originating from other modeling environments may not be translated correctly, especially when dealing with complex parametric surfaces or poorly defined geometry. For this reason, the type of geometric primitives that can be reliably imported depends on the exchange format used. The entities that are generally recognized without major conversion issues typically include the following:

− 2D polylines (with width or height).
− 3D polylines.
− 3D faces.
− Polygonal meshes.
− Polyface meshes.
− Arcs (with height).
− Circles (with height).
− Lines (with height).
− Solid tracks.
− ACIS solids.

Although this list reflects entities historically common in CAD-based workflows, many contemporary modeling systems internally convert these primitives into polygonal tessellations, ensuring compatibility with

rendering engines and lighting simulation algorithms (Bloomenthal, 1988; de Araújo *et al.*, 2015).
When importing, the programs always present a number of very useful features that make it possible to manage coordinate transformations, scaling factors and units of measurement. Since radiometric calculations are to be made on real-world lighting quantities, it is imperative that model dimensions be expressed in known units of measurement. Indeed, it is not the same thing to calculate the illuminance of a lamp with 1500 lm flux in a room 3.2 meters or 3.2 centimeters or 3.2 feet high. Sometimes modeling programs generate geometric models based on undefined units of measurement, so it is essential, after importing the model, to check its actual measurements so that, for example, the height of ceilings or doors can be verified. Another important suggestion is that the Cartesian Z axis should correspond to the vertical dimension of the real world. This is because the photometric solids, which lighting companies use to define the light shape of luminaires, have the vertical axis of the intrinsic coordinates oriented as the Z axis, and although it is possible to manually reorient the luminaires in the environment, this tedious operation can be avoided by keeping Z as the vertical axis.

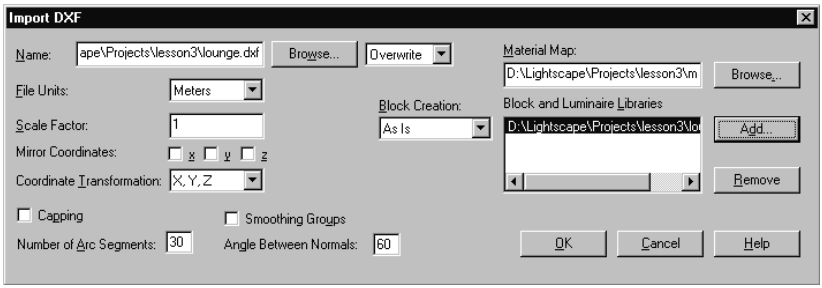


Figure 4.6 Example of a DXF format import window that allows multiple parameters to be defined, including: unit of measure, scale factor and coordinate orientation. The "overwrite" function makes it possible to determine whether the imported model should define a new project or add a geometric model to the project already under development.

Importing the model from the various formats also makes it possible to manage the use of layers for the drawing, as well as geometric blocks similar to what you are used to doing with CAD programs.
Modern modeling systems allow for curved parametric surfaces. One aspect that may seem limiting in its ability to handle curved geometries is that, in

order to make lighting calculations, the program converts all surfaces into sets of plane faces, i.e., polygonises them. However, these patterns, although made up of polygonal geometric surfaces, are represented by interpolating the luminance levels between adjacent flat faces, resulting in providing a blunt rather than an angular representation.

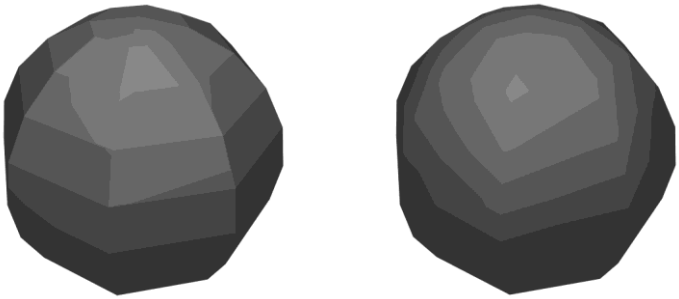


Figure 4.7 A sphere model represented by the polygonal method. On the right, the same sphere, although polygonal, is represented by the software using Gouraud shading to eliminate the angular representation (Gouraud, 1971). This option is just a representation trick and did not change the geometry, in fact the profile is identical.

The geometric patterns we may encounter in reality are always characterized by a shape endowed with a non-infinitesimal thickness. So a wall will have a thickness of a certain size, and a sheet of paper will also have a small but not zero thickness. This means that, ultimately, all objects are enclosed by the surfaces that circumscribe them with respect to matter or their surroundings. Solid modeling is based on these principles. However, modeling systems often allow even surfaces of infinitesimal thickness to be modeled that cannot exist in reality.
For the calculation of the physical distribution of light in the environment, it is always required that objects should be solid as in everyday reality. Since, however, the models are defined by polygonal surfaces, the program assumes that the surfaces delimit solids. For this reason it does not make sense to calculate the illuminance on both sides of a surface, but only on the external side of the solid; with this method the calculations are simplified by half. Ultimately, all flat faces have a front, against which light is calculated, and a back, on which illuminance is not calculated. The front is the one with respect to which the vector normal to the surface is defined and is generally assigned according to the right-hand rule with respect to the

counterclockwise order of the points defining the polygonal plane face; the software always presents options for being able to orient the surfaces enclosing a solid in a physically correct manner.

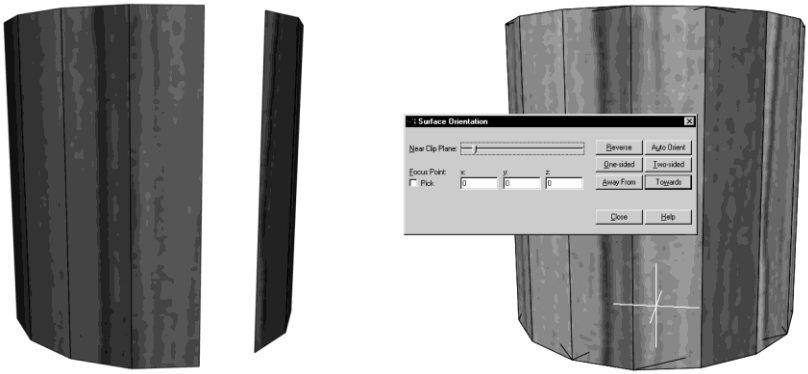


Figure 4.8 Example: a cylinder has been imported that apparently has a missing surface. On the right, activating the surface orientation mode shows that the surface exists, but it is oriented inward, so it will have to be adjusted.

Unfortunately, modeling programs are not accustomed to the physical calculation of light and, in general, do not bother to take care of the orientation of surfaces. For this reason, it may happen that models imported from other software have apparent holes where no illuminance is calculated. When importing these models, the most tedious part of the preparation is exactly checking that the surfaces are oriented in the correct way and turning them if necessary. There is also an option to define double-sided surfaces, but it is not recommended to use it because it involves many unnecessary calculations and increases the time needed to produce the results. It is important to remember that inside a room, objects should have normals oriented outward, while the inner surfaces of walls should be oriented inward.

4.5 Colors and materials

Almost no commercial programs state which local calculation method they use, that is, the method by which the BSDF describing the properties of surfaces is approximated when they interact with light (Phong, 1975; Cook and Torrance, 1981). Controlling the local calculation parameters in the

program is the basis for defining how surfaces reflect light and their visual appearance, so they actually describe the properties of a material and have an effect on both steps of the global calculation. However, all commercial software allows colors to be defined based on the RGB model or more conveniently on the HSV model, in which the parameter V determines the reflection factor of light on a surface. This is obviously an approximation to the radiometric reality of light (Pharr, Jakob and Humphreys, 2017).

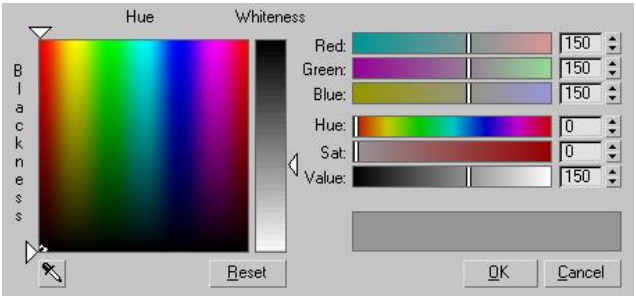


Figure 4.9 Color management with RGB and HSV models.

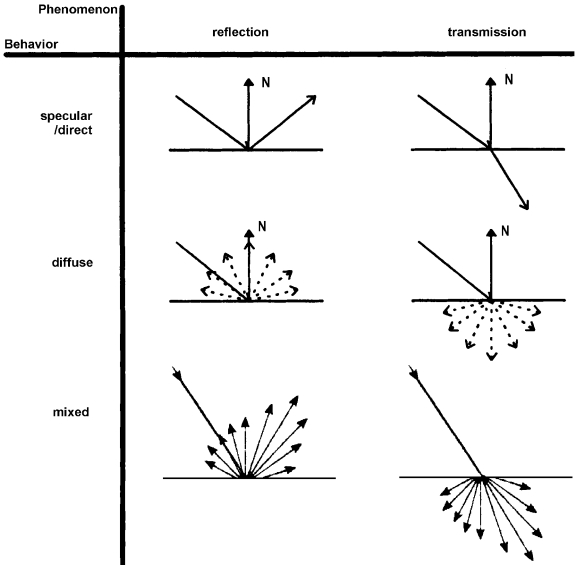


Figure 4.10 Schematic representation of the types of interactions between light and matter.

Next to color are the geometric reflection properties. A material definition is an entity that contains both color information and optical and geometric properties of light reflection and transmission. The interaction between light and matter can result in very different reflection modes (Born and Wolf, 1999). A chalk-finished wall reflects light in a Lambertian way, that is, uniformly in all directions, therefore, once a sample point is taken on its surface, this appears to us with the same luminance even if we change our angle of observation.

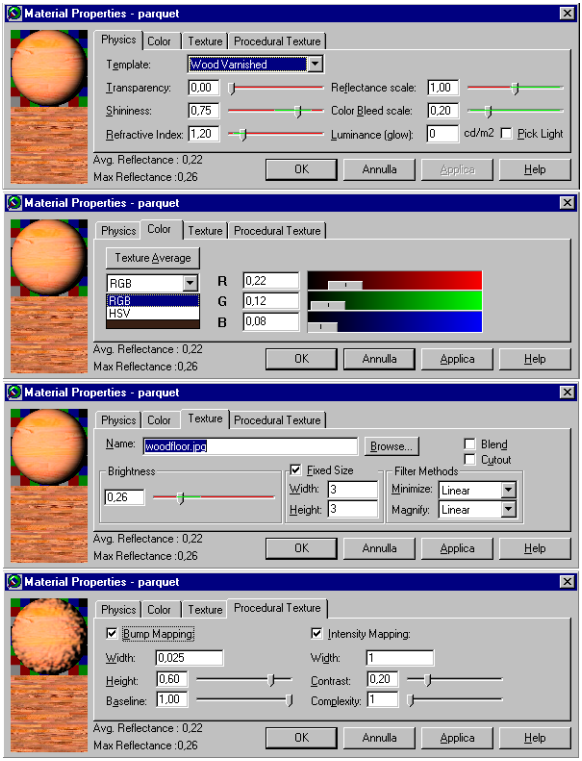


Figure 4.11 A window for defining material properties makes it possible to control the physical appearance, color and textures that characterize materials that can be associated with surfaces.

Conversely, the mirror in which we observe ourselves early in the morning reflects light only in one direction, at an equal but opposite angle to the normal to the surface. In reality there are no ideal perfectly specular or perfectly diffusive surfaces, but all surfaces exhibit a combination, in varying percentages, of these two characteristics. The same considerations can be made regarding the transmission of light through a transparent material.

All software allows materials to be managed through a materials table applied to geometric models of the environment. Material definitions are shown in this table, and from it various management operations can be carried out, such as:

- Creating a new material.
- Saving materials in library files.
- Loading materials from library files.
- Duplicating a definition of material.
- Modifying the characteristics of a material.
- Dragging, with the mouse, a material onto a surface to associate it with that surface.

The definable characteristics of a material determine the appearance of its surface, the amount of light that is reflected and/or transmitted by the surface, and the manner in which reflection and/or transmission occurs. These characteristics, which also include the definition of color and texture, if any, can be controlled in the material properties window.

Since defining the characteristics of a real material according to the parameters presented is a particularly complex task requiring a high level of expertise, the program helps the designer through an extremely useful feature: physical templates. These provide definitions of the physical parameters of a range of materials that can be encountered in everyday reality, such as, for example, raw or painted wood, glass, metals, wall, paper, plastic, and many others. When a template is selected, the physical material definition parameters are automatically set by the program. The designer still has the option of modifying them, but within a limited range of variability, indicated in green color under the parameter control, so as not to distort the material characteristics. Physical parameters make it possible to control:

- Transparency, which is zero for all opaque materials and increases to unity for transparent materials such as crystal, glass, and water.
- Gloss, which determines the percentage of specular reflection of the surface. If it is worth zero the surface is pure Lambertian, while if it is worth one it is specular.

- The refractive index, which, in the local calculation model, controls the light refraction of transparent materials, but it also controls the mirroring effect of opaque materials; indeed, as the refractive index increases, the percentage of specularly reflected light also increases, giving the material a shinier appearance.
- The reflection factor, which allows the total percentage of light reflected by the material to be increased or decreased.
- The control of reflected color or color bleeding. This is a very important feature that serves to decrease the coloration of light reflected from a surface without altering its amount. The purpose is to soften any color dominance that might occur in the room when a lot of light reflects off a saturated-color surface, then diffusing into the room. Indeed, we know that due to the phenomenon of chromatic constancy, the human perceptual system tends to diminish the effect of these chromatic dominants.

Figure 4.12 Effect and compensation of color bleeding. The image on the left has a gray floor. In the one in the center, the floor has been changed to a saturated light blue, blue reflected light affecting all surfaces in the scene. On the right, the color bleeding of the blue floor has been reduced by 90%.

The color of a surface can be homogeneous, and in this case it is best managed through the HSV model, or it can be determined by a surface texture (Blinn and Newell, 1976). The HSV model defines color by hue, saturation and percentage of reflected light (value). The texture is an image stored in a file that can contain any kind of graphic information; the image of a painting, the grain of wood or marble, the pattern of a tile, and anything else that can be imported from the real world with a common camera and image capture scanner as long as it has a proper color capture management procedure. No software does a physical verification of the correctness of the material. For this reason, an unwise designer might also choose the template

of a metal and associate it with the texture of a parquet floor, thus committing a serious design error.

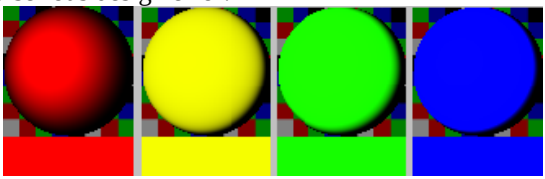


Figure 4.13 The hue control makes it possible to choose a fundamental color from those in the rainbow.

