Mohamed Khider University of Biskra
Faculty of Architecture, Urbanism, Civil Engineering and Hydraulics
Department of Architecture

Master 2: Academic

Theme 3: Architecture, environment and technologies

Course: Evaluation of Comfort in Buildings and Energy Diagnosis

Course Handout Title: Evaluation of Comfort in Buildings and Energy Diagnosis

Field: Architecture, Urbanism, and City Professions

Specialty: Academic Architecture

Level: Master 1 – Architecture

Prepared by: Dr. Daich Safa

Academic year: 2022/2023

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PREFACE

Maintaining ideal indoor conditions in buildings is one of the primary concerns for designers, particularly regarding energy consumption. However, achieving these conditions is often highly energy-intensive, which contributes to significant pollution and the degradation of Earth's ecosystems. Over the past decades, the field of computer science has grown rapidly to address complex design challenges related to user comfort and building energy performance. Building performance simulation tools now need to be capable of handling a wide range of tasks, including overheating analysis in highly insulated, glazed, and naturally ventilated buildings; realistic modeling of HVAC systems and energy technologies such as cogeneration and solar thermal systems; simulation of thermal processes; implementation of complex control strategies; and the evaluation of advanced active façades.

The present course handout is a support for the teaching course, entitled ''Evaluation of Comfort in Buildings and Energy Diagnosis'' which was developed on the basis of the 2018/2019 framework, option: Architecture, validated by the Ministry of Higher Education and Scientific Research. The overall objective of this module is to provide an introduction to, and facilitate the acquisition of, fundamental concepts concerning the conceptual, methodological, and logistical tools required to conduct building comfort and energy diagnoses.

The details of the course, in accordance with the syllabus, are presented in the tables below:

SEMESTRE 3											
Unité d'Enseignement	VHS	V.H hebdomadaire					Coeff	Crédits	Mode d'évaluation	
	14-16 sem	C	TD	TP	Atelier	Total			Continu	Examen
UE Fondamentales							10	18		
Matière 1 : Enoncé théorique du Projet/Mémoire	135h				9h		6	12	100%	-
Matière 2 : Matière d'appui 1 (voir canevas)	22h30	1h30					2	3		100%
Matière 3: Matière d'appui 2 (voir canevas)	45h	1h30	1h30				2	3	40%	60%
UE Méthodologie							7	9		
Matière 1 : Stage de mise en situation professionnelle	90 h					15 jours	5	6	100%	
Matière 2 : Intelligence artificielle	45h			3h			2	3	100%	
UE Découverte/Transversale							3	3		
Matière 1 : Entrepreneuriat	22h30	1h30					3	3		100%
Total Semestre 3	360h	4h30	1h30	3h	9h	6h	20	30		

3 - ARCHITECTURE, ENVIRONNEMENT ET TECHNOLOGIES						
Palier	**Semestre**	**Unité**	**Coefficient**	**Crédit**	**Cours**	**TD**
M2	3	UEF	2	3	1H30	1H30
Intitulé de la matière					**Atelier**	**TP**
MATIERE D'APPUI 2 / EVALUATION DU CONFORT DANS LE BATIMENT ET DIAGNOSTIC ENERGETIQUE						

retour

THEMATIQUE : ARCHITECTURE, ENVIRONNEMENT ET TECHNOLOGIES

INTITULE DE LA MATIERE D'APPUI 2 : EVALUATION DU CONFORT DANS LE BATIMENT ET DIAGNOSTIC ENERGETIQUE
UNITE D'ENSEIGNEMENT : UE F3
SEMESTRE : 3
NOMBRE DE CREDITS : 3 **COEFFICIENT :** 2
VOLUME HORAIRE HEBDOMADAIRE TOTAL : 3H

COURS (NOMBRE D'HEURES PAR SEMAINE) : 1H30
TRAVAUX DIRIGES (NOMBRE D'HEURES PAR SEMAINE) : 1H30
TRAVAUX PRATIQUES (NOMBRE D'HEURES PAR SEMAINE) : 00 H

OBJECTIF GENERAL DE LA MATIERE D'ENSEIGNEMENT

Initiation et acquisition des notions de base concernant les outils conceptuels, méthodologiques et logistiques nécessaires à l'établissement des diagnostics en rapport avec la thématique.

OBJECTIFS SPECIFIQUES /THEMATIQUE

Initiation aux méthodes d'évaluations et de diagnostics
Initiation aux « logiciels » de simulation et de modélisation

CONTENU DE LA MATIERE D'ENSEIGNEMENT

Calcul et évaluation des notions de confort dans l'espace architectural à l'aide des outils informatiques (logiciels disponibles au niveau du département d'architecture). Les déperditions thermiques, consommation d'énergétique et confort thermique, le taux de ventilation et confort olfactif naturel, l'éclairage naturel et confort visuel, niveau de bruit et confort acoustique….

MODE D'EVALUATION

Nature du contrôle	Pondération en %
Examen	60 %
Travaux dirigés	40 %
Total	100%

RÉFÉRENCES & BIBLIOGRAPHIE

4. RECAPITULATIF THEMATIQUES /MATIERES / MOTS CLES

	THEMATIQUE DE L'ATELIER	MATIERE D'APPUI	5 MOTS CLES*
1	HABITAT ET POLITIQUES DE LA VILLE	**Matière 1 :** Logement : espaces et usages	Notion d'habité / modes et modèles universaux et locaux / habitat urbain et habitat rural / Conception de l'espace domestique / logement efficient
		Matière 2 : Renouvellement urbain et politiques de la ville	Politique publique / gestion sociale et patrimoniale du logement / Ville innachevée / Espaces résidentiels / Maitre de l'usage
2	ARCHITECTURE URBAINE (URBAN DESIGN)	**Matière 1 :** Projets et contexte urbain	Espace public / Echelles / Ambiances physiques / Habitats et cultures / Design urbain
		Matière 2 : Méthodes et outils d'analyse urbaine	Méthodologie et modèles de lecture / Imagibilité / Paysage urbain / Typo-morphologie / Approche sensible
3	ARCHITECTURE, ENVIRONNEMENT ET TECHNOLOGIES	**Matière 1 :** Performance environnementale et innovations technologiques dans le bâtiment	Sensibilisation aux enjeux environnementaux / Approche vernaculaire / Stratégie et simulation environnementale / Culture de l'écologie
		Matière 2 : Evaluation du confort dans le bâtiment et diagnostic énergétique	Notion de confort / Diagnostic énergétique / Bâtiments éfficients / matériaux innovants / Projet urbain durable
4	PATRIMOINE BATI ARCHITECTURAL ET URBAIN	**Matière 1 :** Conservation et valorisation du patrimoine architectural et urbain	Instruments de sauvegarde / Formes urbaines / Savoirs interdisciplinaires / Approches critiques et différentes opérations / Notion d'actualisation
		Matière 2 : Etudes préalables et diagnostic selon les pathologies du système de construction	Méthodes diagnostiques / Pathologie des ouvrages / Technologies numériques / Techniques de conservation / Méthodes de réhabilitation

(*) : certains mots clés peuvent faire allusion à des thématiques spécifiques alors que d'autres dépassent le cloisonnement apparent. Il s'agit d'une particularité transdisciplinaire, la connaissance de toute les thématiques est nécessaire pour identifier les corrélations et éviter les chevauchements.

Etablissement : Université Mohamed KHIDER -Biskra
Intitulé du master : Master en Architecture
Année universitaire : 2025/2026
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The evaluation of comfort in buildings and energy diagnosis are central issues in the design, operation, and renovation of the built environment. Buildings are expected not only to minimize energy consumption but also to provide healthy, comfortable, and productive indoor environments for occupants. Achieving this balance is particularly critical in the context of climate change, rising energy costs, and increasingly strict environmental regulations.

This course introduces the fundamental concepts of indoor environmental comfort, including thermal comfort, visual comfort, acoustic comfort, and indoor air quality, and examines their interactions with building design, materials, systems, and occupant behavior. At the same time, it provides the principles and methods of energy diagnosis, enabling the analysis of building energy performance, identification of inefficiencies, and proposal of improvement strategies.

Through theoretical foundations, standards and indicators, practical examples, and diagnostic tools, students will learn how to assess building comfort conditions and energy performance in both new and existing buildings. The course aims to develop a holistic understanding of how comfort and energy efficiency can be jointly optimized to support sustainable, resilient, and user-centered buildings. To achieve this objective, the course is structured as follows:

The first chapter covers fundamental concepts and general principles of comfort in buildings—including thermal, visual, acoustic, and olfactory comfort—so that students can understand the various physical phenomena that create conditions of comfort or discomfort.

The second chapter focuses on methods for calculating and evaluating comfort and energy consumption in buildings. It is divided into three complementary sections: the first addresses the concepts of sustainable development and environmental quality, as well as technological and regulatory advances in the energy and environmental fields. The second section examines the various methods available for assessing and measuring comfort in buildings, including in-situ measurements, simplified and empirical calculation methods, comfort indices, computer-based simulations, and reduced-scale models. The final section presents energy diagnostic methods, such as consumption measurement, the energy expenditure index, energy signature analysis, and the Hm method.

The third chapter is designed to provide a more specialized study of simulation and modeling tools in the building sector, enabling the calculation of heat loss, energy consumption, and thermal comfort (e.g., PLEIADES COMFIE, EnergyPlus, TRNSYS, ESP-r, and Dymola); natural lighting and visual comfort (e.g., Ecotect, DIALux, Relux, IES VE, and Radiance); as well as noise levels and acoustic comfort (e.g., AcouBAT, Mithra Sound, Ecotect, and CadnaR).