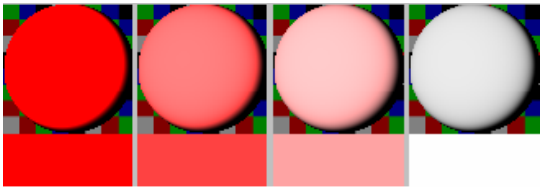


Figure 4.14 Saturation control determines color purity, that is, the amount of white that is added to the fundamental hue.

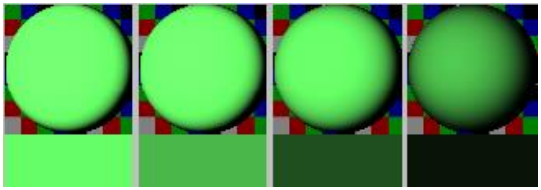


Figure 4.15 Value control determines the total percentage of light reflected from the material, the rest of the light is absorbed. The light reflected from a surface contributes to the overall illumination of the room.

Since the texture is a bitmap-type image imported from a file that can be of various formats, but is still a map of points, the program allows makes it possible to determine the scale factor by which the image size is projected onto the surface of the material. High scale factors could give rise to aliasing effects, showing the image dots greatly enlarged and resembling colored tiles. One solution is to use textures defined by very high-resolution images; however, this approach requires the availability of a lot of memory in the computer and can slow down the calculations considerably. Instead, it

is recommended to use low resolution images and enable the anti-aliasing features that are always provided by the programs.

Figure 4.16 Surface textures make it possible to increase the realism of surfaces. Courtesy of Gianluca Guarini.

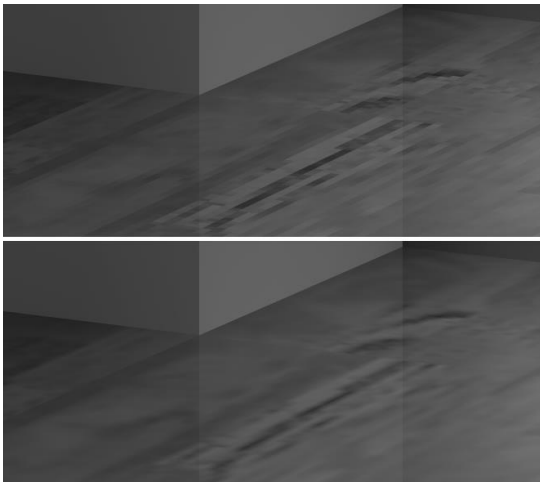


Figure 4.17 Enlarged detail of the parquet texture, without filter (top) or with linear interpolation filter (bottom).

In addition to surface textures, the software also makes it possible to define other types of procedural textures that change the appearance of surfaces. The procedural texture is not an image, but a mathematical function associated with the surface, which changes the behavior of one or more parameters of the local computational model (Ebert *et al.*, 1998). This process is called bump mapping and, as the name suggests, makes it possible to show on the surface of the material a series of rough elements, grooves and protrusions of controllable frequency and size, such as in the peel of an orange (Blinn, 1978). This allows many relief effects used in human construction to be simulated, but they are only an optical effect that does not modify the surface geometry. Displacement mapping, which instead uses the content of an image or feature to actually change the geometry to which it is applied, is a method for simulating, for example, the fuzziness of carpets or other fabrics without having to shape them by hand (Cook, 1984). However, this effect can greatly complicate the geometry being computed and increase the time required to produce the images. Intensity maps, which change, by areas of controllable size and intensity, the level of reflection of a surface, make it possible to simulate the deterioration and soiling of real surfaces degraded by time and weathering, enhancing the realism level.

Figure 4.18 Example of applying bump mapping to walls. The relief effect is achieved by a perturbation of the normal in the material calculation; the surface geometry remains unchanged.

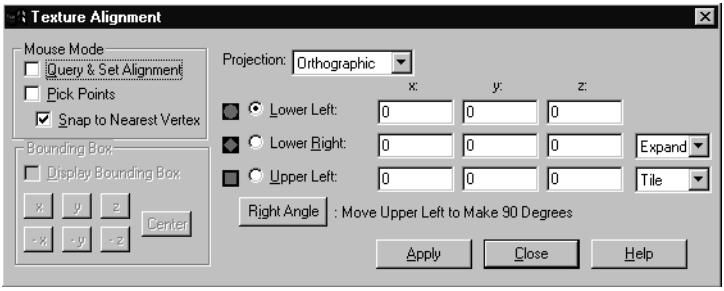


Figure 4.19 The texture alignment window. Through this function it is also possible to determine the type of projection, parallel, cylindrical or spherical, by which the image is applied to the surface.

Often it may be necessary to associate the same texture image with several adjacent surfaces. Two basic rules must be followed for proper image coupling: the texture image must be wrapped and coupled on the four adjacent sides, taken in pairs, without discontinuity; the program user must provide texture alignment through the specially provided functions. These features also make it possible to determine the type of projection with which to apply the texture to the material and how to repeat the image on the surface.

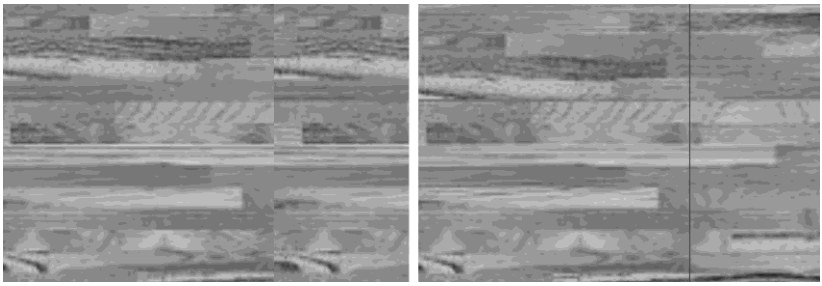


Figure 4.20 Incorrect (left) and correct (right) texture alignment at the joining line between two adjacent surfaces.

4.6 The management of light sources

In lighting simulation software used for lighting design, it is essential to consider both artificial and natural light sources in order to obtain a realistic evaluation of the luminous environment. Artificial luminaires represent controllable sources whose photometric distribution and spectral characteristics can be defined through measured or manufacturer-provided data. However, in most architectural situations the visual and luminous conditions of a space are also strongly influenced by daylight, which includes both the direct contribution of the sun and the diffuse luminance of the sky vault.

The direct component of sunlight originates from the solar disk and can be described as a highly directional source whose position changes continuously according to geographic location, date, and time of day. This component produces well-defined shadows and strong contrasts and is therefore responsible for significant variations in illuminance and luminance within interior and exterior spaces.

In addition to this direct component, daylight also includes the diffuse light coming from the sky. Unlike direct sunlight, sky luminance is distributed across the entire celestial hemisphere and results from the scattering of solar radiation in the atmosphere. Its distribution depends on numerous factors, including atmospheric conditions, cloud cover, turbidity, and the relative position of the sun. As a result, the sky can exhibit very different luminance patterns, ranging from nearly uniform overcast skies to highly anisotropic clear-sky distributions. For this reason, lighting simulation tools must incorporate models capable of describing both electric lighting systems and the various components of daylight, allowing designers to evaluate their combined effects on the overall lighting performance of architectural spaces.

4.6.1 Artificial light sources

In software useful for lighting calculation, a luminaire is a photometric solid with light intensities (Roelens, Fertey and Peroche, 1992), with which a geometric block is associated that defines its shape and geometry. This can also be a single polygon, but it must still exist as a geometric model. This implies that the devices must be visible as they are in everyday reality.

Depending on the software, the usable photometric solid is that which can be obtained from online catalogs of manufacturers and, generally, should be relative to the luminaire rather than the lamp. Excluding the case where the luminaire consists of an elementary structure and actually coincides with the lamp itself; for example, in the borderline case of a bulb hanging from a

wire. Using the photometric solid of a lamp and placing it within the geometry of the luminaire to obtain the final illuminance effect, leads to a serious computational error. Indeed, no lighting calculation software can simulate the behavior of light within the lighting product.
However, the ability to represent the shape of luminaires is a significant potential provided by programs for supporting lighting design in relation to architectural structures. However, the following question arises: if the program uses the photometric solid of the luminaire, and these two elements are geometrically coupled in neighboring areas of virtual space, could the geometry of the luminaire model affect the photometric solid and change the calculated distribution of emitted light intensities, thus generating a calculation error? Unfortunately the answer, as paradoxical as it is, is affirmative (Ward and Shakespeare, 2004).

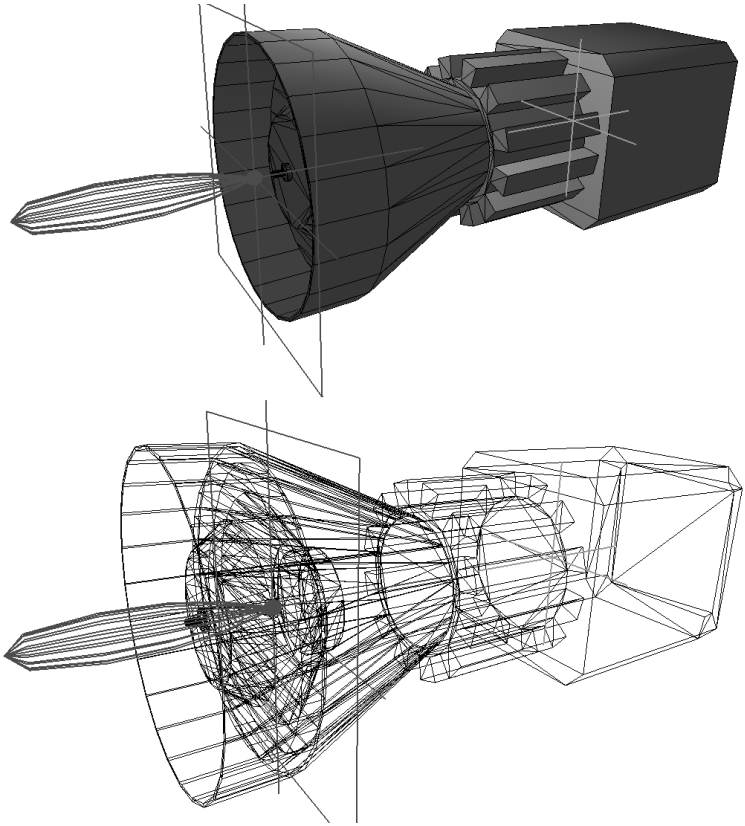


Figure 4.21 The paradox of the interaction between geometric model of the luminaire and photometric solid of the same, shown with an Erco Eclipse 75326 projector. Top: The photometric solid is applied externally to the luminaire and only develops in the half-space where the geometric structures are not, so there is no harmful interaction between the two. Bottom: The center of the photometric solid has been moved inside the luminaire and is still changed whether the material is transparent or opaque. Placing the center of projection always on the outside of the photometric solid is generally not correct, as that may not be the correct position, or the photometric solid may have an intensity distribution over the whole space around the center, and therefore the direction of light would still end up meeting the geometries of the luminaire.

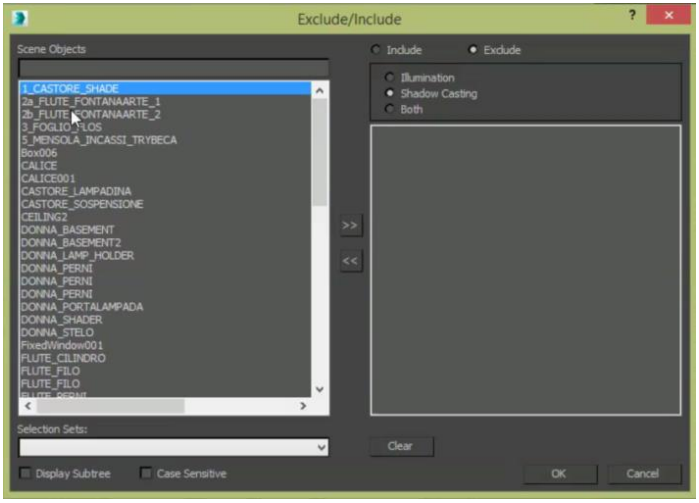


Figure 4.22 Window for checking/excluding the geometric structures of a luminaire from the light calculations that are made for its photometric solid.

To solve this problem, the software allows the designer to implement a little trick. It is necessary to select all luminaire surfaces that can affect the photometric solid and exclude them from the lighting calculation for that light source. This feature makes it possible to determine that the selected surface does not occlude or reflect light during calculation. This trick has nothing to do with the characteristics of transparent materials and does not even make any sense from a physical standpoint, yet it allows the above problem to be solved by making a negligible computational error. In real terms, ambient and luminaire light will neither be reflected nor occluded by

these surfaces, but since these are generally very small, the calculation error generated is minimal.

In some cases, the proximity between the center of the photometric solid and the luminaire surfaces means that these, due to computational approximations, are not as bright as in reality. Therefore, through another artifice, it is possible to define materials with their own luminance, independent of the light in the environment. Through this self-brightness function, defined in cd/m^2, and by applying this material to the illuminated surfaces of the luminaire, the luminous surfaces can be represented. Since luminance depends on location, this artifice is therefore an empirical method, and it is difficult to establish appropriate luminance values for all possible cases. The following table, listing some typical commercial products and plausible observation positions, can help determine the luminance value:

	a = b =
Lighting Bulb, Philips (diam. 55mm x 50mm - 414lumen – sosp.) **14082** cd/m^2	
Castore, Artemide (diam. 420mm - 4200lumen – sosp. a soffitto) **2327** cd/m^2	a=300cm - b=50cm
Tolomeo, Mega, Artemide (diam. 320mm – 1999lumen– da tavolo) **1202** cd/m^2	a=100cm - b=60cm
Float circolare, Artemide (diam. 555mm - 4000lumen – sosp. a soffitto) **843** cd/m^2	a=300cm - b=100cm
Glo Ball Basic 2, Flos (diam. 450mm h.350mm – 4210lumen – da tavolo) **917** cd/m^2	a=100cm - b=20cm
IC F1, Flos (diam. 200mm h.1350mm – 820lumen – da terra) **8180** cd/m^2	a=100cm - b=15cm
Puck, Vibia (diam. 318mm – 671lumen – applique da parete) **880** cd/m^2	a=300cm - b=50cm
Light Fields, Zumtobel (600x600mm – 4290lumen – soffitto) **1361** cd/m^2	a=300cm - b=110cm
Ecoos LED a Sospensione (1200x120mm– 4030lumen – soffitto) **2195** cd/m^2	a=300cm - b=50cm

Figure 4.23 Table of luminance values for some typical commercial products according to a typical observation position.

Based on the photometric solid, which geometrically describes the light intensity coming out of a luminaire, the program performs the lighting calculation through the first step of the global calculation model. The geometry associated with the photometric solid determines the size of the surface from which the light exits the luminaire, and this influences a very important aspect of photorealism: the shading of the shadows that will appear in the final rendering. How this is handled may differ between software programs, but it is based on a fundamental principle: all luminaires have a defined geometric dimension from which light comes out, which is larger than the size of the light source they contain.

Figure 4.24 In the case of this downlight with a halogen source, light actually comes out of the entire circular area shown in yellow, although it is emitted only by the small lamp in the center.

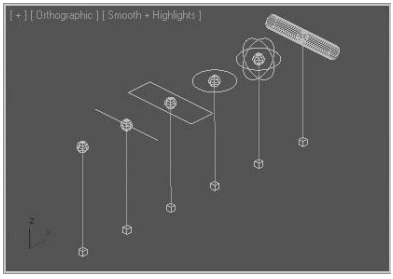


Figure 4.25 Examples of dummy surfaces that can be associated with the photometric solid to simulate the light-emitting surface from a real lighting product.

The types of geometric shapes that can be used to simulate the light-emitting surface are generally those listed below:

- Point: Light comes out of a point; rather unreal, maybe only single LEDs can be considered this way, it is hardly ever used.
- Line: Light emitted from a line; also quite unreal, perhaps usable with some LED strips, but only in very limited cases.
- Rectangle: Light emitted from a rectangle; this is a very real and common case for most products.
- Disk: Light emitted from a circle; this is also a very real case, such as the output area of a projector.
- Sphere: Light emitted from a spherical shape, such as a frosted glass bowl.
- Cylinder: Light emitted from a cylindrical surface, can simulate many elongated luminaires that emit light over their entire surface.

Figure 4.26 Control of shadow gradation in rendering calculation. Top, point source. Middle, linear source. Bottom, area-type source. Each source emits a flux of 1750 lm. On the left, the reflectance level of walls and floor has been reduced by 30 %.

This aspect may not be decisive for the correctness of the lighting calculation, but it is crucial for rendering purposes, since in reality we never have sharp shadows, but these always have a gradation that depends on three factors: the size and shape of the lighting products, the number of light points in the room, and the nature of the materials of the surfaces in the room. A small source tends to produce shadows sharper than one with a linear-type geometry or extended area; as the number and distribution of sources increase, shadows tend to fade; the presence of light-colored materials with Lambertian reflectance tends to increase the amount of indirect illumination for diffuse inter-reflections, softening the contrast of shadows.

We leave as an exercise for the reader a practical check of the contrast and level of shadows present in daily living environments. Therefore, factual experience allows us to state that a correct and accurate illuminance calculation, although more time-consuming, is certainly better suited in most applications aimed at obtaining photorealistic renderings of lighting designs.

For the management of the luminaires used in the project, the software then provides, in the luminaire table, a number of useful features to define four basic aspects of the luminaire:

- Source geometry.
- The position and orientation of the photometric solid with respect to the intrinsic coordinates of the geometric model that defines the luminaire. This should not be confused with the orientation of the device within the room.
- The photometric solid, loading it from a file in .ies or .ld format.
- The color characteristic of the lamp by choosing it from those used in lighting design, such as, for example, incandescent, fluorescent, halogen and many other sources, or by directly defining the color temperature.

Regarding color, recent studies have highlighted significant limitations in the way lighting design and visualization software manage color information. In lighting simulation tools, light sources are often simplified and described using RGB values, which do not correspond to the actual spectral power distribution (SPD) of real luminaires. A design-oriented approach proposes integrating spectral information into lighting design workflows, allowing more accurate descriptions of colored light sources and

their interaction with the environment (Rossi, 2023). At the same time, research on BIM-based visualization systems has shown that maintaining color consistency between real materials and their digital representation remains an open issue. Differences in rendering engines, color management practices, and visualization pipelines can lead to discrepancies between the intended design color and the color perceived in digital images (Guarini and Rossi, 2024). Together, these studies underline the need for improved color management strategies that bridge the gap between the physical properties of light and materials and their representation in contemporary digital design tools.

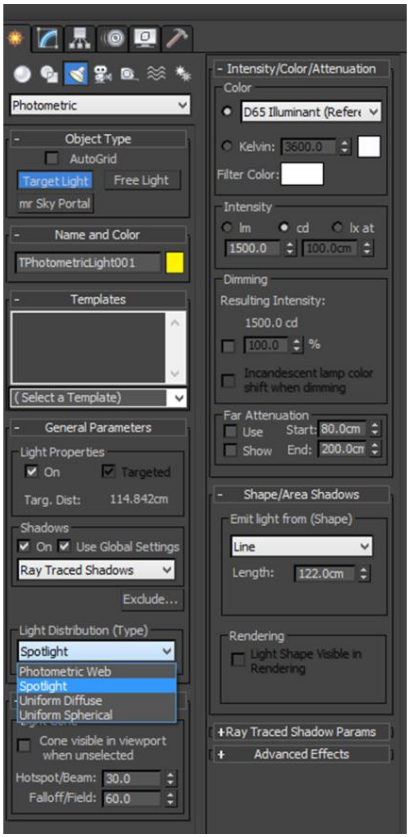


Figure 4.27 Example of a window controlling all parameters of a luminaire.

Once the position of the photometric solid has been established with respect to the geometry of the luminaire model, this can be moved and oriented as appropriate with the translation and scaling transformations also available for geometric blocks. However, compared to the latter, a transformation applied to a device will have a joint effect on both the geometry and the photometric solid.

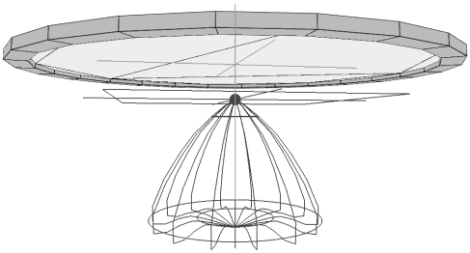


Figure 4.28 Example of intrinsic coordinate systems and geometries defining a recessed luminaire. The coordinate system of the geometric block and those of the photometric solid are distinguished.

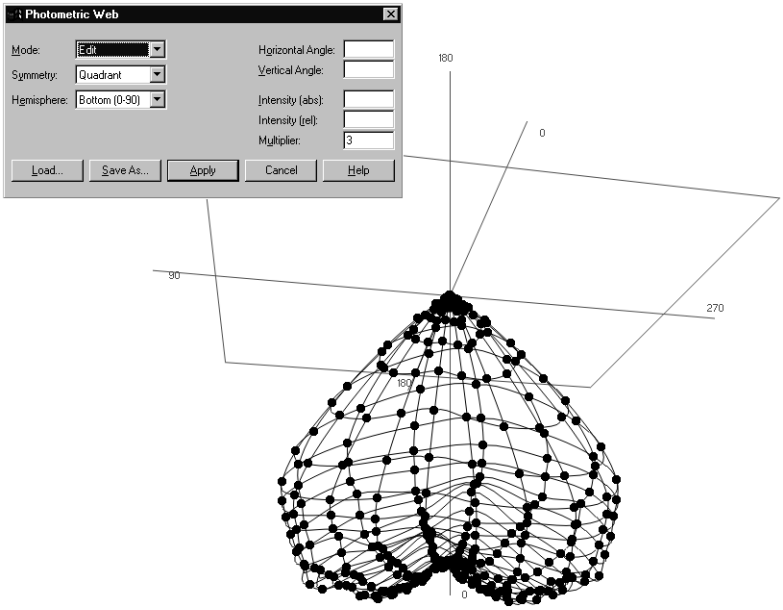


Figure 4.29 Example of a photometric solid editor. It is a tool for creating and editing photometric solids in 3D.

These programs also make it possible to define generic light sources with Lambertian, isotropic and spot emissions. However, such solutions are to be avoided because they do not relate to real lighting products. The most correct method is always to determine the shape of the light emitted by a luminaire, by selecting a file in which the photometric solid describing the luminous intensity distribution is defined.
In case the photometric file in the format provided by the manufacturer cannot be handled by the software, there are conversion programs such as QLumEdit available free of charge on the Internet, which also allows the user to view all the photometric information of a product.
In other cases, which are uncommon today, the information inherent in the distribution of light intensities that define the photometric solid could be provided in hard copy, for example in technical catalogs. For this eventuality, some programs provide a function through which a 3D photometric solids modeler allows users to enter data related to light intensities in a graphical format.
The same function can be used to analyze the photometric solids provided with the program library, or even to create new ones in the event that a luminaire must be produced with specific photometric characteristics. In this way, designers can reconstruct the luminous intensity distribution starting from tabulated or diagrammatic data and integrate it into the digital model used for simulation and calculation.

4.6.2 Daylight management

In reality, natural light from the sun is diffused by the atmosphere depending on the climatic conditions of air humidity (Languénou and Tellier, 1992). In the virtual environment, this phenomenon is simulated by means of two types of illuminance, that produced directly by the sun, which has a strong directional characteristic, and that from the sky, which is of the diffuse type (Mardaljevic, 2000).
As is intuitive to imagine, the total amount of natural light that contributes to room illuminance obviously depends on how the room is oriented with respect to the cardinal points. In the northern hemisphere, a façade or window facing north will never receive direct sunlight, but the exact opposite is true if you move to the southern hemisphere.
So another important parameter that we should be aware of is the latitude of the site where the environment is located; at the equator the illuminance is certainly higher and at a different angle than in Scandinavian countries, and

the magnitude of this difference also depends on the time of year and the time of day.

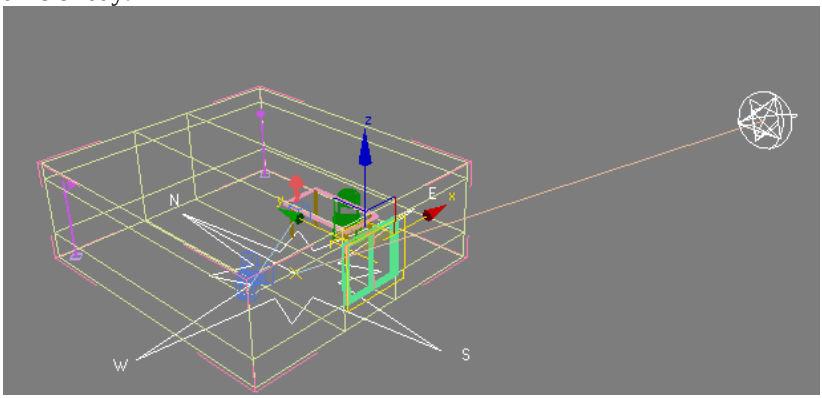
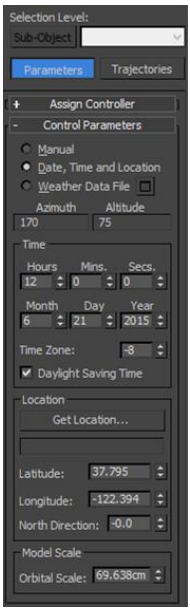


Figure 4.30 Example of defining cardinal points with respect to an indoor environment. The fictitious position of the sun depends on a multiplicity of parameters and identifies the direction of the sun's rays, which, given the distance of the sun, are all considered to be parallel to each other.



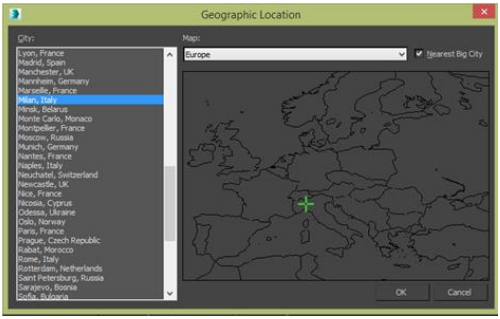


Figure 4.31 Example of the definition of all the parameters that contribute to determining natural light. Date of the year, time of day, and location on the globe.

With parameters quite similar to those of artificial light, it is possible to include, for both direct sunlight and sky light, light sources. A fundamentally important aspect of calculating natural light in interiors is to define the windows and openings from which light can penetrate and diffuse into the room. Contrary to what you might think, it is not enough to consider window glass materials transparent. In fact, the material characteristic mainly influences the appearance of the material with respect to the visual properties of reflection and transparency.

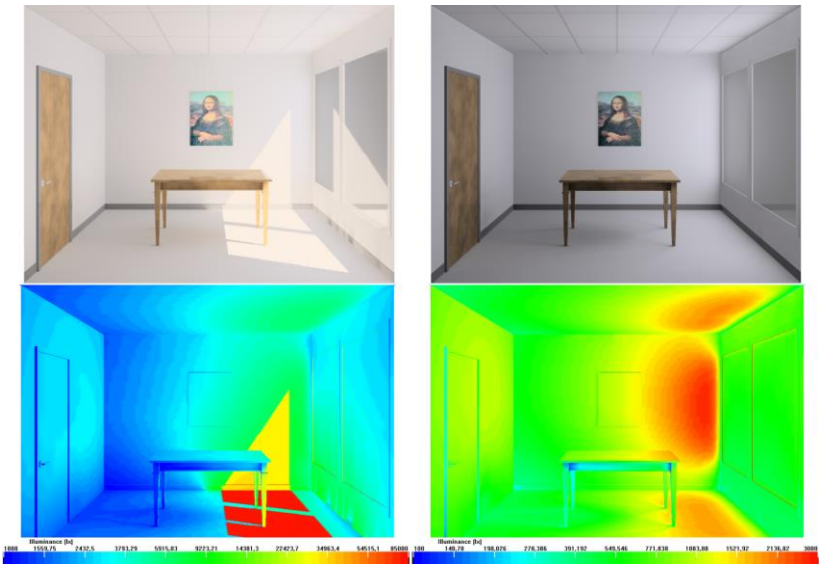


Figure 4.32 Milan June 21, 11 a.m. (daylight saving time), east-facing windows, comparison of the natural lighting present in an interior on a clear day (left), and on an overcast day. Below, comparison of illuminance levels with different false-color logarithmic scales.

It is therefore necessary to add geometric structures, such as sky portals, that allow the software to know how to calculate the sky light entering from the outside, thus avoiding many unnecessary calculations related to all the light rays hitting the outside of a building. In order, the steps to define natural light are as follows:

1. Definition of windows and openings from which light can enter the indoor environment through sky portals.
2. Time zone definition with respect to Greenwich.
3. Selection of annual date.
4. Selection of the time of day.
5. Selection of geographic location.
6. Orientation of the floor plan of the environment with respect to the cardinal points.
7. Definition of the weather condition of the sky, between clear, overcast, or intermediate cloudy conditions.