CHAPTER 1 :

1 Comfort in building

Introduction

According to Olivier Lemaître (2013), people spend 20 to 22 hours per day in enclosed spaces, such as homes, workplaces, schools, or public areas. Therefore, these spaces must be designed to ensure thermal comfort year-round, minimize noise pollution, support clear communication and necessary noisy activities, optimize visual performance with minimal energy use, and reduce unpleasant odors regardless of their source.

1.1 THERMAL COMFORT

Introduction

Thermal comfort can be defined as a person's perception of temperature and humidity in relation to the ambient conditions of the space they occupy. It refers to the sensation of being neither too hot nor too cold, and neither too humid nor too dry, depending on factors such as climatic conditions, individual characteristics, and thermal uniformity within the space. Ensuring hygrothermal comfort involves maintaining a consistent indoor temperature throughout the year (typically between 18 and 20 °C), a relative humidity of 40–60%, and a maximum temperature difference of 3 °C between the indoor air and the surrounding walls.

1.1.1. Human metabolism, (M)

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), metabolism (M), thermogenesis, or power output refers to the body's production of internal heat through the chemical reactions that transform food. This heat must be released into the environment to maintain thermal equilibrium and a stable internal temperature. Metabolic heat production depends primarily on physical activity and can range from 70 to 900 W in adults. A portion of this energy, generated in the core and muscles, can be converted into mechanical work (W), while the remainder—referred to as net metabolism ($M_{net} = M - W$)—must be dissipated as heat. Heat transfer from the body's core to its periphery occurs through conduction via biological tissues and convection through the blood. To perform vital functions, humans must maintain an internal temperature of approximately 37.0 ± 0.5 °C, despite external temperatures that can range from −50 °C to +50 °C.

1.1.2. Heat transfer in the human body

Heat transfer, or thermolysis, between the body and its environment occurs through all classical heat transfer mechanisms, both at the skin surface and via the respiratory system. Exchanges through evaporation, conduction, convection, and radiation are most often heat losses but can become heat gains in warm environments.

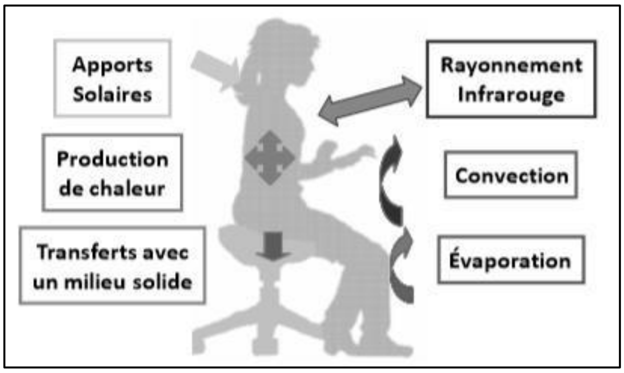


Figure 1. Heat transfer in the human body (Thellier et al., 2011)

1.1.3. Thermal balance of the human body

The heat balance of the human body can be calculated using the following formula (1):

$$C_h \frac{dT_h}{dt} = Mnet + Ray_{sol} - Evap \pm Conv \pm Ray_{IR} \pm Kond \qquad \textit{Equation (1)}$$

Where :

- Solar Radiation (Raysol).
- Cutaneous and respiratory evaporation (Evap). - Cutaneous and respiratory convection (Conv). - Infrared radiation (RayIR).
- Conduction with a solid medium (Kond).

1.1.4. Overall thermal balance of a building

The overall thermal balance of a building is the sum of internal heat gains, including heat released internally (P_int), heat supplied by HVAC systems (P_gc), heat transfers through the building envelope (walls, windows, roof, etc.) (Φ_env), and airborne heat transfers related to air renewal (Φ_air), such as infiltration and ventilation. It also includes solar heat gains through glazing (Φ_sol). The overall thermal balance can be calculated using formula (2)

Ch= dTh/dt = Pint+Pgc+Φsol+Φenv+Φair *Equation (2)*

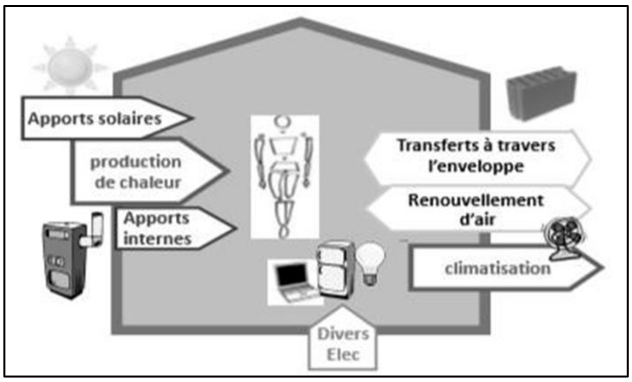


Figure 2. Heat transfer in a building (Thellier et al., 2011)

1.1.5. Overall thermal balance (Humans and Habitat)

The overall heat balance is the sum of the heat balance of the human body and that of the building, and it can be calculated using the following formula (3):

$$C \times dTh/dt = Prod + \Phi in - \Phi out \qquad \text{Equation (3)}$$

Where:

- **C** is the total heat capacity (J/°C),
- **T** is the average temperature of the system (°C),
- **t** is time (s),
- **Prod** represents the power produced (W), and
- **Φ** is the heat flux exchanged (W), with **in** indicating incoming flux and **out** indicating outgoing flux.

1.1.6. Parameters influencing hygrothermal comfort

Various parameters and factors are used to assess a person's perception of the thermal environment and, more specifically, hygrothermal comfort. The main parameters include metabolism (reflecting the individual's level of physical activity), air temperature, surface temperatures of walls, relative humidity, air velocity, and clothing insulation.

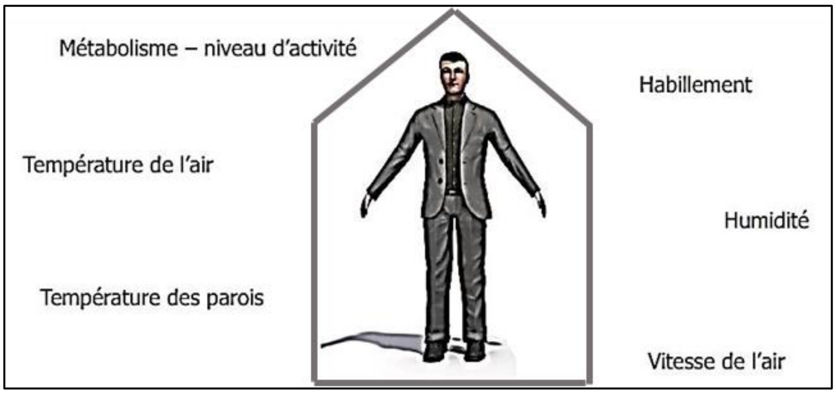


Figure 3. Parameters of hygrothermal comfort
(Hygrothermal comfort and reduction of energy consumption, 2014)

Hygrothermal comfort helps to reduce thermoregulatory physiological responses, such as sweating and shivering, as well as psychological sensations of heat or cold. To achieve this, several factors must be considered: the thermal insulation of the building envelope, which should be designed in relation to solar exposure (orientation, size, and shading of glazed surfaces); effective ventilation; the possible use of passive or active cooling systems; and the proper regulation of heating and cooling systems. In addition, thermal comfort can be improved by gaining a better understanding of summer comfort, analyzing comfort zones and the uniformity of hygrothermal conditions within the building, and carefully selecting appropriate equipment.

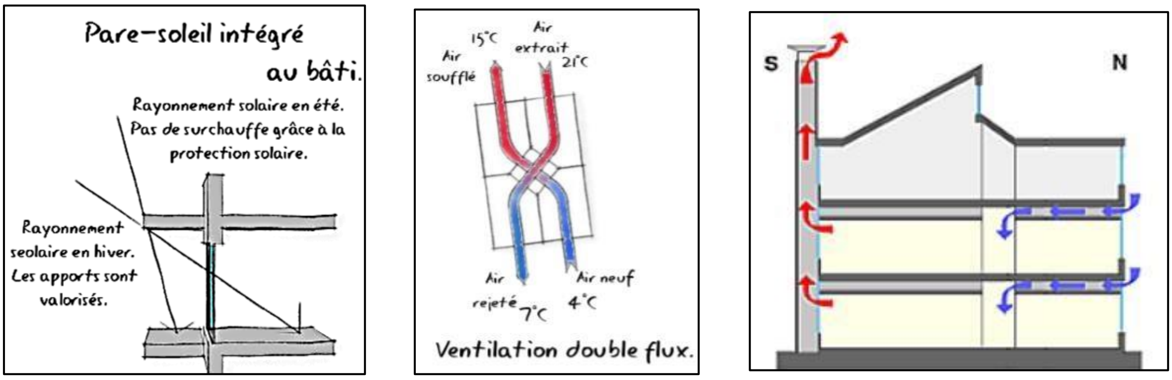


Figure 4. Strategies to mitigate hygrothermal comfort
(Hygrothermal comfort and energy consumption reduction, 2014)

1.1.6.1. Improved consideration of summer comfort

Better consideration of summer comfort can significantly reduce overheating and maintain pleasant temperatures in all rooms of a building during the summer months. This can be achieved by: reducing solar heat gains through careful consideration of building orientation and site conditions; taking advantage of proper insulation; utilizing the building's thermal inertia (the greater the mass of a room, the more delayed the temperature transfer between the exterior and interior); employing sunshades; and, where necessary, using air conditioning.

1.1.6.2. Hygrothermal comfort zone

The bioclimatic diagram is based on a psychrometric chart and provides a graphical representation of various hygrothermal comfort zones. These include: the standard hygrothermal comfort zone; the extended comfort zone achievable through ventilation; the zone compensated by thermal inertia in combination with solar protection and light-colored finishes; the zone mitigated by passive evaporative cooling systems; the zone requiring air humidification; and the zone compensated through passive solar building design.

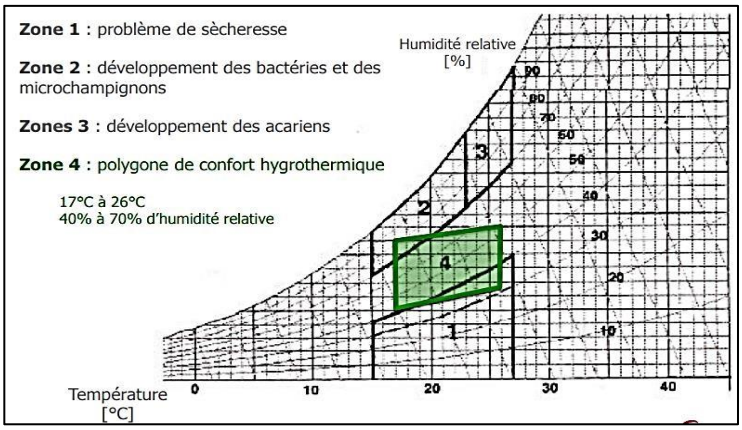


Figure 5. Bioclimatic diagram (Hygrothermal comfort and reduction of energy consumption, 2014)

The homogeneity of hygrothermal conditions can be achieved through careful placement and orientation of glazing, as well as by optimizing the building's thermal inertia and insulation. These strategies enhance occupant comfort and promote energy savings by using materials that gradually store and release heat or coolness, allowing for gradual warming or cooling. Moreover, comfort should be consistent across summer, winter, and transitional seasons, taking into account temperature differences between the lower and upper body, as well as the effects of airflow, cold surfaces, and other environmental factors.

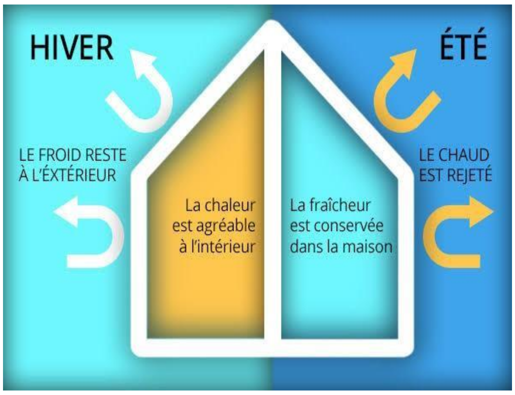


Figure 6. Homogeneity of hygrothermal environments
(https://www.maison-passive-eco.com)

1.1.6.3. Equipment selection

On the other hand, to ensure thermal comfort during winter, heating systems should be selected based on the characteristics and use of the space, including surface area, volume, indoor environment, occupancy, and type of activity. For example, radiant heating is often preferred over convective heating because it distributes heat more evenly, preventing significant temperature differences between the head and feet, which occupants may find uncomfortable.

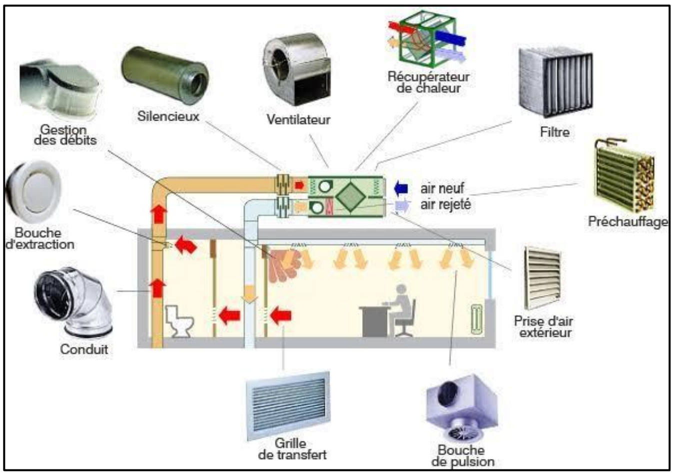


Figure 7. Equipment selection (https://energieplus-lesite.be)

1.2 VISUAL COMFORT

Introduction

Visual comfort has several definitions: it can refer to a satisfactory visual relationship with the outdoors, optimal natural lighting in terms of comfort and energy efficiency, or satisfactory artificial lighting that supplements natural light. In general, visual comfort is a subjective perception related to the quantity, quality, and distribution of light. It reflects a person's satisfaction with the visual environment, providing a sense of comfort when objects can be seen clearly and without strain, within a pleasant and well-balanced color ambiance.

1.2.1. The perception of light

The process of vision involves the near-simultaneous interaction of both eyes and the brain through a network of neurons, receptors, and other specialized cells. The first step in this process is the stimulation of light receptors in the eyes, the conversion of the light stimulus or images into signals, and the transmission of these electrical signals, containing visual information, from each eye to the optic nerve. This information is processed in several stages before finally reaching the visual cortex of the brain. Visual perception is the excitation of the retinal material, which triggers a photochemical reaction where coupling occurs through an electrical interaction between the electromagnetic wave and the receptor.

1.2.2. The visual field

The visual field is the area defined by the eye's spatial perception, without moving the head. Since the visual field varies slightly from person to person, the vertical range of the eyes covers an angle of approximately 130°; it is limited upwards by the brow ridges and downwards by the cheeks. The total horizontal field of vision is approximately 180° when the eyes are focused on a fixed object. Each eye has a field of vision of approximately 150°. Where the visual fields overlap, humans have binocular vision; they overlap in the midline area where the same object is seen simultaneously by both eyes but from different angles.

Figure 8. Le champ visuel (Bodart et Deneyer, 2008)

The visual field can also be defined as the eye's ability to capture visual information, depending on its relative position within the visual field. The fovea is a relatively narrow visual field of 2° that allows us to perceive details; the further we move from this central area, the more difficult it is to perceive details. The ergonoma is a visual field of 30° relative to the line of sight, allowing us to distinguish shapes. The panorama is a visual field of 60° relative to the line of sight, enabling us to distinguish movement.

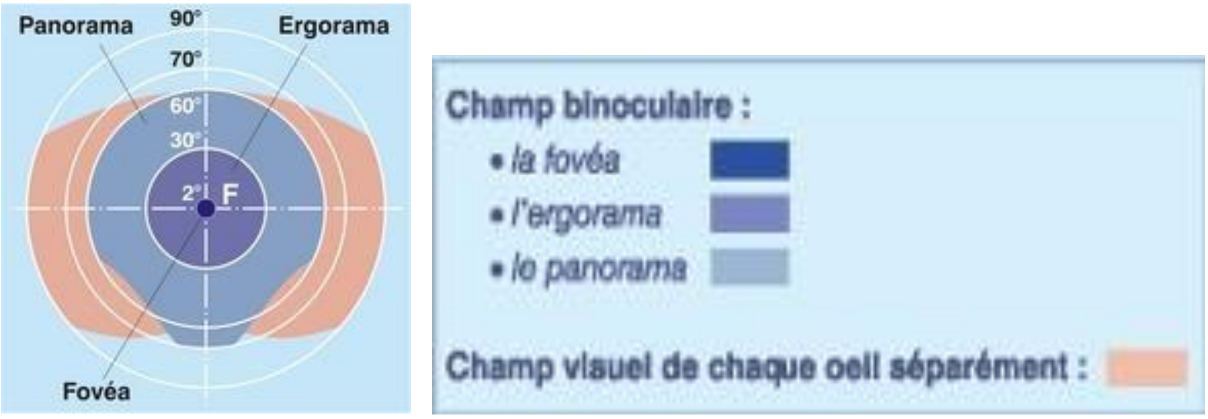


Figure 9. The visual field (Bodart and Deneyer, 2008)

1.2.3. Color Perception

The color of an object depends on the light illuminating it: blue is a cool color (rich in blue light) while red is a warm color (rich in red light). The eye perceives colors differently; we are very sensitive to yellow and have difficulty seeing blues and reds. The eye's receptive system (the retina) is made up of a set of cones and rods: the former, being very sensitive to light, are responsible for the perception of colors (blue, green, red). The latter, 100 to 500 times more sensitive than cones, allow us to see in low-light conditions. Light is characterized by a reflectance factor that varies from one color to another. This factor is the ratio between the amount of light L falling on a surface and the amount of light λ reflected by that surface. It is expressed as a percentage.

The nature of light makes colors visible and is described by:

- The color rendering index CRI, expressed as a percentage, represents the ability of a source to faithfully render the colors of an object (a CRI of 100 indicates that the light in question contains 100% of existing colors).
- Colour temperature, measured in Kelvin degrees, which designates the hue of the light emitted by a body as a function of its temperature (the higher it is, the more the light considered contains large quantities of colours).

1.2.4. Visual performance

Visual performance is a rating of the visual system used to quantify a person's ability to detect, identify and analyzethe details falling within its scope vision is based on the speed, accuracy, and quality of perception. It depends, among other things, on the specific characteristics of the task to be performed, the observer's visual acuity, the nature of the background, lighting conditions, etc. The visibility of detail depends on: its angular size and shape, its luminance and color, its contrast with the immediate background, its position in the visual panorama, the adaptive luminance, the age of the observer, and the observation time.