If any of the parameters listed above are changed, it is necessary to repeat the global calculation model. In addition, natural light produces illuminance levels that can be three orders of magnitude higher than those of artificial light. Thus in an interior surfaces exposed directly to the sun may have illuminance levels in excess of 50,000 lux, as opposed to the 500 lux that can be produced by an average level of artificial lighting. The computation of natural light and in particular sky light, which is simulated with a huge invisible virtual hemisphere surrounding the environment, involves a very large number of counts and a consequent increase in computation time.

4.7 Calculations and results

4.7.1 Calculation parameters

The calculation of global light is done in two successive steps. In a first step, Radiosity (Cohen and Wallace, 2012) or Photon Mapping (Jensen, 2001) determines the light emitted by the sources and diffusely reflected from the surfaces, essentially carrying out the lighting calculation. By the end of this phase, the designer can already make virtual measurements and technical representations of the illuminances and luminances in the environment using various methods, as explained in chapter 3.

The use of backward Ray Tracing (Whitted, 1980), in the second step, is a method by which to increase the level of photorealism for specular reflection effects, transparencies and appearance of materials. These phenomena occur in the presence of polished stone materials such as, for example, marble, or large windows with views inside and outside the room. Another very important aspect of the second calculation phase is the possibility of adding the effects achievable with procedural textures to increase the level of photorealism of materials.

In all software, however, the calculation parameters can be divided into two main categories: the parameters that influence local computation, which are modifiable for each individual surface and determine the behavior and

appearance of materials, and those that control computation for the entire environment on a global level. We have already seen the calculation parameters that act locally on lights and surfaces by presenting materials, luminaires and natural light.

Another delicate and difficult aspect to control in the calculation phase is the level of subdivision of surfaces for polygonization (de Araújo *et al.*, 2015). Typically, this parameter is controlled globally for the entire environment. However, there are special cases where it is appropriate to change it manually for some individual surfaces. As the level of subdivision increases, the accuracy of the computation increases, but so does the computation time. Thus, the management of the partition parameter is based on an optimal choice that reaches a good compromise between accuracy and computation time. A fairly uniformly illuminated surface does not need to be subdivided into as many faces, but the more the illuminance varies, the more the adaptive method provides for its subdivision into an increasing number of faces, automatically and according to the level of computational accuracy required by the designer. However, the initial subdivision of surfaces into flat faces, depends on the modeling program used, and in many cases, unfortunately, can be irregular, presenting a mixture of triangular, quadrangular and other faces. This can result in visible artifacts in the calculated illuminance levels, so the level of subdivision of some surfaces must be manually controlled by the designer. In these cases you have to go back to the modeling system to generate a smoother polygonization. This problem frequently arises in design practice, for the 3D models with which the lighting designer has to deal have often been made by other people and for other purposes than lighting calculation and photorealistic rendering of light, and any reconstruction of them would require a significant increase in the time and cost of the lighting design process.

The control of global calculation parameters for the environment is always possible for all rendering software, and often involves several dozens of different parameters. For the definition of these parameters, an even higher level of preparation in the area of image synthesis is required of the user, skills that exceed the curricular training required of the lighting designer. For this reason, lighting CADs typically present shortcuts with a very useful simplified functionality, accessible through a special command with dialog boxes in which the program asks questions to the designer to semi-automatically set global calculation parameters. In this dialog box, it is possible to define the level of accuracy of the calculations for a few main parameters from a choice of several different levels. The lowest is the

fastest, but also the least accurate, while the opposite is true for the highest level. In order to save time it is generally convenient to start with a low level of accuracy during the design processing phase and then refine the calculations for the final design checks and the production of technical representations and renderings.

Figure 4.33 Example of Photon Mapping parameter control. Top left: Small hemisphere and number of photons emitted by light sources too low, resulting in a very approximate indirect illumination lighting calculation. Top right: Small hemisphere but the number of photons emitted by the light sources has been greatly increased, resulting in a correct lighting calculation. Below, compared with the previous image, the radius of the hemisphere and the number of samples considered in each hemisphere was increased to the minimum necessary to smooth the sampling of the photon map.

In the first stage of the global calculation, if, for example, it is carried out by the photon mapping method, among many others there are 4 basic parameters:

- The size of the integration hemisphere of the photon map.
- The number of samples considered in each hemisphere.
- The number of photons emitted by light sources.
- The maximum number of photon reflections on surfaces (generally not less than 10).

For a correct lighting calculation, it is always convenient to start with a small size of the hemisphere and the samples considered in it, and gradually increase the number of photons emitted by the light sources until a good coverage of the surfaces is obtained, and then increase the size of the hemisphere and the samples considered in it to the minimum necessary to have a good average uniformity of light on the surfaces.

For the second step of the global calculation method, some of the parameters that can be controlled at this stage concern: the precision of image calculation, the precision of shadow gradation calculation, the precision of glossy reflections calculation, the precision of transparency calculation, and the maximum number allowed by the user for reflections and refractions of light rays.

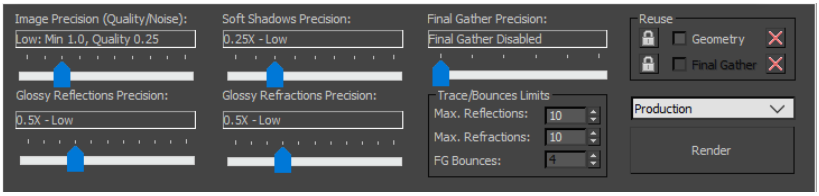


Figure 4.34 Example of a window that makes it possible to control the accuracy of the second calculation step (Ray Tracing) to obtain renderings.

4.7.2 The virtual camera for rendering

To achieve a good rendering, a virtual camera framing from which the desired view is to be obtained must first be defined (Kolb, Mitchell and Hanrahan, 1995). With this, the designer can immerse him or herself in the virtual environment and place the camera. Similarly to a professional camera, the parameters that can be defined for framing are:

- The size of the film/sensor. For example, 35 mm on SLR cameras. This determines the existing relationship between focal length and angle of view.

- Focal length. For example, 20 mm for a wide-angle lens or 100 mm for a frame similar to a telephoto lens, this parameter is inversely proportional to the view angle.
- The exposure of the image that depends on three parameters: aperture, exposure time and equivalent film sensitivity (in ISO).
- The location of the camera.
- The position to which the camera is oriented.
- The tilt angle, i.e., possible rotation about the axis of the lens for slanted shots.
- The cutting planes of the image. A virtual trick, which has no analogy in photographic reality, and allows everything within, and beyond, a certain distance from the observer to be removed from the shot.

The position of the camera and that of the observed point can also be selected interactively with the mouse on the project plan. In addition, each view definition can be saved, associating it with a reference name, in order to reuse it later without the need to have to redefine camera parameters.
Similarly to what is done with an ordinary camera, the relationship between film sensitivity and exposure time must then be established. In other words, the perceptual problem of the virtual image must be solved. This is the most difficult aspect of producing photorealistic images.
Indeed, based on what we have seen in the previous chapters, we know that the dynamics of luminance variation in a photorealistic virtual synthesis image is a couple of orders of magnitude higher than the luminance dynamics reproducible by classical reproduction devices, such as a monitor and printed paper.
A starting point for determining these values is to decide whether the image concerns an exterior or an interior illuminated by artificial light alone or by natural light. In the case of natural light, you can start with f/4.0 values, ISO 200 and 1/125s and change the exposure time depending on the framing and the amount of light actually present, because natural light can change a lot depending on the location of the framing and the characteristics of the visible materials, the time of day, day, geographical location of the environment and the weather conditions of the sky.
In the case of artificial light, an ISO sensitivity equivalent to 400 or 800 should be set, exposure times from 1/10s to 1/50s, and a fairly open f/1.4 aperture.

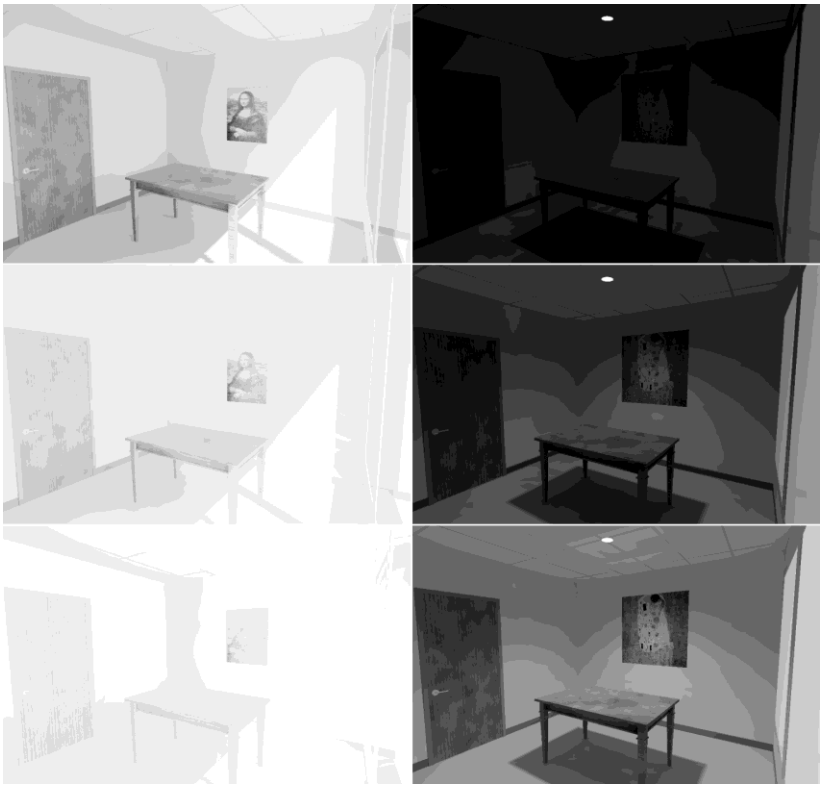


Figure 4.35 Variation of rendering according to virtual camera exposure. From top to bottom increasing exposure. On the left direct natural light, on the right artificial lighting with a 1750 lm lamp flux.

It is important to note that exposure control should be done according to the amount of light in an environment, but an overexposed image should not be confused with an overlit project, as the actual amount of light is determined based on the technical analysis presented in the previous chapter.
For all the environments and images made, one must then, through a series of attempts, arrive at the exposure values that, under the various conditions, allow one to create images that most closely resemble reality. In this experimental activity, it is extremely important to consider parallel to the

renderings the same images in the form of technical representation of false-color luminance levels. Indeed, it is the set of perceived luminance levels that contributes to the adaptation phenomena of the human visual system, and the ability to learn how to associate certain exposure levels with perceived luminance levels is still one of the most keenly felt problems in this field.

However, exposure management of synthetic images is not an exact science, and even the experimental approach presented above cannot solve some problems, one of which is particularly important: the possibility of simultaneously comparing virtual photographs of the same scene taken at completely different illumination levels, artificial light and natural light, in order to evaluate illuminance levels. In fact, that perceptual condition is not realizable in reality. If the same exposure parameter is used for the two images, one of them will definitely be underexposed or overexposed, while using two different parameters will compensate for the real perceptual difference between the two. Better then, for the purpose of comparing illuminance or luminance levels, to rely on false-color images, and to separate the presentation of photorealistic views with natural light from those with artificial light. The problem of correct perception of synthetic images, which we have mentioned several times in the text, is an open problem of worldwide research that is aimed at describing a more complete model of perception than the CIE tristimulus theory. In the case of mixed lighting, the problem arises only as natural illuminance levels decrease.

The last step in producing the photorealistic image is to take the virtual photograph. The function used for this purpose is accessed through the classic Render command, which activates the render control window for the set camera frame. Do not confuse real time renderings, which are available as wire-frame, flat, and Gouraud renderings that can be properly used only as a representative function of the geometries of the environment but are of no value from the standpoint of light and material analysis, with photorealistic rendering that can be computed using a two-step global computation method.

In the rendering control window you must indicate the name of the file in which you want to save the image and what size in pixels it should be. The file containing the image can be in various graphic formats, but we do not recommend using formats, such as JPG, which, while having the advantage of a high level of data compression, cause degeneration of the quality of the synthetic image. The concept of image compression is related to the size of the stored files. Indeed, the purpose of compression is to decrease the amount of data needed to store the image without altering its size, resolution

and quality. Some compression algorithms (such as jpeg and mpeg) allow for high levels of compression at the expense of image quality. Others prefer to compress less (such as LZW, Packbits, and RLE) to safeguard 100 percent of the original image quality. The most commonly used format is TIF. The latter is compatible with various compression algorithms that do not degrade image quality, such as the LZW format. Compression is extremely important because high levels of resolution must be used to make good quality images, and these generate large files. In addition, the programs can make it possible to automatically make a series of images according to previously defined views or, even, individual frames of a digital video. The large number of images can then saturate the computer's hard disk by blocking the program's automatic generation of renderings.

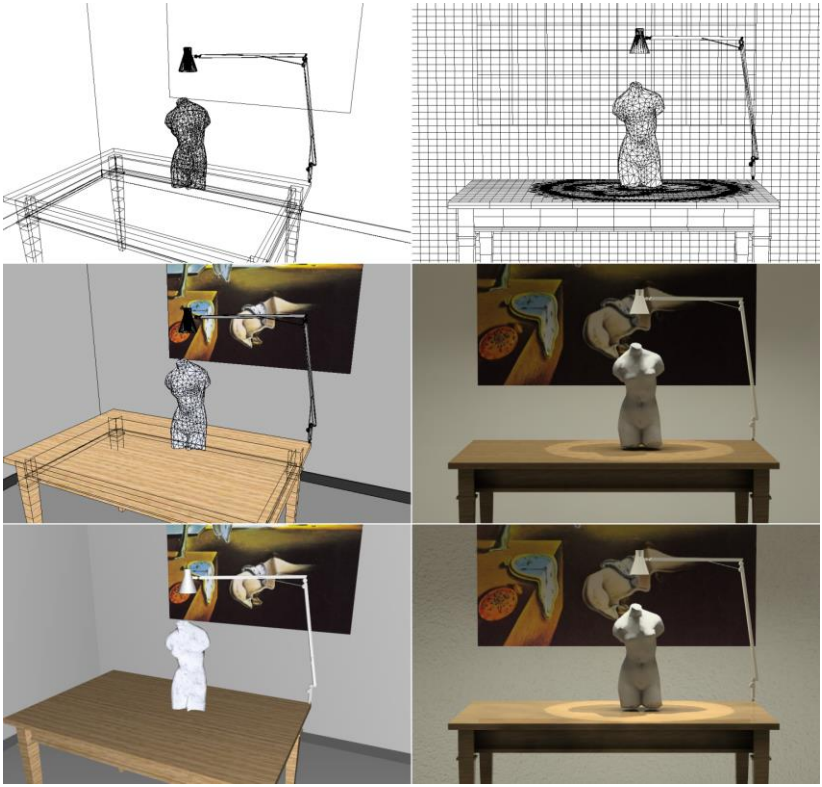


Figure 4.36 Types of images that can be created. Left from top: Wire-frame, flat-shading and Gouraud-shading. Right, from top: Wire-frame, calculation of the first step only and calculation of the second step as well.