1.2.5. Criteria for visual comfort

The sensation of visual comfort varies from person to person. Some individuals prefer natural lighting, even if it is uncomfortable, over certain artificial lighting provided by sources with spectral characteristics that do not match those of white light. Color temperature is an important factor in assessing visual comfort, as it reflects the quality of lighting. The Kruithof diagram establishes the perceived comfort conditions for different combinations of illuminance and color temperature. It shows that in dimly lit environments (zone A), comfort is associated with warm light, whereas in brightly lit environments (zone C), comfort is associated with overly cool light. The intermediate zone (zone B) represents the area of visual comfort. Visual comfort can also be assessed using objective criteria, which must be carefully considered to achieve the comfort threshold.

These include: the characteristics and constraints of the site; the number, size, and orientation of openings; the amount and quality of natural light; the quality of artificial lighting in terms of comfort and energy efficiency; and the visual connection with the outdoors.

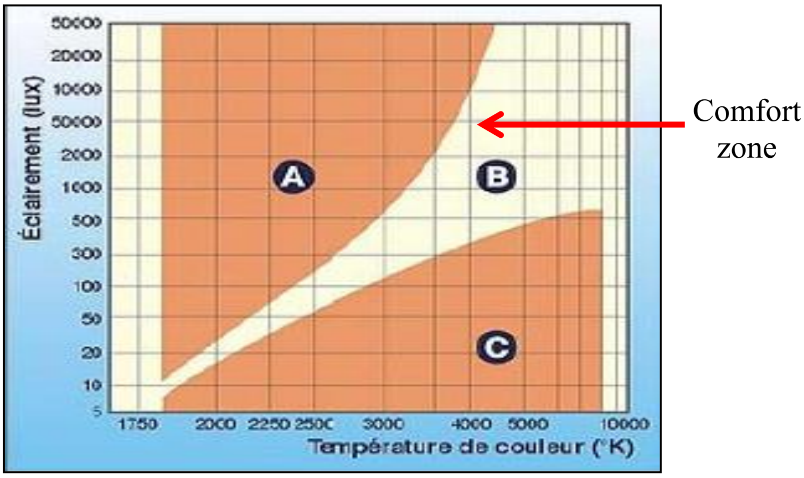


Figure 10. The Kruithof diagram (Suzel Balez, 2008/2009)

1.2.6. Visual comfort parameters

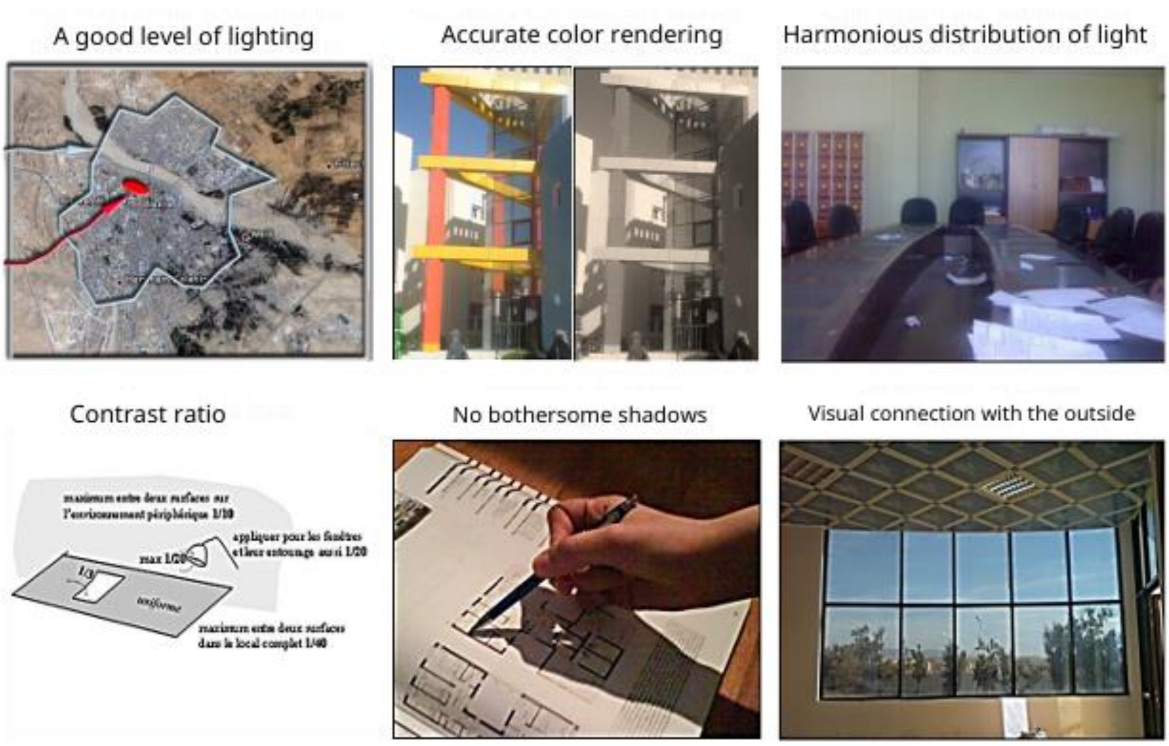


Figure 11. Parameters of visual comfort (Daich, 2011)

1.6.2.1. A good level of lighting

Every activity requires a specific level of lighting in the area where it is performed. Generally, the more visually demanding a task, the higher the average illuminance should be. A minimum illuminance is necessary for clear, fatigue-free vision, while excessive lighting can cause discomfort. Recommended average illuminance levels are typically determined by the function of the space and the precision of the visual task.

Recommendations are often expressed in terms of illuminance rather than luminance for easier measurement. However, since perceived brightness is more accurately represented by luminance, the surface reflectance must be taken into account when selecting illuminance levels. The lower the reflectance coefficient and the darker the color of a surface, the more challenging it is to see, and the higher the illuminance must be.

1.6.2.2. Accurate color rendering and pleasant lighting

The different wavelengths that make up natural light become visible when refracted or reflected by water droplets. Since the human eye is adapted to daylight, artificial light sources should have a spectral composition similar to that of sunlight and the sky to ensure accurate color perception and prevent visual impairment. The visual system combines the reflected radiations to produce the perception of color, which is closely linked to the light spectrum. Objects with warm colors, such as red and orange, appear more pleasing under warm light than under cool light. Warm colors are generally preferred in larger spaces, while cool colors are often chosen for smaller spaces. Therefore, color can significantly influence the perceived size of surfaces and volumes.

1.6.2.3. A harmonious distribution of light in space

To maximize the distribution of daylighting throughout a room, it is essential to position furniture so that it does not block light and to arrange work areas thoughtfully. Work surfaces should ideally be located near openings where natural light is readily available. The uniformity of luminance and overall light distribution in a space depend on the placement of light sources and the reflectivity of surrounding surfaces. Uniformity is achieved when reflections from all surfaces are high and evenly distributed. Luminance uniformity should be maintained: (1) between the primary field of vision during work (the work surface) and the surrounding environment (the walls), and (2) between different reference surfaces, such as the work area and adjacent areas.

1.6.2.4. Luminance ratios present in the room

The lighting distribution within a space must be designed to avoid excessive differences in luminance, ensuring that occupants can see properly and that no areas appear excessively dark or overly bright. Contrast refers to the difference in brightness between an object and its surroundings, or between different parts of the object, which allows one element to stand out from another. The perception of details in a visual task is improved when there are sufficient luminance and color contrasts between those details and their background. However, large luminance differences within the visual field can lead to visual discomfort. The maximum recommended values for luminance ratios are as follows:

- Background of the visual task to its immediate surroundings: 1/3
- Background of the visual task to the wider visual field (180°): 1/10
- Light sources to adjacent surfaces: 1/20
- For the entire interior space: 1/40

It is therefore essential not to exceed certain contrast thresholds between the different areas of the visual field.

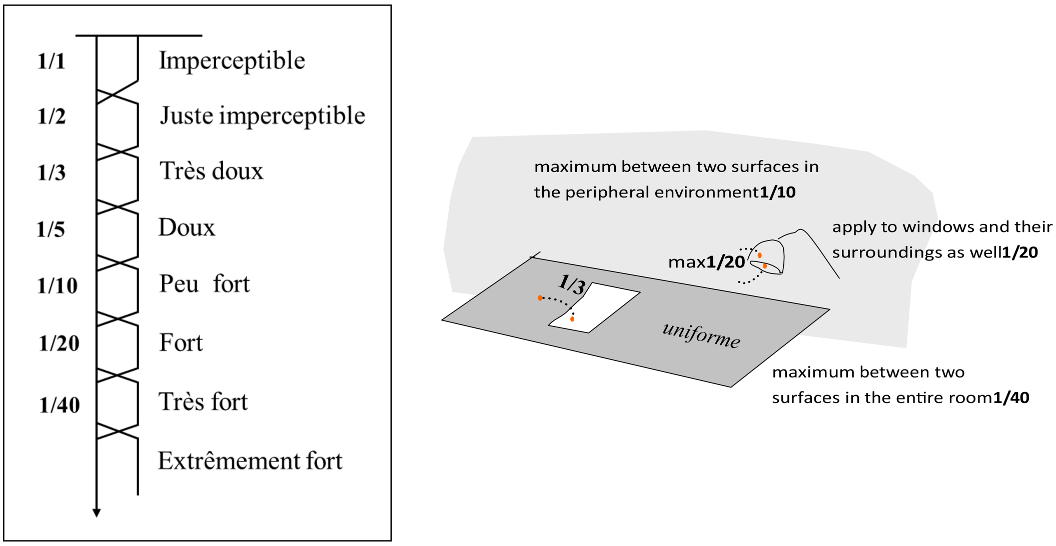


Figure 12. Luminance ratios present in the room: on the left, sensations related to different contrast levels; on the right, recommended contrast values (Mudri, 2002)

1.6.2.5. The absence of distracting shadows

When an opaque object is illuminated by a light source, certain areas behind the object receive no light, creating its shadow. A shadow also appears when an object is placed very close to the light source. The shadow cast on an illuminated object consists of two distinct parts:

(1) Self-shadow: the area of the object facing away from the light source, which receives no direct light.