4.7.3 Videos

If a picture is worth a thousand words, what about a movie? Once the calculation of the first step of the global model is finished, the program can make it possible to make digital video footage of the environments in which the lighting design was made. The frames can then be edited and possibly dubbed to make a digital video. For each frame, only the framing position changes, so only the second step of the global model, i.e., Ray Tracing, needs to be recalculated. This requires defining the parameters of the animation. In this case, the animation must be relative only to the observer; actually, the movement of any object in the environment would result in the need to have to recalculate the first step of the global model as well. To create a new animation, it is necessary to define what follows:

- The path of the observer, via a three-dimensional parametric curve that can be modeled as desired.
- The movement of the observer on the path, which can be constant or vary according to time, thus giving rise to acceleration and deceleration.
- The observation orientation, which is the direction of observation at each point on the path.

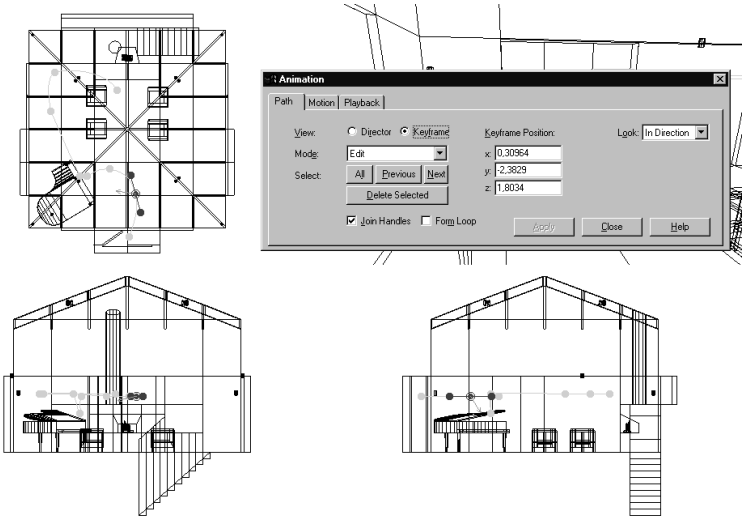


Figure 4.37 Sample dialog box for managing animations in path line definition mode.

For path definition, the graphics window is divided into four parts that present the three orthogonal views and the perspective view to the designer. The path curve is defined by a set of points called keyframes; these can be added to or removed from the curve. In addition, in each keyframe you can control the radius and angle of curvature on either side of the point. The first and last keyframes can be linked automatically in order to make a cyclic animation that ends in the same frame from which it began.
For motion control, the Cartesian graph of space versus time is shown, and the line described on this graph represents instantaneous velocity. On the abscissae is the time, and on the ordinates is the space on the path curve. On the velocity graph, keyframes are represented through appropriate elements; thus the user can associate the space traveled on the curve, with time and velocity in the various keyframes. The instantaneous velocity curve can also be modified as desired by inserting points to control its trend. Through a specific parameter, it is also possible to define the number of frames per second that are intended for the animation.

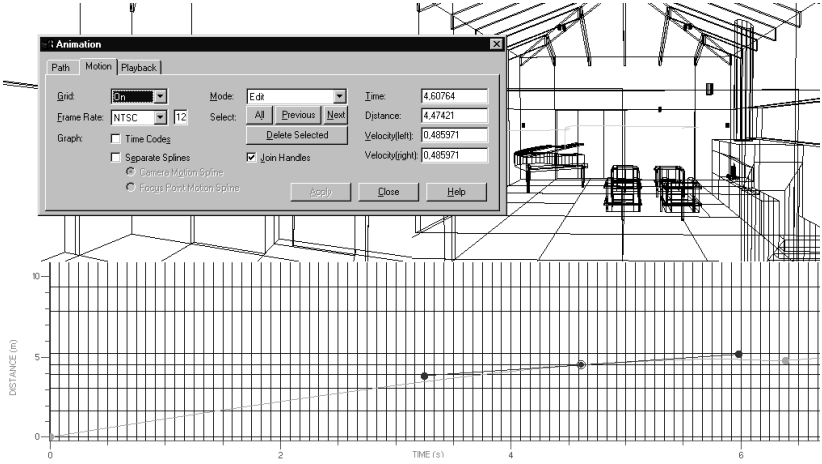


Figure 4.38 Example of graphic window in animation motion definition mode.

The definition of observation orientation can be accomplished by several methods that can also be integrated on the same path in different keyframes. The first method, which is the one initially used by the program to create a

new animation, is simply to look toward the direction of the path in which the observer is moving. The second method is to always observe in the same angular direction with respect to the reference axes. The third method makes it possible to look toward the motion path from a position ahead in time by a definable interval. The last method, on the other hand, enables observation toward a fixed point in space. In the graphics window, orientation is represented by a vector, associated with each keyframe, which can also be rotated as desired.
When creating animations, it is recommended that you always try wire-frame animation first. Once the animation preparation is finished, all photorealistic renderings, i.e., the frames needed for video editing, can be produced.

4.8 Case studies

Lighting design requires a multi-disciplinary skill set that obviously includes lighting engineering as one of its foundations. Experience has shown us that the technological and engineering character of the subject, based on the foundation of solid mathematical skills, can, in a variety of cases, be a significant obstacle in the basic training of the designer, directing him or her to other areas in his or her specialization stage. It is our belief that this attitude is mainly due to the purely theoretical nature commonly used in teaching the subject. In a field of education such as design, in which the theoretical nature of the fundamentals and applications of the subjects are generally complemented by the presentation and illustration of real experiments and practical cases, the risk of obtaining an attitude of rejection from some of those approaching the subject is really present.
The exclusively theoretical teaching approach to basic lighting engineering, however, is not motivated by a sadistic desire on the part of the teachers, but rather by the objective impossibility of having laboratory facilities and tools that allow for step-by-step comparisons of theory with practical experimentation. In addition, the spaces typically involved in light design do not lend themselves to laboratory prototyping due to economic, technological and especially perceptual problems.
And here, in this very gap between theory and practice, the innovative virtual prototyping of light can contribute to the construction of an integrated training path between the quantitative objectivity of formulas and the subjective qualitative perception. Indeed, the software tools that define the scopes of the virtual digital laboratory for light prototyping and experimentation, in addition to the support of the experienced designer, can

have an equally important function in the educational training of the industrial designer of light, for interiors and exteriors. Let's look at some examples.

4.8.1 Lighting of a building façade

Italy is extremely rich in historic buildings, and for many years now there has been a growing awareness with respect to the importance of restoring and preserving as well as enhancing our cultural heritage. Artificial lighting plays a crucial role in the urban scenic framing in which a historic building can make itself a performer in the evening hours. In many cases, viewing historical monuments and buildings at night can give us a different view of how much, on the other hand, day-to-day life conceals to a full appreciation. However, let us not forget that in almost all cases the work of the author of the building was done with the contribution of, and finalized according to, daylight. How much, and how, can artificial lighting distort the original perceptual idea? Can the temptation of excessive stage dramatization through the use of artificial light be justified by the purpose of enhancement, or must it be mediated and diluted so as not to turn the urban landscape of historic centers into the stage for an architectural performance? The chronicles of recent years, in industry and non-industry publications, report examples of criticism of both the excesses in the use of nighttime accent lighting and criticism of the opposite approach, in which artificial light has excessively flattened the contrast of luminances perceived by the observer. There is no one-size-fits-all criterion, everything has to be contextualized; in any case, the reader will have realized by now that the purpose of this text is not to provide definitive answers for this kind of evaluations, but rather to help the lighting designer, and those interested in the project, in an objective and subjective evaluation of these aspects through experimentation with the computational tools dealing with virtual prototyping.

To this end, we will consider the case of the Roman Theater of Aosta. The building is a rare example of a covered Roman theater. Due to earthquakes and the inexorable passage of time, only the façade and part of the bleachers remained. Adverse weather conditions have also heavily damaged the constituent materials of the remains, travertine and puddinga. On the virtual theater model we will experiment with two different approaches to artificial lighting.

The analysis of the actual location subject to artificial lighting must be the starting point of the design activity. Particular attention should be paid to the possible positions of the real observers, which should be reproduced in

the virtual model. In many cases these positions enjoy large degrees of freedom, so the lighting designer will have to make a choice about which positions to favor among the plausible ones. An analysis of the luminance levels in the building, structures, and surrounding nature is also extremely important. Indeed, at the urban level it is appropriate to determine whether, and how much, the luminance values of the building will have to be higher than the surroundings to give it a primary or secondary accent in the perceptual context.

The most difficult aspect of the analysis, however, is the reflection levels of the materials. Indeed, we have shown that luminance depends on illuminance levels but also on reflection factors of surfaces. And, even intuitively, we know that at the same illuminance, lighter surfaces appear brighter and gain a more accentuated perceptual dimension than darker ones. As we saw earlier, describing the correct spectral reflection characteristics of materials is one of the open problems of lighting design and, of course, also of its virtual simulation. For this reason, we will use the approximate benchmarks recommended in lighting design and given in industry manuals.

In the case of the façade of the Roman Theater in Aosta, the degraded and dirty condition of the surfaces mean that puddinga and also travertine should be considered in the category of medium-dark stones, which are characterized by low levels of reflection and therefore need medium to high levels of illuminance. However, the nocturnal surroundings are characterized by low to medium luminance levels that are lost to the distance in the darkness of the Aosta Valley mountains. Therefore, to give the façade an accent, which without overdoing it makes it stand out from its surroundings, we can assume an average surface illuminance between 60 and a maximum of 100 lux.

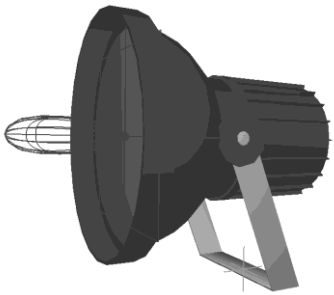


Figure 4.39 The luminaire used is a Bega 8394MHW outdoor floodlight with a 19,800 lm metal halide lamp, and maximum on-axis intensity of 14,870 cd.

Figure 4.40 Artificial lighting of the façade of the Roman Theater in Aosta, 20 m high and 28 m wide at the base, by means of two pairs of floodlights located on the ground 12 m away from the building.

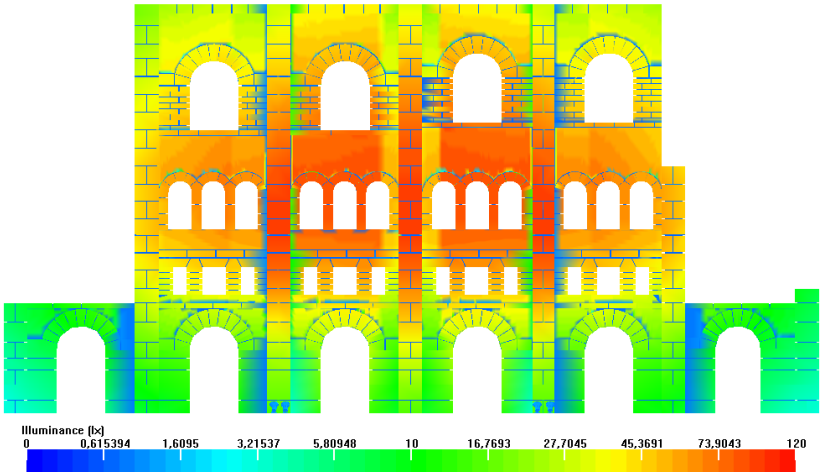


Figure 4.41 Illuminance levels positioning of luminaires on the ground.

Figure 4.42 The luminaires were placed on two six-meter-high poles and further off-center to increase the shadow contrast of the vertical pillars in order to decrease the flattening of the façade. The tilt of the luminaires is decreased thus containing the upward scattered light flux.

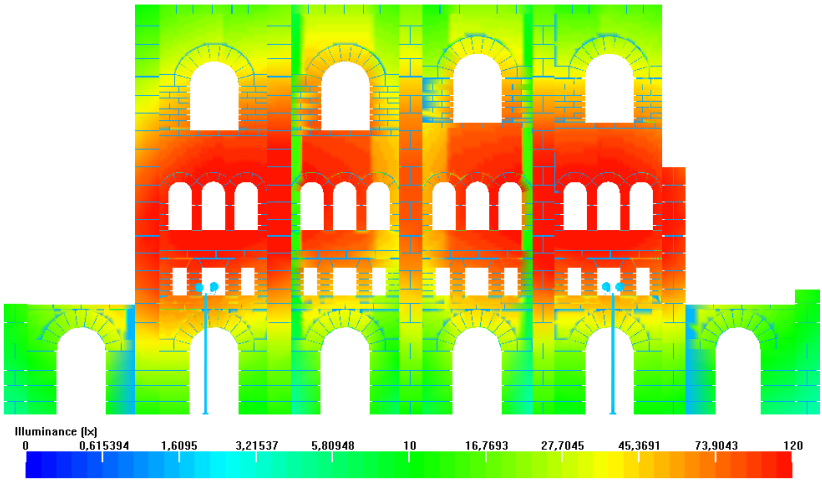


Figure 4.43 The elevation of the luminaires made it possible to lower the aiming without increasing the possibility of direct glare; the illuminance is now more uniform in the central part and has decreased in the upper part.

Figure 4.44 Changing sources from metal halide to low-pressure sodium vapor. There is a slight yellow color cast on the screen that may be missed when printing. The lighting designer should not forget that the reproduction of color perception is one of the most complex and problematic aspects of virtual prototyping. The evaluation of these aspects must therefore be accompanied by the development of real experimentation and practical observation.

A first solution is to deploy 2 pairs of floodlights frontally on the ground at a distance of 12 meters from the façade. The axis of the projectors is aimed at a height of 14 meters. Frontal viewing positions makes it possible in this case to perceive fairly modest luminance contrasts. The shadows are projected from the bottom to the top in the same direction of observation. Ground lighting luminaires can be protected by placing them in manholes or in the center of fenced flower beds.

The ground arrangement, while the simplest from the standpoint of installation and maintenance, is not always possible for topological and safety reasons; in addition, the presence of observers on the planned paths may cast unwanted shadows. In many cases, in façade lighting, luminaires can be placed on adjacent buildings or on special poles. The laying of poles is generally the most expensive solution, if these do not already exist, and is

also the most aesthetically questionable choice, because poles are not much liked. However, in the absence of adjacent buildings this option can be considered.

Figure 4.45 In this rendering, the level of photorealism was raised through the use of procedural textures such as bump mapping to better simulate the irregularity of the aged stone surfaces.

Raising the luminaires to 6 meters above the ground lowered the pointing to a height of 10 meters, thus containing the undesirable effects of light pollution. Finally, the decentralization of the sources achieved the effect of casting longer shadows that help to elevate the perceptual effect of the relief of protruding elements. In some cases this effect can be further emphasized by placing some localized lighting fixtures directly on the façade itself. However, in the case of cultural property, there can often be regulatory constraints that prevent installations from being placed on buildings.
The light sources used for the purpose can be metal halide, sodium, or the more modern LED floodlights that are also beginning to be available for the large wattages needed in exteriors. When the work to be illuminated has a wide gradation of color tones, it is advisable to use sources with high color rendering; in the opposite case, one can opt for the more efficient ones with low color rendering.

Another very important aspect in lighting design for historic buildings concerns the aesthetic respect of the structure. During the daytime, artificial lighting is not used, and therefore lighting fixtures can become unsightly intruders in the context of the building. The sensitivity of the designer in respecting both topological and concealment constraints of the luminaires, in search of solutions that do not clash with the architectural context, can also be facilitated by the use of new floodlights with a particularly compact and harmonious design, aimed at deflecting the view of the luminaires from the attention of observers during daylight hours.
The methodology of analyzing the results of the calculation according to the type and arrangement of the luminaires cannot, and should not, disregard a joint analysis of the photorealistic rendering and the illuminance values that can be obtained on the affected surfaces. Indeed, numerical values, isolux curves and false-color images, enable an objective quantitative assessment of light distribution, while virtual photographs provide indications that can induce a good estimate of the subjective and qualitative perceptual effects of illumination.

4.8.2 Daylight simulations

The simulation of natural light enables the evaluation of illuminance variation according to a variety of parameters found in everyday reality. Specifically: geographical location and orientation, time of year and time of day, and climatic conditions. The presence of adjacent structures that occlude direct sunlight.
However, there is also a significant limitation: the inability to properly simulate the light scattering effect due to curtains or other diffusing transparent surfaces. This problem has already been addressed in recent times in the field of image synthesis by the research community, and some solving models have been presented and tested at the level of scientific research. Therefore, we believe that, in the near future, software tools for virtual prototyping of lighting design will be updated to also simulate the diffusive effects of transparency. This possibility is already present in some experimental software available to the scientific community but is not usable for actual and practical light design by the industrial designer.
Direct sunlight illuminance even in an interior can easily exceed 50,000 lux, which is why a single south-facing window may be sufficient to illuminate a large room through diffuse inter-reflections, which, in the virtual model, are well calculated by Radiosity and Photon Mapping. Due to the very high illuminance levels caused by sunlight, it should be noted that if these fall on surfaces with particularly saturated color, the calculation of light can easily

produce excessive color bleeding as an undesirable effect. Through practical observation of the surfaces affected by direct sun illumination, compensation of the level of chromatic reflection can be made.

In reality, the high intensity of direct solar radiation casts highly visible shadows characterized by considerable variations in illuminance. In the virtual simulation these can have oblique projections with respect to the subdivision of surfaces made by the progressive method, thus originating unpleasant staggering at the edges of the shadows. This artifact can be mitigated by maximizing the precision of the calculation to decrease aliasing effects. In all cases, for the creation of photorealistic renderings, it is still essential to apply a two-step calculation method in order to have a correct lighting evaluation and for the correct simulation of glossy reflection, transparency and procedural texture effects.

On the following pages we show the analysis of natural lighting with clear skies, using virtual photos and false-color images of illuminance levels, of an interior with one window and one glass door, on February 21, at five times of the day: 9 a.m., 11 a.m., 1 p.m., 3 p.m. and 5 p.m. The comparison is made between two different geographical locations: London and Cairo. The corner of the room with the piano is facing exactly north.

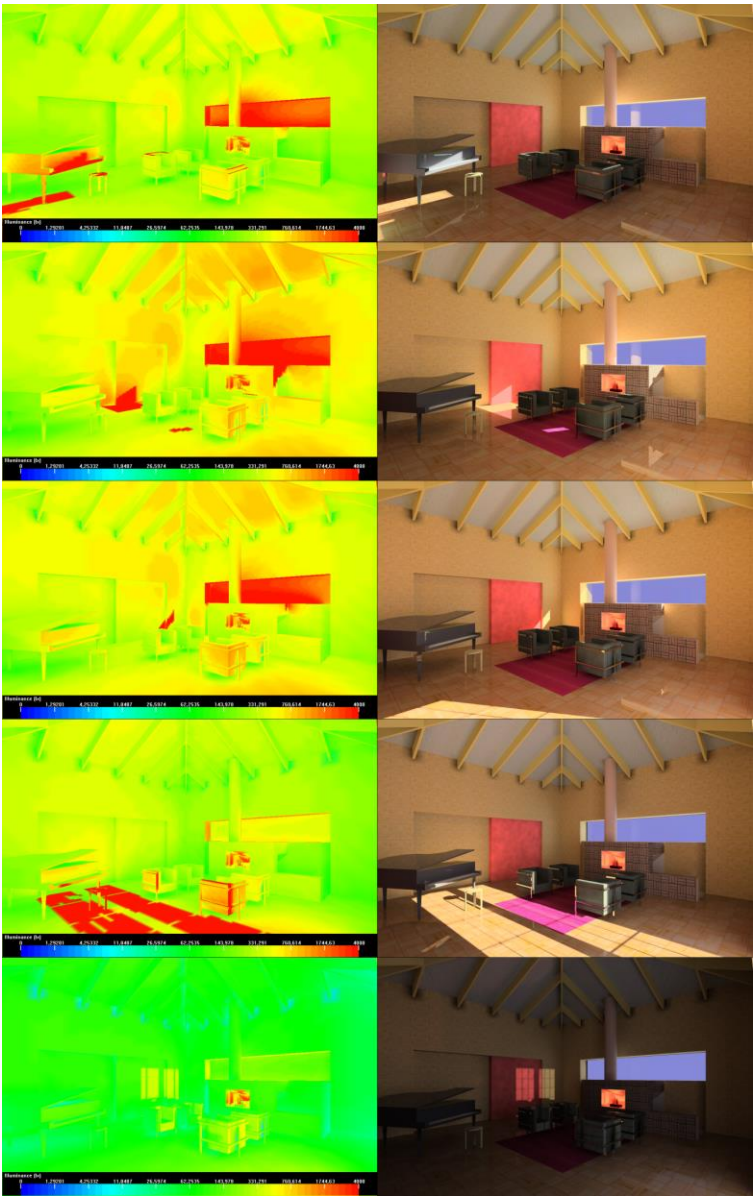


Figure 4.46 London, daylight variation from 9 a.m. (top) to 5 p.m. (bottom).

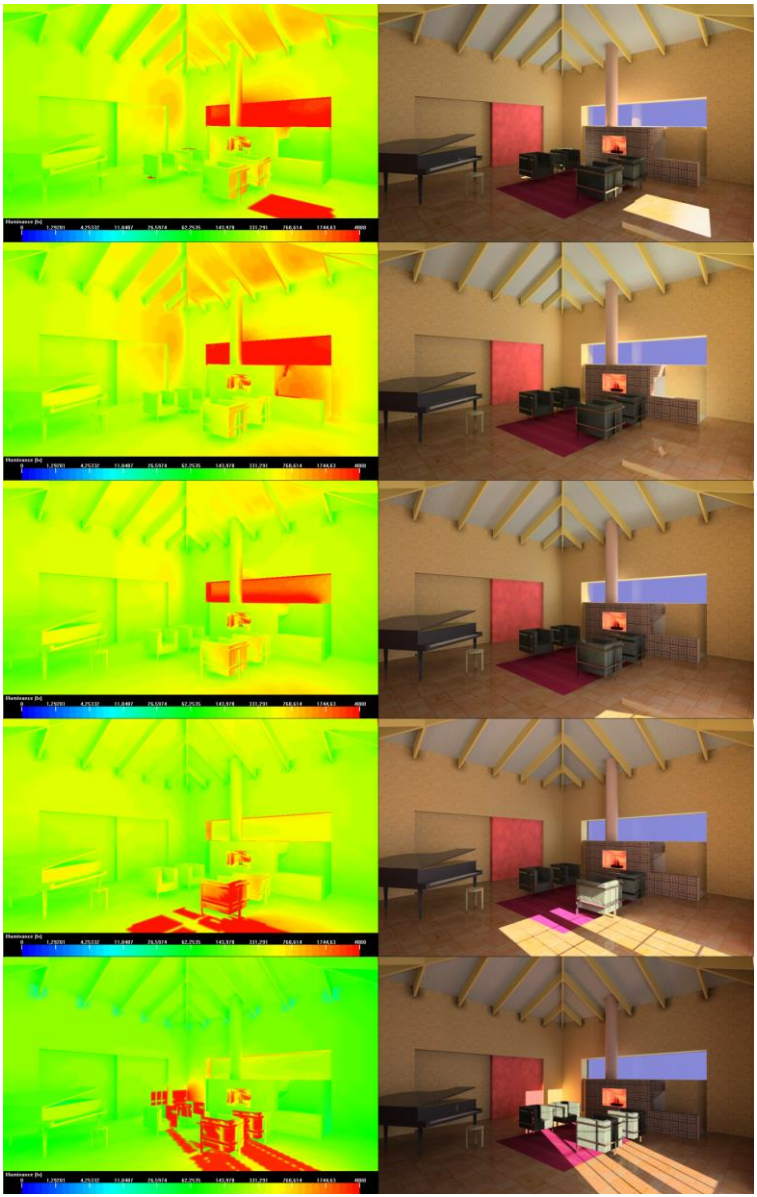


Figure 4.47 Cairo. Full scale of false colors = 4,000 lux.

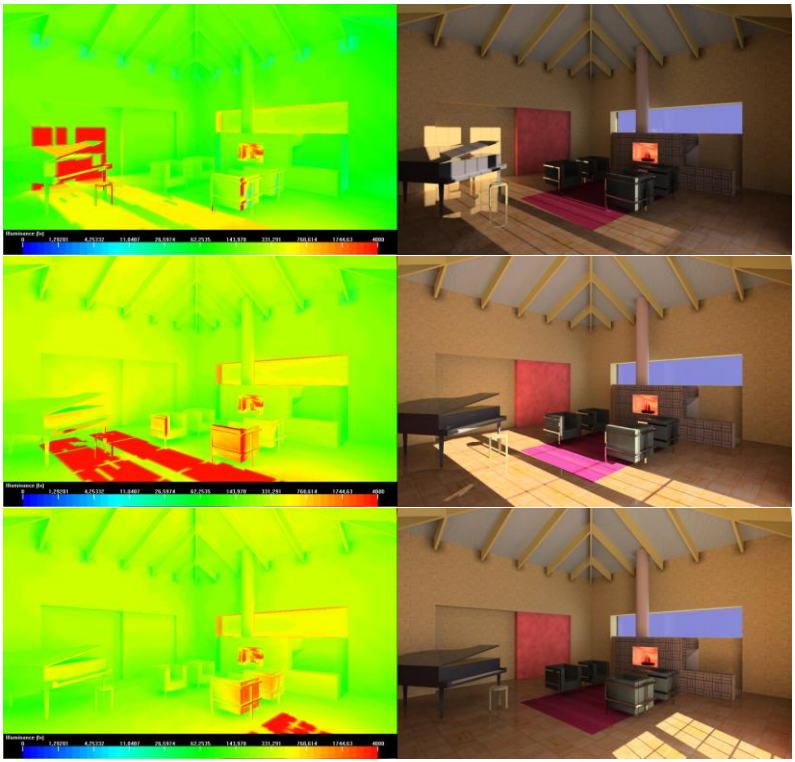


Figure 4.48 Simulation of the seasonal variation in natural lighting. The interior shown is located in London under clear sky conditions at 3 p.m. Above is the natural lighting for December 12. In between is February 21. At the bottom June 12. In the last case, the angle of light also changes due to daylight saving time.

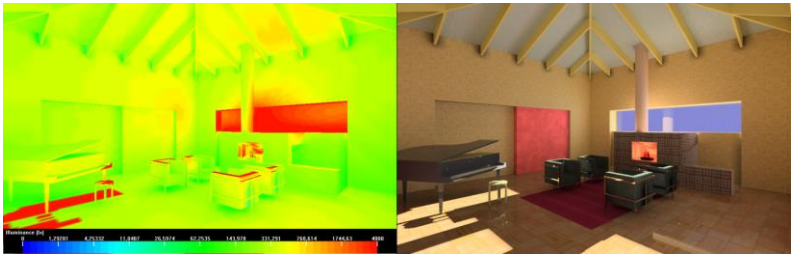


Figure 4.49 For the same interior, at 3 p.m. on Feb. 21, the orientation with respect to north was changed, which is now behind the observer.

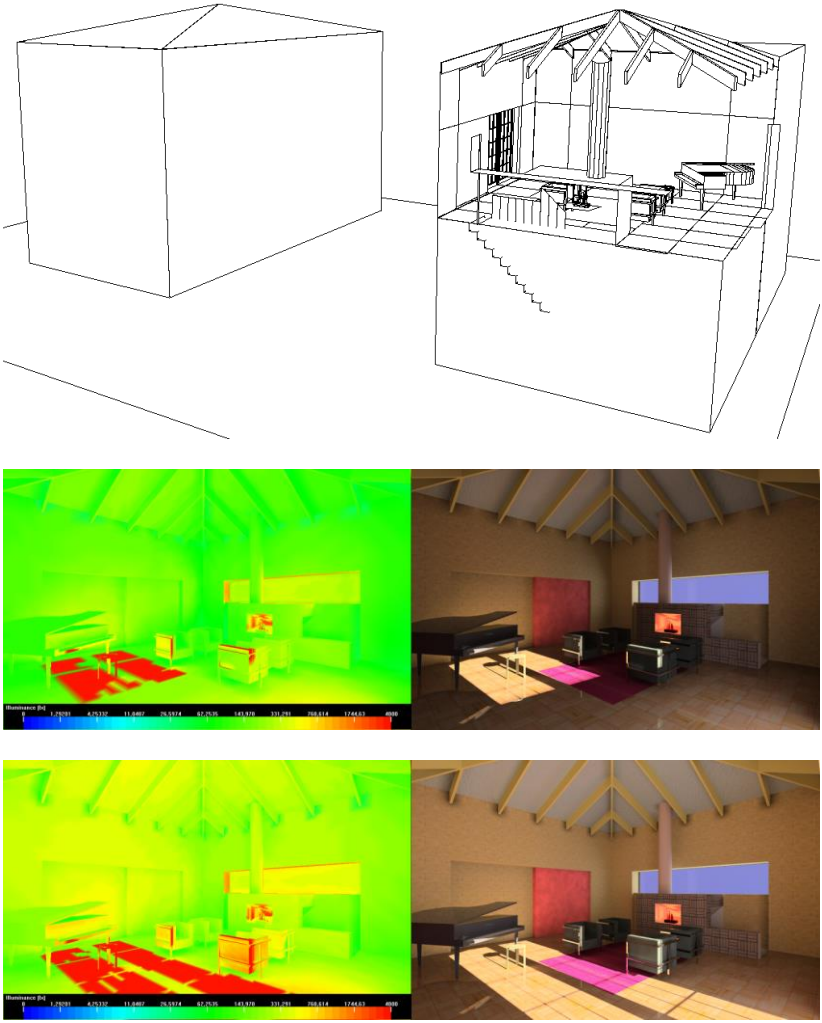


Figure 4.50 Effect on natural illuminance due to the presence of adjacent structures on an interior located on the first as well as the top floor. London, at 3 p.m. on Feb. 21, a building of the same size as the one concerned by the calculation is present to the southwest at a distance of 10 meters. The rendering above shows the change in shape and values of the natural illuminance caused by the shadow cast by the neighboring building. Below the situation without adjacent buildings is provided for comparison.