(2) Cast shadow: the darkened area on a surface such as a wall or screen positioned behind the object, which is shielded from the light source by the object and therefore receives no light.

It is important to note that:

- The visibility of an object depends on the light source.
- Directional light creates shadows on the object, causing visual fatigue and discomfort.
- Non-directional light makes it difficult to perceive details.
- Lateral light penetration allows a three-dimensional perception of relief, details, and colors.
- Lateral light penetration is the most effective solution.

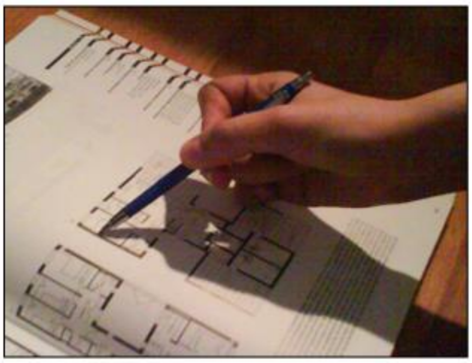


Figure 13. Impact of distracting shadows (Author, 2011)

1.6.2.6. The relationship with the outside world

The relationship with the outside world describes how a building connects to its external environment through light, ventilation, views, thermal exchange, and spatial continuity. Large windows, which allow natural light to enter, offer the dual advantage of providing visual connection with the outdoors and giving access to distant views—both essential for resting the eyes after prolonged close-up work. They also play an undeniable aesthetic role by integrating the surrounding landscape into the indoor visual environment. Natural lighting and access to outdoor views are among the most important factors contributing to employee satisfaction with their workspace.

Figure 14. The relationship with the outside world (Author, 2011)

I.3. ACOUSTIC COMFORT

Introduction

Acoustics in architecture aims to provide the most suitable sound quality for different types of spaces, including listening venues such as performance halls (opera houses, cinemas, theaters) as well as public areas like sports facilities (gymnasiums, swimming pools) or transit hubs (train stations, airports). Acoustic comfort involves two essential aspects: the ability to clearly hear sounds produced within a space, and protection from disruptive noise—whether originating from outside, from impacts, or from building equipment.

1.3.1. Review of basic concepts

A pure tone is a vibration in an elastic medium (air, water, or solid material) characterized by its frequency (number of vibrations per second), amplitude (sound level or volume), and duration. According to frequency, sounds are classified into three categories:

- Low-frequency sounds: below 100 Hz
- Medium-frequency sounds: from 100 Hz to 2 kHz
- High-frequency sounds: above 2 kHz

Sound intensity is measured in decibels (dB), a logarithmic unit. This means:

- Adding two identical sound sources results in an increase of 3 dB (for example: 50 dB + 50 dB = 53 dB).
- A tenfold increase in sound power corresponds to a 10 dB increase (for example: multiplying 50 dB by 10 in power = 60 dB).
- When two sounds differ by 10 dB or more, the louder one masks the quieter one (for example: 50 dB + 60 dB = 60 dB).

1.3.2. Definition of noise

Noise is an air vibration characterized by its frequency, intensity, and duration. Unlike a pure tone, noise is a complex mixture of many tones with different frequencies and amplitudes. It is generally associated with any unpleasant, disturbing, or unwanted auditory sensation (for example: airplane noise, machinery noise, conversations, etc.).

1.3.3. Noise propagation

This refers to the path taken by sound waves emitted by a source as they travel to our ears. The speed of sound propagation depends on the medium through which it travels; in air, it is approximately 340 m/s. In an acoustically open space, sound encounters no obstacles, and its intensity decreases as the distance from the source increases. This is known as free-field propagation.

In a built environment, however, sound encounters many obstacles that may absorb or reflect it. As a result, the sound level becomes nearly uniform throughout the space. This is known as diffuse-field propagation.

There are three main types of noise:

- Airborne noise, occurring both indoors and outdoors (sounds that originate and propagate through the air): speech, music, vehicles, aircraft, etc.
- Impact noise (sounds generated by an impact on a building element and transmitted through the structure): footsteps, dropped objects, tools, etc.
- Equipment noise (sounds produced by building systems): ventilation, heating systems, boilers, pumps, etc.

An acoustic wave is defined by two key characteristics: its sound level and its frequency, as illustrated in the figure below (Figure 16).

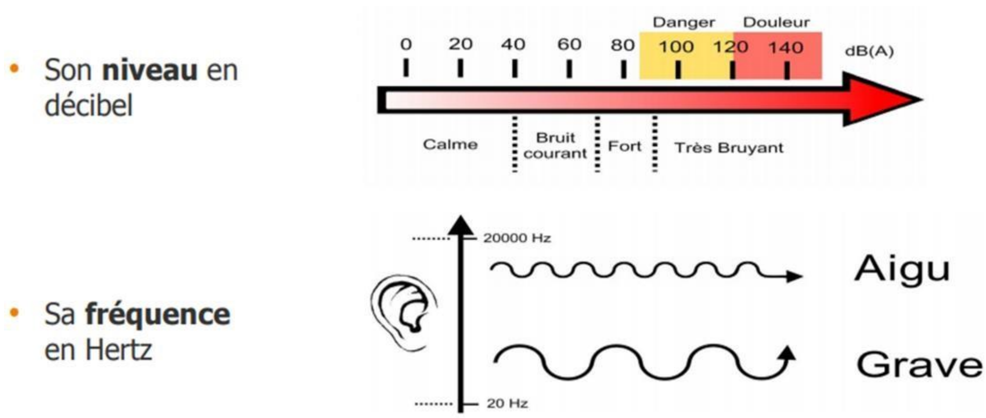


Figure 15. Characteristics of an acoustic wave (Matthew, 2016)

1.3.4. Solutions against acoustic interference

Appropriate technical solutions must be implemented to mitigate existing or anticipated noise pollution, depending on the intended use of the space. Conducting a noise analysis is recommended to identify internal and external noise sources and to characterize their type, duration, frequency, and level.

The main strategies include:

- Acoustic correction: Controlling the reverberation of sounds generated within a room to improve speech intelligibility and overall acoustic comfort.
- Acoustic insulation: Ensuring a minimum level of protection against noise transmitted from adjacent rooms, building elements, or the external environment.
- Reduction of impact and equipment noise: Addressing both the source and the transmission path of noise by using high-absorption materials, decoupling floors from the building structure, and installing anti-vibration pads between mechanical or plumbing equipment and walls or floors.
- Acoustic zoning: Implementing differentiated acoustic treatments based on the type of activity in each space, organizing rooms to create buffer zones near noise sources, and considering the specific functional requirements of each area.

To achieve satisfactory acoustic comfort within a building, it is essential to implement preventive measures during the programming and design stages, as remedial solutions are typically much more costly. These measures include: (1) protecting the room from external noise, such as airborne transmissions and vibrations, after identifying and characterizing the sources of disturbance, and (2) protecting the room from internal noise generated within the building, including reverberation and lateral sound transmission.

1.3.4.1. Protection against external noise

The siting and orientation of a building are primary measures for protecting against external noise, once the sources have been clearly identified. In multi-building developments, one building can serve as a sound barrier for the others. For single-building developments, or when this configuration is not feasible, natural or artificial noise barriers can be considered. Additionally, acoustic zoning within the interior can be applied based on the intended use of each room. Beyond these architectural strategies, acoustic comfort can be enhanced through technical measures on walls and windows. Solid walls are often insulated internally using non-rigid insulation materials such as mineral wool or EPS dB. For windows, acoustic attenuation can be achieved by using double glazing with panes of different thicknesses and ensuring airtight seals at the junctions between walls and window frames.

1.3.4.2. Protection against internal noise

Noise can propagate either through the air (direct transmission or reverberation) or through building structures (vibrations). Within a building, the noise level generated by equipment should not exceed 35 dB in primary rooms and 50 dB in service areas. To mitigate this noise pollution, it is necessary to: select the quietest possible equipment and implement technical solutions to limit the transmission of sound and vibrations, such as wall decoupling, floating floors, and other vibration isolation techniques.

1.3.5. The propagation of sound waves

Sound waves emitted by a source within a room propagate through the air toward the boundaries of the space, interacting with walls and any obstacles present. Their behavior from the moment of emission is governed primarily by the characteristics of the emitted signal and the acoustic impedance of the materials they encounter. The main factors influencing the structure of the resulting sound field include the sound source, the propagation medium, the nature of the walls, and the characteristics of obstacles within the room.