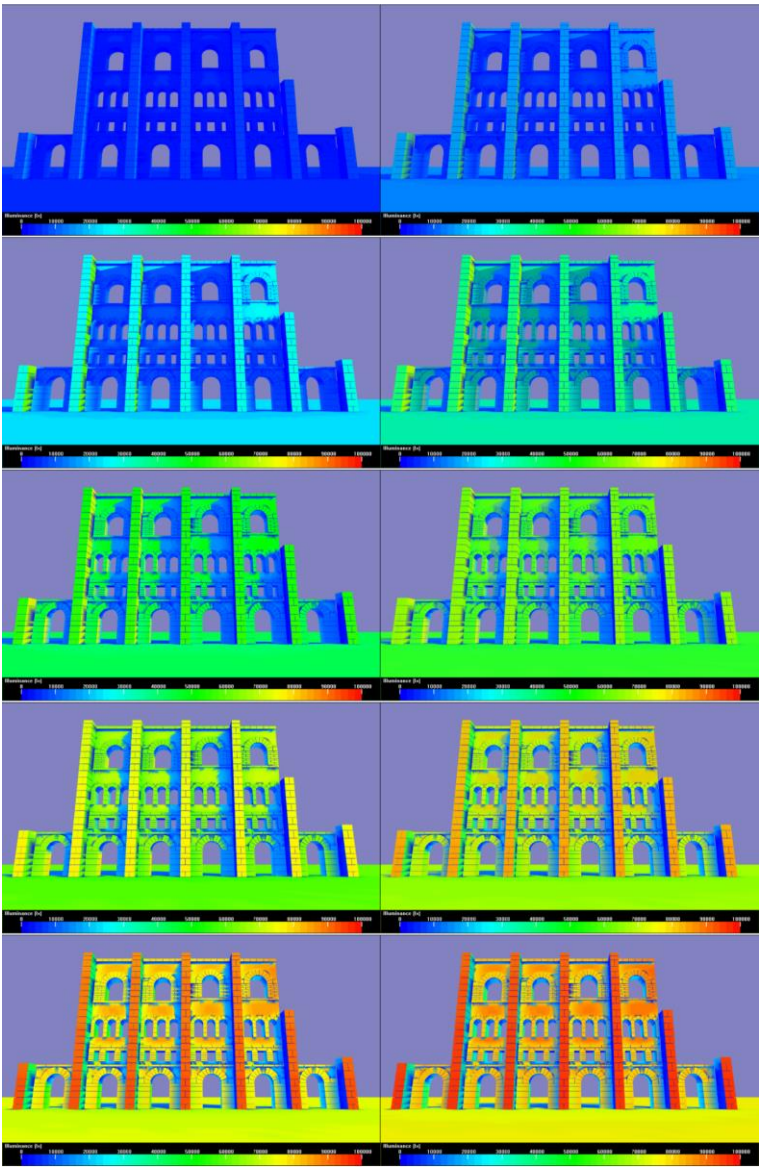


Figure 4.51 Study of the variation of natural lighting on the façade of the Roman Theater in Aosta.

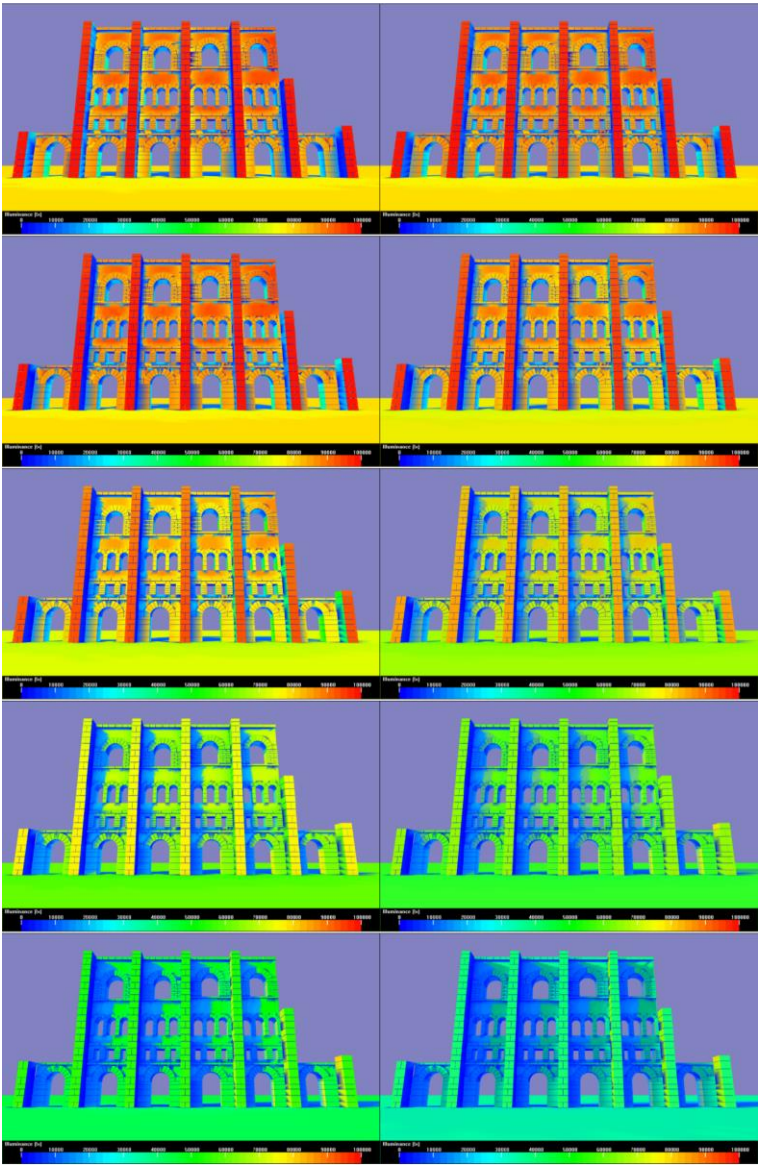


Figure 4.52 The full scale of false colors is worth 100,000 lux.

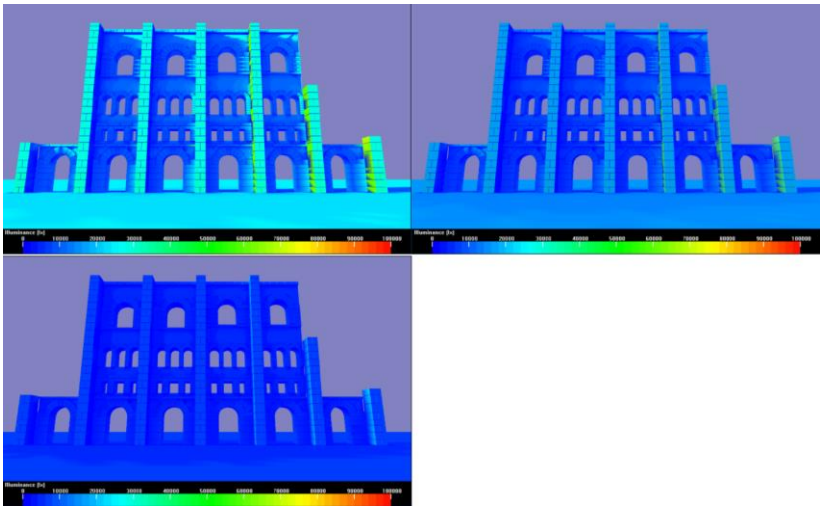


Figure 4.53 This and the previous two figures show the analysis of the variation of direct solar illumination during the day on the façade of the Roman Theater in Aosta on March 21 with clear skies. False-color shots run from 8 a.m. to 7 p.m. every 30 minutes.

The ability to simulate the behavior of natural light is also useful in exterior environments, particularly for the presentation and evaluation of complex architectural designs. Daylight simulation allows designers to analyze how a building interacts with its surroundings during different hours of the day and throughout the seasons. This makes it possible to study how façades, volumes, and materials are perceived under changing natural lighting conditions. Such evaluations can also support design decisions for nighttime lighting, helping ensure that artificial illumination enhances the architecture without altering the visual character the building exhibits during the day. In addition, daylight simulation allows the study of the daily and seasonal amount of solar irradiation that can affect façades, coatings, and other exposed materials. This analysis is particularly useful for interior exhibition spaces such as museums and galleries, where photosensitive materials may be present. Frescoes, oil paintings, tempera paintings, and similar works should not receive more than a prescribed annual amount of illuminance. For this reason, the lighting designer must evaluate the combined contribution of natural and artificial light and, when necessary, introduce arrangements capable of limiting excessive illuminance levels.

Figure 4.54 Photorealistic renderings of exteriors. Courtesy of Guillermo LLaguno.

Figure 4.55 Photorealistic renderings of exteriors. Courtesy of Guillermo LLaguno.

4.8.3 Evaluation of lighting on artworks

Lighting design aimed at illuminating art works has three main objectives. The first is, of course, to enable the enjoyment and visual appreciation of the work through adequate illumination. The second objective, also common to lighting design as a whole, is to limit glare, i.e., to achieve a perceptual situation of visual comfort. Indeed, an exposure characterized by lighting with disturbing glare induces reactions of annoyance and disturbance in the observer, who is thus placed in a perceptual condition that is psychologically disadvantageous for a full and objective evaluation of what he or she is looking at.

The third objective, of paramount importance for some types of artworks, is protection from radiation that can be a cause of degradation, such as excessive illumination, direct heat, or infrared and ultraviolet radiation. Indeed, it is well known that light, whether natural or artificial, is a major cause of degradation to which many types of materials are inexorably exposed (CIE, 2004). International research has allowed materials to be divided into three categories according to their sensitivity to light (CEN, 2014, p. 16163):

- Group 1: Extremely light-sensitive materials, which should not normally be exposed to illuminance greater than 50 lux. This group includes highly photosensitive materials such as textiles (especially silk), carpets, tapestries, works on paper such as watercolors, drawings and prints, manuscripts, books, dyed leather, feathers, ethnographic materials colored with plant dyes, and paintings executed with unstable or unprotected media.
- Group 2: Very light-sensitive materials, which should generally not be exposed to illuminance greater than 100 lux. This group includes various organic materials and artworks containing pigments or colorants that may deteriorate under prolonged light exposure, including certain textiles, prints, painted objects and decorative surfaces with moderately sensitive materials.
- Group 3: Moderately light-sensitive materials, which should not normally be exposed to illuminance greater than 200 lux. This category includes varnished oil paintings, tempera paintings, frescoes, and other organic materials such as ivory, bone, horn and similar substances that exhibit a moderate sensitivity to light.
- Group 4: Low light-sensitivity materials, which can tolerate illuminance levels of 300 lux or more, although unnecessary heating and excessive radiation should still be avoided. Typical examples include metals, stones, ceramics, glass and other predominantly inorganic materials.

Figure 4.56 Illumination of a painting by indirect illumination with linear fluorescent lamps placed in the skylight recesses on the ceiling. Illuminance on the surface of the painting is visible on the right. The uniformity is very good, E_{min} /E_{med} = 0.89 and E_{max} /E_{min} = 1.21 , with an average illuminance of 109 lux.

Figure 4.57 Compared with the previous figure, the painting has been tilted 4° downward. Average illuminance decreased by 5 lux, while uniformity ratios deteriorated slightly: E_{min} / E_{med} = 0.88 and E_{max} / E_{min} = 1.22.

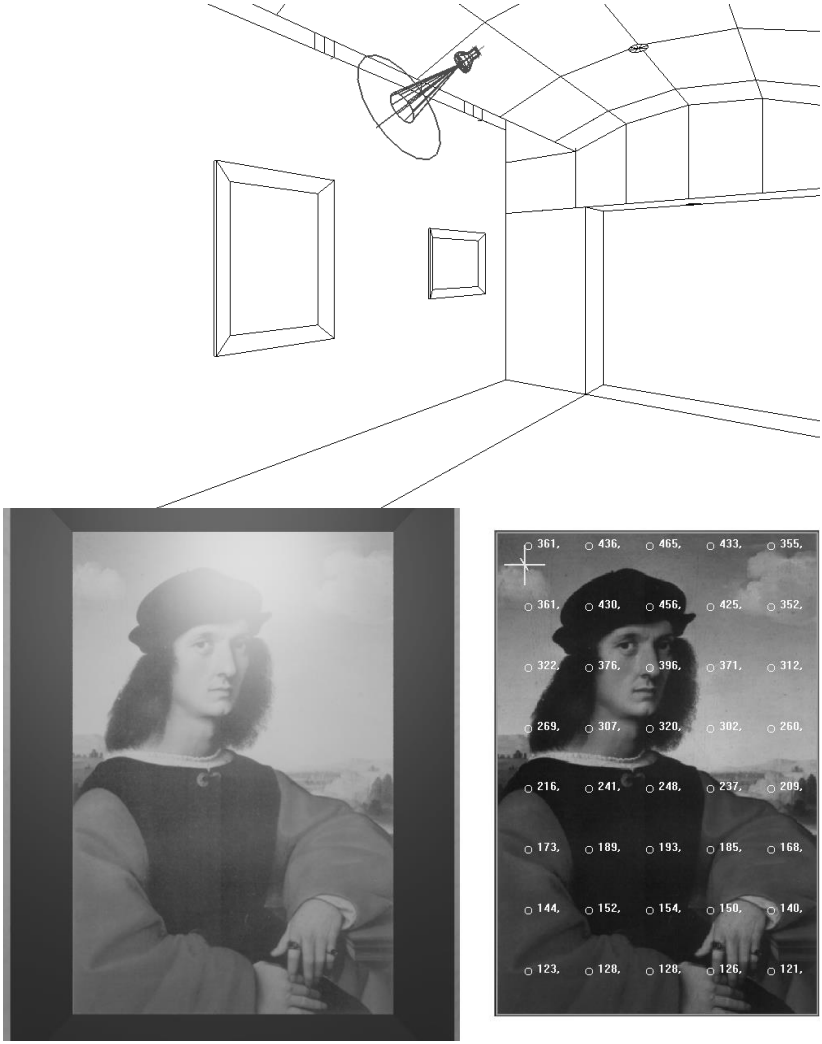


Figure 4.58 The lighting of the work has been modified by installing a projector for direct lighting on the ceiling and pointing it toward the painting. Three damages were produced in one operation: 1) The average illuminance level of 256 lux is too high for the type of material. 2) Contrast rendering is very bad; indeed, on the left, it can be observed that in the frontal rendering view, the light source is reflected resulting in loss of contrast rendering and glare to the observer. 3) Uniformity ratios have drastically deteriorated: $E_{min} / E_{med} = 0.43$ and $E_{max} / E_{min} = 4.32$.