1.3.5.1. Reverberation

The impulse response of a room can be modeled as a sequence of reflections reaching the receiver, referred to as an echogram. Statistically, the density of echoes arriving at the receiver increases with the square of time. During propagation, a sound wave is subject to reflection, diffraction, diffusion, and absorption by obstacles such as floors, walls, ceilings, and furniture, as illustrated in Figures 16 and 17. It is important to note that the direct sound wave and the reflected waves combine, collectively influencing the quality of the perceived sound.

- **Causes of reverberation :**

- Hard, smooth surfaces (concrete, glass, tiles) that strongly reflect sound
- Large room volumes with few sound-absorbing materials
- Insufficient acoustic treatment (lack of carpets, curtains, acoustic panels, or ceilings)
- Room geometry that promotes multiple sound reflections.

- **Consequences of reverberation :**

- Reduced speech intelligibility
- Listening fatigue and discomfort for occupants
- Increased noise levels in the space
- Difficulty in communication, especially in classrooms and offices
- Negative impact on concentration, learning, and productivity

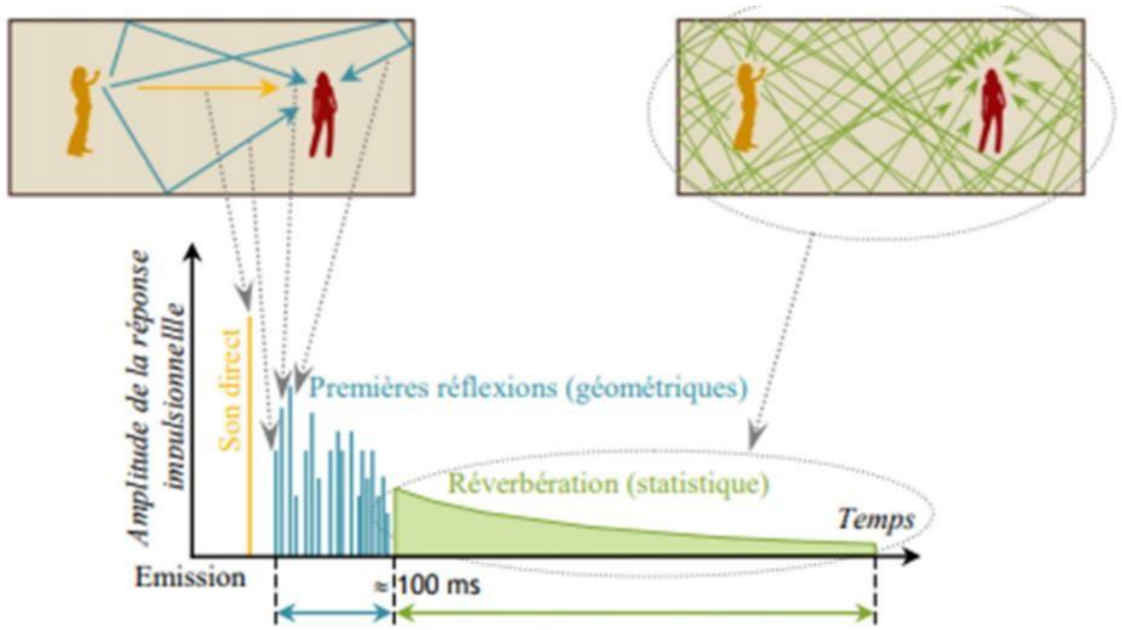


Figure 16. Reverberation in a room (Molinaro, 2017)

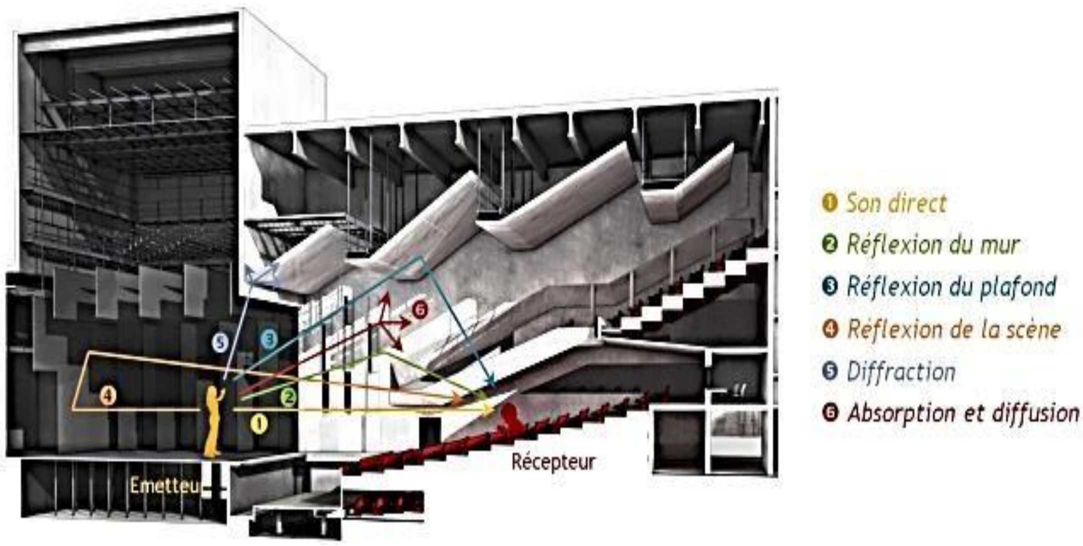


Figure 17. The physical behavior of an acoustic wave in an auditorium (http://www.uncubemagazine.com)

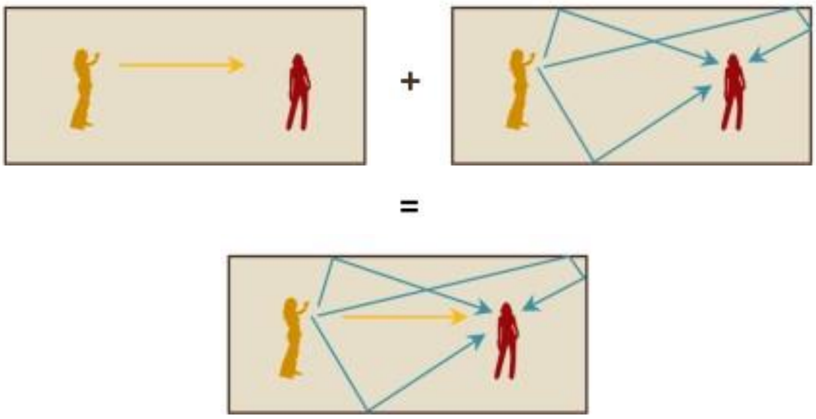


Figure 18. The propagation of a sound wave (Molinaro, 2017)

- Solutions to Reduce Reverberation: To minimize or eliminate reverberation, the following strategies can be applied:

1. Use sound-absorbing materials: Carpets, curtains, upholstered furniture, acoustic panels, or acoustic ceiling tiles.
2. Modify room surfaces: Replace hard, reflective surfaces (concrete, glass) with softer or textured materials.
3. Control room geometry: Avoid parallel walls and flat surfaces that create strong reflections; use angled or irregular surfaces.
4. Add furnishings and partitions: Bookshelves, plants, or movable partitions can break up sound reflections.
5. Install acoustic ceilings: Suspended or perforated ceilings can significantly reduce reverberation in large spaces.
6. Use sound-diffusing elements: Diffusers scatter sound waves, reducing the intensity of direct reflections.
7. Electronic solutions (if needed): In some cases, sound masking or electronic acoustic treatment can complement physical measures

I.4. Olfactory COMFORT

Introduction

Olfactory comfort is a key aspect of indoor environmental quality that relates to how pleasant or unpleasant the smells in a space are. It directly affects occupants' well-being, satisfaction, and productivity. Unlike thermal, visual, or acoustic comfort, olfactory comfort focuses on the sense of smell and the perception of air quality. A space with good olfactory comfort is free from unpleasant odors, well-ventilated, and maintains fresh and clean air, contributing to a healthier and more comfortable indoor environment.

1.4.1. Olfactory comfort

Olfactory comfort refers to the quality of the air in a space with respect to odors, ensuring that the environment is free from unpleasant smells and contributes to occupants' well-being. It is an important aspect of indoor comfort, alongside thermal, visual, and acoustic comfort. Comfort and indoor air quality (IAQ) depend on several factors, including thermal regulation, control of internal and external pollutants, supply of clean air, occupant activities and preferences, and proper operation and maintenance of building systems.

Ventilation and infiltration alone are not sufficient to ensure acceptable indoor air quality. Human metabolism in enclosed spaces requires oxygen (O_2) intake and carbon dioxide (CO_2) removal, which are transported by the blood after air passes through the upper and lower airways, where it is filtered and conditioned for temperature and humidity.

The flow rate of expired CO_2 is shown in Table 1:

Table 1. The flow rate of expired CO_2 (Ioan and Călin, 2011)

Activity	M [W/pers]	Inspired air [m³/h]	Expired CO_2 [l/h]	Consumed O_2 [l/h]
Sedentary	–	0.30	12	14
Intellectual	120	0.375	15	18
Physical very easy	150	0.575	23	27
Physical easy	190	0.75	30	35
Physical hard	>270	>0.75	>30	>35

The composition of air in indoor spaces differs from that of outdoor air. While the carbon dioxide (CO_2) concentration in outdoor air ranges between 300 and 400 ppm, indoor levels can reach approximately 900 ppm. The maximum allowable CO_2 concentration in inhaled air is 1000 ppm, known as Pettenkofer's number. Table 2 shows the effects of various CO_2 concentrations on the human body.