For the enhancement of colorful works, certain guidelines for choosing the color temperature of the light source should also be followed. Regarding the choice of color temperature, the rule of trying to favor the natural chromaticity of the work applies. For works with warm hues, i.e., colors with hues above 565 nm, such as yellow, orange and red, the source must have a color temperature between 2500-3300 K. For works with cool tones, i.e., colors with hues below 565 nm, such as green, blue and violet, the source must have a color temperature between 5000-6000 K. For works without prevailing hues, the source should have color temperature between 3400-5000 K.

The lighting criteria then vary according to the visible geometry of the work to be enhanced. For flat works such as paintings, frescoes and tapestries, good uniformity of illuminance is required, which is essential to avoid mistakenly altering the perception of brightness that the artist intended to imprint when creating the work. Notoriously, artists have always tried to create their paintings and frescoes under uniform lighting conditions. On surfaces in which there is usually a work of art, it is practically impossible to achieve perfectly even illumination. The quality of illuminance uniformity on a flat surface can be assessed by the uniformity ratios between the minimum illuminance E_{min}, the medium illuminance E_{med} and the maximum illuminance E_{max}. In the ideal case these ratios should tend toward the unit value, but more generally other values can be accepted:

$$\frac{E_{\min}}{E_{med}} > 0{,}5 \qquad \frac{E_{\max}}{E_{\min}} < 5$$

If the flat surface is also coated with a material characterized by even a small percentage of specular reflection, such as glass, the problem of contrast rendering arises. Indeed, there is a risk that due to inappropriate placement of lighting sources, they will reflect off the specular surface causing partial glare and thus disturbing the perception of the artwork. Therefore, the position of the lighting source relative to the work must be such that it does not present a specular reflection angle of light that may fall back into the preferential observation zone.

For three-dimensional works, such as statues and bas-reliefs, the criterion of maximizing illuminance uniformity should not be applied at all. In fact, depth perception, in addition to stereoscopic vision, is also based on the perception of luminance variations due to shadows that occur near the sinuous element of the work's surface. Diffuse and uniform illumination over the entire surface of the work would greatly attenuate depth perception. Compatible with the exhibition requirements and the size of the three-

dimensional work, the main lighting should be unidirectional and in a position so as not to dazzle observers in the possible paths of enjoyment of the work. Assuming this basic principle, the lighting direction must also consider the average distribution of the work's surfaces in order to obtain good average levels of reflected luminance to enable its appreciation. If the work is in front of below the observer's eyes, the light must come from above, otherwise it must come from below, in both cases the similarity between the direction of observation and the direction of illumination ensures optimal luminance perception.

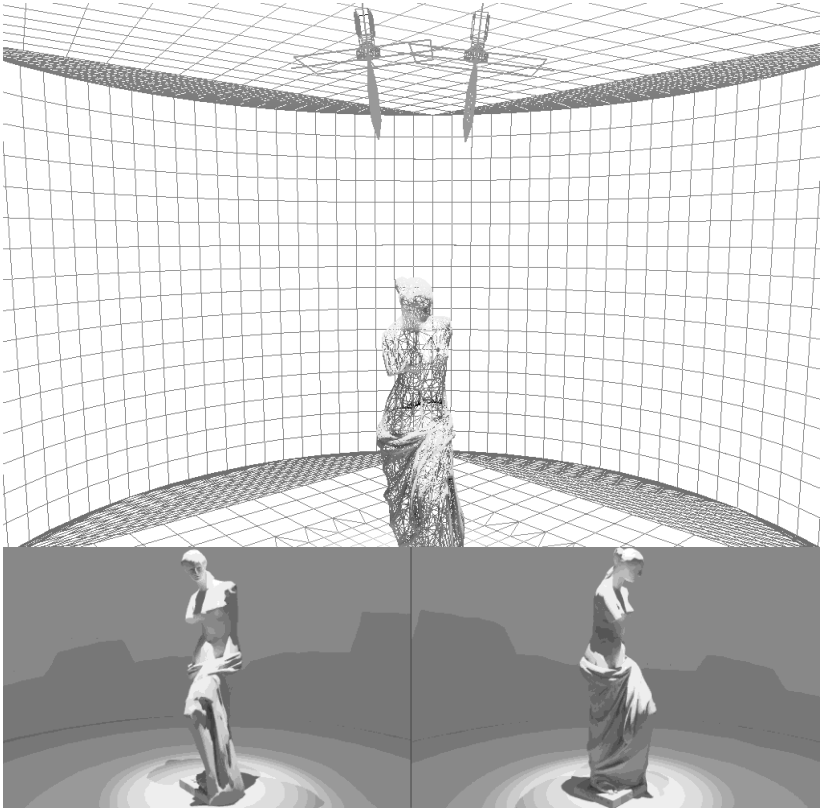


Figure 4.59 Accent lighting using two spotlights installed above a statue placed in a circular room. The two luminaires are hung from the ceiling and shifted radially 20 cm from the axis of the sculpture. Both are oriented with a slight tilt toward the abdomen.

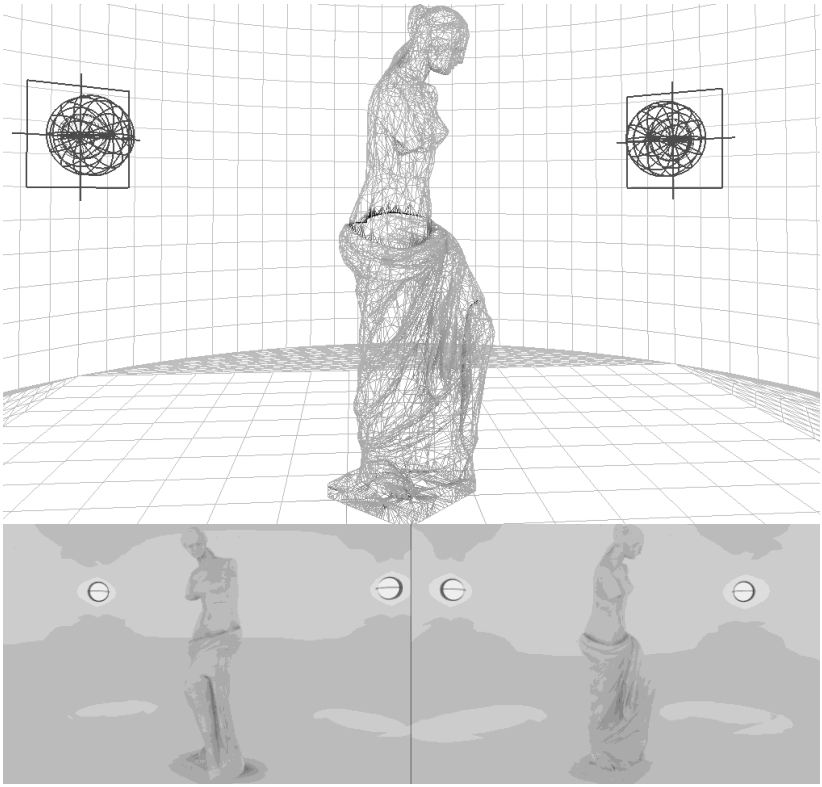


Figure 4.60 In this example, for the same room as in the previous figure, the lighting was modified by eliminating the spotlights and placing four wall-mounted luminaires, which, in part due to the special geometry of the room, produce a diffuse type of illuminance. The contrast levels of the work diminish in accent, and the sculpture loses its personality by flattening out and blending into the background.

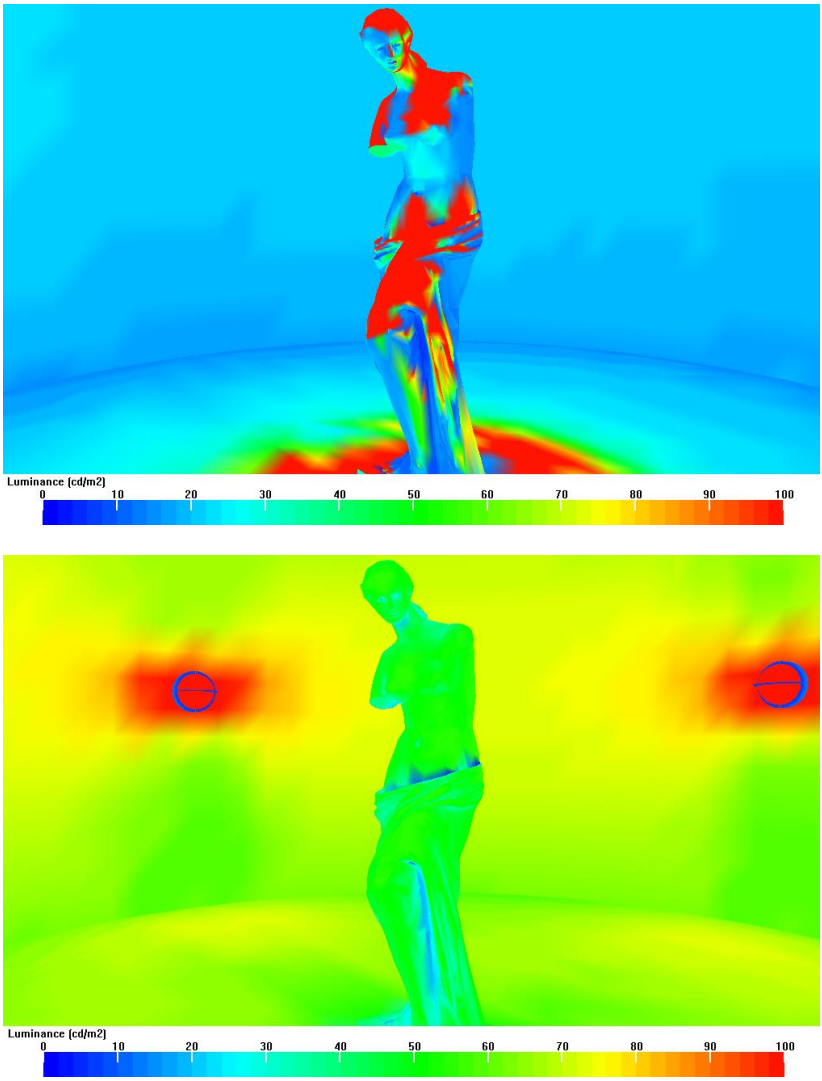


Figure 4.61 False-color comparison of luminance levels shows that in the case of diffuse illumination (bottom), the surface of the statue is perceived evenly and with luminance levels even lower than the wall behind. In addition, the presence of the light sources within the field of view can cause disturbing glare.

4.9 Conclusions

The analysis presented in this chapter highlights the methodological role of photorealistic rendering within the broader framework of digital lighting design. Rendering should not be interpreted as a substitute for quantitative lighting verification but rather as a complementary tool capable of supporting perceptual evaluation and communication of design intentions. While lighting CAD systems allow designers to calculate illuminance, luminance and other photometric quantities with technical rigor, rendering techniques make it possible to explore the qualitative aspects of light distribution, material appearance and spatial perception that strongly influence the observer's experience.

The discussion of global illumination models — such as Ray Tracing, Radiosity and Photon Mapping — has shown how contemporary rendering techniques attempt to approximate the complex physical behavior of light in real environments. Despite the remarkable progress achieved in computational methods and hardware performance, perfectly photorealistic images remain difficult to obtain. This limitation is not only related to numerical approximations in light transport calculations but also to the intrinsic complexity of the human visual system and to the restricted dynamic range of digital display devices. For this reason, rendering results must always be interpreted critically and supported by quantitative lighting analysis.

The chapter has also emphasized the importance of correct model preparation, including the management of geometric data, materials, textures and light sources. Accurate definition of photometric properties, surface reflectance and daylight conditions is essential to ensure that simulation results maintain a meaningful relationship with physical reality. Errors in geometric modeling, incorrect material parameters or inappropriate use of light sources can easily compromise the reliability of the simulation and lead to misleading visual representations.

Through the presented case studies, it has been shown how digital simulation can effectively support both professional design practice and educational activities. Virtual prototyping allows designers to explore alternative lighting strategies, evaluate their perceptual consequences and compare different design solutions before any physical intervention takes place. In this sense, rendering technologies represent a powerful bridge between the objective measurement of light and the subjective experience of illuminated spaces.

4.10 Conflict of interest declaration

The author declares that there are no actual or potential conflicts of interest related to this chapter. Specifically, no financial, personal, or professional relationships with individuals or organizations have influenced, or could be perceived to have influenced, the content, analysis, or conclusions presented herein. The research and writing of this chapter were conducted independently and objectively. The author confirms that no competing interests exist within the meaning of the RCASB guidelines.

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Frontiers of Lighting Design with CAD and BIM

This volume explores the role of digital tools in contemporary lighting design, framing them as essential instruments for analysis, verification, and visual interpretation within an increasingly complex built environment. Lighting design is addressed as a multidisciplinary process that integrates physical measurement, perceptual evaluation, and design intent, operating across artificial and natural lighting conditions. The book establishes a conceptual distinction between tools developed for quantitative lighting verification and those oriented toward visual communication and rendering, clarifying their respective scopes, limits, and complementarities. Through a progressive structure, the chapters examine the theoretical foundations of digital lighting simulation, the use of Lighting CAD systems for normative evaluation, and the methodological implications of virtual prototyping in the absence of physical mock-ups. Particular attention is given to the integration of lighting design within Building Information Modeling (BIM) workflows, highlighting the differences between Closed BIM and Open BIM approaches, issues of interoperability, and the resilience of lighting data across platforms. The analysis demonstrates that current BIM environments only partially support lighting-specific requirements, often necessitating external or hybrid workflows. The volume also addresses photorealistic rendering as a perceptual and interpretative tool rather than a substitute for quantitative verification, discussing global illumination models, computational strategies, and the inherent limitations of digital representations of light, color, and visual perception. Across case studies and software comparisons, the book emphasizes methodological awareness and informed tool selection as critical competencies for lighting designers. Overall, the volume provides a coherent theoretical and practical framework for understanding digital lighting design as a balance between scientific rigor, technological mediation, and experiential judgment.

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