Table 2. the effects of various CO_2 concentrations on the human body (Ioan and Călin, 2011)

CO_2 concentration		Effect
[%]	[ppm]	
3	30000	Deep breathing, strong
4	40000	Head aches, pulse, dizziness, psychic emotions
5	50000	After 0.5…1 hours may cause death
8...10	80000...100000	Sudden death

1.4.2. Olfactory discomfort

Potential olfactory nuisances can originate both outside and inside buildings, yet they are often overlooked in building programs and design projects. Olfactory discomfort is the equivalent of noise pollution in the auditory domain. Olfactory comfort is defined either by the absence of unpleasant odors or by the presence of pleasant scents. Achieving it requires maintaining good ambient air quality through two main strategies: limiting pollutants at their source and ensuring appropriate ventilation.

1.4.3. Reducing sources of unpleasant odors

Olfactory comfort is essential for indoor environmental quality. Unpleasant odors can negatively affect occupants' well-being, productivity, and perception of the space. They can originate from:

- Inside the building: sources include building pathologies such as mold, stored products (paper, food, waste), or cigarette smoke.
- Outside the building: sources include nearby polluting facilities, factories, agricultural operations, or traffic.

1.4.4. Sources of Odors

(a) Cleaning and maintenance products: Strong detergents, disinfectants, and chemicals can produce lingering odors.

(b) Waste: Organic waste (food), chemical waste, or industrial residues can generate strong smells if not properly managed.

(c) Building materials and equipment: Some paints, adhesives, carpets, and machinery release volatile organic compounds (VOCs) that cause odors.

(d) HVAC system problems: Poorly maintained ventilation systems can accumulate dust, mold, or contaminants, spreading odors through airflow.

1.4.5. Strategies to Minimize Odors in the built environment

Creating a comfortable and healthy indoor environment is a fundamental consideration in architectural design. Ventilation and air circulation play a crucial role in minimizing unpleasant odors and maintaining olfactory comfort in the built environment. In this section, we will explore the importance of ventilation, discuss key strategies to optimize airflow, and address related measures such as Material Selection, Waste Management, and System Maintenance.

1.4.5.1. Ventilation and Air Distribution

In confined spaces, the air composition changes due to the presence of occupants and eventually becomes unfit for breathing. Therefore, it is essential to select a high-performance ventilation system and to size it appropriately, considering factors such as occupancy patterns, system controls, and window use. It is crucial to ensure that air supply and exhaust rates provided by technical equipment meet the actual needs of each room. Balancing this requirement for ventilation with energy efficiency can be challenging, as ventilation systems often consume significant energy.

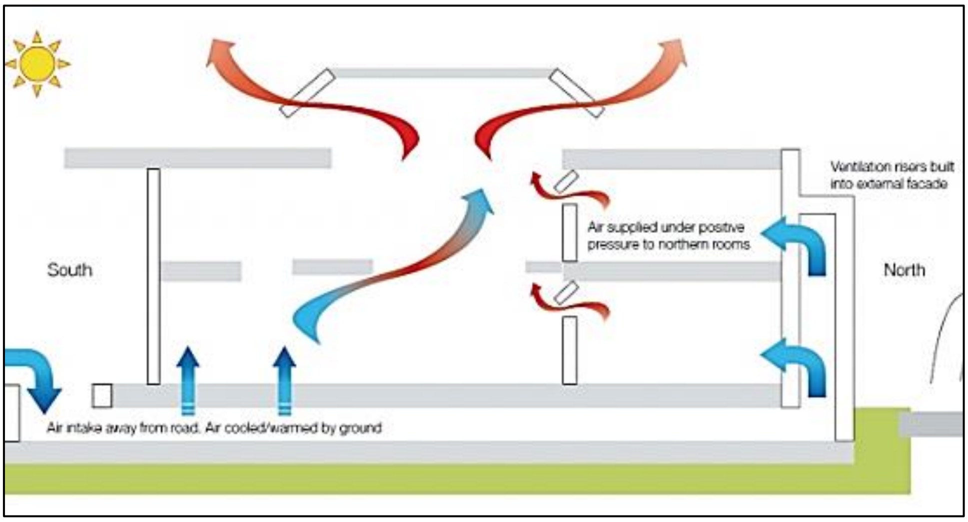


Figure 19. Ventilation in building (https://www.designingbuildings.co.uk/wiki/File:Schematic_section.jpg)

To ensure effective ventilation, it is important to:

- Ensure air supplied to rooms is odor-free using filters, activated carbon, or UV purification in HVAC systems.

- Position air intakes away from sources of odors such as waste areas, kitchens, or exhaust vents.
- Design exhaust vents to efficiently remove odorous air without allowing it to recirculate.
- Maintain a slight positive pressure in occupied areas to prevent infiltration of odors from corridors, service areas, or outside sources.

1.4.5.2. Material Selection

Proper selection of building materials and furnishings is crucial for maintaining olfactory comfort in indoor spaces. Materials can release volatile organic compounds (VOCs) or other odorous substances that negatively impact air quality and occupant well-being. Strategies include:

- Low-VOC or odorless products: Use paints, adhesives, sealants, and coatings that have low or no VOC emissions. This reduces the release of chemical odors into the indoor air over time.
- Furniture and finishes: Select furniture, flooring, wall coverings, and upholstery that are certified for low emissions and do not produce strong smells as they age. Materials like natural wood, fabrics with low chemical treatment, or formaldehyde-free panels are preferable.
- Sustainable and natural materials: Whenever possible, incorporate natural, breathable materials (e.g., untreated wood, bamboo, cork, natural stone) that do not trap or emit odors.
- Avoid strong-smelling materials: Materials such as certain carpets, laminates, synthetic resins, or particle boards can emit unpleasant odors over time, so they should be minimized or replaced with low-emission alternatives.
- Regular monitoring and testing: Newly installed materials can release odors during the first weeks. Periodic air quality checks or the use of odor-free certified products ensures long-term comfort.

1.4.5.3. Waste Management

Effective waste management is essential for maintaining olfactory comfort in indoor environments. Poorly managed waste can produce unpleasant odors, attract pests, and negatively affect air quality and occupant well-being. Strategies include:

- Sealed storage: All waste, whether organic or chemical, should be stored in airtight, sealed containers to prevent odors from escaping into occupied spaces. Containers should be made of materials that are easy to clean and resistant to leaks.

- Regular removal: Waste should be removed frequently, ideally daily or according to building usage, to prevent the accumulation of odor-causing materials. Delays in disposal can lead to strong and persistent smells.
- Waste separation: Separate organic waste (food, plant matter) from chemical or industrial waste. Organic waste tends to produce strong odors if combined with other materials. Proper segregation helps manage odor intensity and facilitates recycling or safe disposal.
- Designated collection points: Establish well-ventilated, enclosed areas for temporary waste storage away from occupied spaces to reduce odor exposure.

1.4.5.4. Maintenance

Proper maintenance of ventilation systems is essential to ensure effective airflow, healthy indoor air quality, and olfactory comfort. Neglecting maintenance can lead to the accumulation of dust, microbial growth, and odors, reducing system performance and occupant comfort. Key strategies include:

- Regular cleaning of ventilation ducts and air handling units: Dust, debris, and particulate matter can accumulate in ducts and fans over time, obstructing airflow and becoming a source of unpleasant odors. Routine cleaning ensures efficient air distribution and prevents the spread of contaminants.
- Inspection and maintenance of humidifiers, filters, and drains: (a) Humidifiers: Must be cleaned and sanitized regularly to prevent mold and bacterial growth. (b) Filters: Air filters should be inspected and replaced according to manufacturer recommendations to maintain clean air and prevent clogging that reduces system efficiency, and (c) Drains and condensate pans: Should be checked to prevent stagnant water, which can encourage microbial growth and produce foul odors.
- Preventive maintenance schedule: Establishing a regular inspection and maintenance schedule ensures all components of the ventilation system function correctly, maintaining air quality and olfactory comfort over time.
- Monitoring system performance: Track airflow rates, filter condition, and humidity levels to identify issues early and avoid indoor air quality problems.

CHAPTER 2

2 ASSESSMENT AND DIAGNOSTIC METHODS

Introduction

Ensuring comfort within buildings is one of the primary concerns of architects and engineers. To achieve this, several methods, approaches, and tools have been developed to optimize, analyze, and evaluate the physical parameters within a built environment. The main goal of these methods is to guarantee user well-being in all seasons while reducing building energy consumption, thereby contributing to the preservation of our planet. The first part of this chapter provides an overview of the concept of sustainable development, its challenges, and the principles of high-performance buildings. The second part presents, in detail, the various methods for evaluating and diagnosing comfort within buildings.

2.1. Sustainable Development and Environmental

Introduction

The demand for a sustainable environment, and particularly for sustainable architecture, is increasingly widespread. The intensive consumption of fossil energies leads to a significant rise in greenhouse gas emissions such as carbon dioxide, methane, and others, and consequently to global warming. These dangers faced by our planet and its inhabitants make it essential to reconsider our lifestyles. This involves, among other measures, adopting sustainable development principles and promoting ecological or eco-responsible architecture—architecture that is comfortable, functional, efficient in its use of raw materials, and respectful of the environment.

2.1.1. The challenges of sustainable development and environmental quality

- Climate change: greenhouse gas emissions, climate instability
- Human health and biodiversity: generated pollution, health risks, and the diversity of fauna and flora
- Resource depletion: land, forests, primary energy, water, materials, and air
- Social imbalances: population growth, access to energy and water, technological risks
- Changes in the building market: building renovation, emergence of new companies, commercial franchises, construction-broker franchises, and foreign companies
- Cultural transformation: contributing to the protection of the planet and making informed decisions regarding material selection, adopted methods, used technologies, etc.

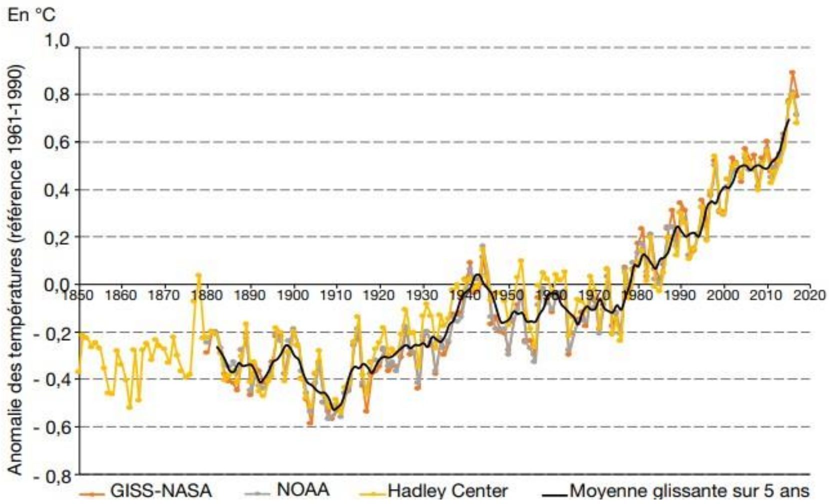


Figure 20. Evolution of the global average annual temperature from 1850 to 2017 (source: NASA, NOAA, Hadley Center)

2.1.2. Technical and regulatory developments

Technical and regulatory developments have emerged in response to new precautionary principles, media pressure, the need to control the provenance and origin of materials, working conditions, indoor air quality requirements, new energy sources, and industrial innovation. Today, environmental quality and energy efficiency play an increasingly important role in the building sector, both in new construction and renovation. Since the 1980s, labels, standards, certifications, processes, and guidelines have multiplied at national, European, and global scales. The energy and environmental context of the early 21st century is characterized by concerns about sustainability with regard to mineral and energy resources, living environments, human health, and biodiversity.

2.1.2.1. From an energy perspective

The imbalance between energy production—largely dependent on finite mineral resources extracted from the Earth’s crust—and rapidly growing consumption creates tensions of various kinds (economic, geographic, social, etc.).

2.1.2.2. Environmental impact

Human activities draw on the resources provided by the Earth's biosphere and release the by-products of their production back into that same biosphere. The rapid intensification of these activities generates significant short- and long-term impacts at all scales—local, regional, and global.

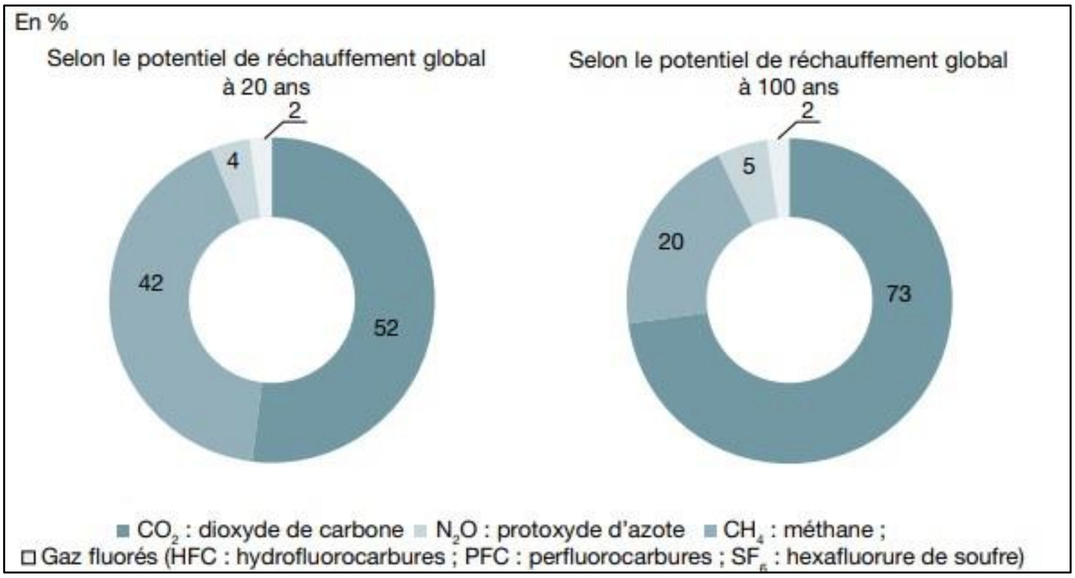


Figure 21. Distribution of global GHG emissions (including LULUCF) by gas in 2010
(According to the IPCC, 3eworking group, 2014)

Following the 1992 Earth Summit in Rio, the Kyoto Protocol of 1997 established international targets for reducing greenhouse gas (GHG) emissions, along with a global implementation timeline. This was followed by the 2002 European Energy Efficiency Directive. France subsequently committed to combating GHG emissions, multiplying national initiatives such as the Factor 4 objective and the POPE program.

- In 2004, France launched the Climate Plan, whose "Factor 4" objective aimed to reduce national GHG emissions by a factor of four by 2050.
- In 2005, the POPE Law (Energy Policy Guidelines Program) defined the main directions of national energy policy up to 2020, with the overall goal of reducing energy consumption and GHG emissions by 30%.

2.1.3. The Grenelle Environment Forum

The Grenelle Environment Forum set forth a broad and ambitious objective. Its proposals were developed within six working groups, each addressing specific goals:

- Combating climate change: modernizing buildings and cities, improving energy and carbon efficiency, enhancing urban planning and territorial governance, and developing sustainable mobility and transport.
- Preserving biodiversity and natural resources.
- Establishing a health-friendly environment.
- Promoting sustainable production and consumption patterns.

- Encouraging environmentally responsible development approaches that support employment and competitiveness.

The Grenelle Environment Forum introduced a pioneering framework for new construction. The *low-energy building standard (BBC)*—corresponding to buildings consuming less than 50 kWh/m² per year—was to be applied to all new buildings starting at the end of 2012, and, in anticipation, to all public and tertiary buildings starting at the end of 2010. The long-term objective is to achieve *positive-energy buildings (BEPOS)* by 2020.

2.1.4. The importance of certifications and labels

Obtaining a certification or label is a voluntary process carried out by a project owner or developer who wishes to have the quality of their construction or renovation projects assessed and recognized. These various labels and certifications serve as indicators for future buyers or tenants regarding comfort, energy performance, and environmental responsibility. Today, many project owners and developers are particularly aware of the environmental and energy challenges previously mentioned. Certification also enables them to validate the performance achieved and meet client expectations by providing concrete and verifiable proof of results. In the context of the current economic crisis, prospective buyers or tenants—whether residential or commercial—are seeking high-quality, energy-efficient buildings that offer both a secure investment and potential cost savings. Increasingly conscious of the need to protect the planet, they are also turning toward eco-construction and eco-renovation. To meet these expectations, project owners and developers must equip themselves with the tools to guarantee the environmental and energy quality of their projects. This is achieved through verification by a qualified and independent organization or association, generally supported by a national network of accredited assessors. The building sector is therefore particularly impacted by this evolution, which is at once ethical, regulatory, and economic.

2.1.5. High-performance building concepts

The concepts of high-performance buildings are most often defined within the framework of certifications, labels, or regulations. They are associated with specific criteria describing their objectives or with methods for evaluating their performance levels. The names of these buildings vary, with each emphasizing a particular characteristic; however, these names are necessarily somewhat reductive. A typology of the terms found in the literature has been developed to highlight the main characteristics of these buildings and the principal concepts associated with them. Broadly, two types of approaches can be distinguished:

(1) Purely energy-based approaches
(2) Broader approaches

2.1.5.1. Purely energetic concepts

Purely energy-related concepts are associated with regulations aimed at improving the energy performance of buildings:

- Thermal Regulation 2005 [JORF 2006] in France.
- In France, the regulations provide five labels: HPE, THPE, HPE EnR, THPE EnR, and BBC 2005.
- Other international labels include Minergie in Switzerland [Minergie 2008], Passivhaus in Germany [Passivhaus 2008], and Casa Clima / Klimahaus in Italy [Klimahaus 2008].
- These regulations and labels often define several performance levels and encourage the integration of renewable energy sources into buildings [JORF 2007].

2.1.5.2. Broader Concepts

Some concepts originate from holistic approaches that consider a wide range of interactions between a building and its environment, with energy efficiency being only one component of these interactions. Examples include:

- CASBEE (Japan) [CASBEE 2008]
- LEED (United States) [USGBC 2008]
- BREEAM (United Kingdom) [BREEAM 2008]
- R-2000 standard (Canada), which is associated with regulations [R2000 2005]

In France, the HQE (High Environmental Quality) approach, available to project owners, does not impose specific performance targets [AssoHQE 2006].

2.2. Evaluation and diagnostic methods

Introduction

Regardless of the environment in which they find themselves, humans always strive to ensure their well-being. To this end, buildings must provide the most comfortable interior conditions for their occupants. Consequently, methods have been developed to define, interpret, and optimize indoor environments—including thermal, acoustic, visual, and olfactory aspects. These methods translate sensory factors into measurable comfort indices and can be derived using empirical calculation methods, indices and diagrams, field measurements, or experiments with physical and numerical models.

2.2.1. The field measurements

On-site measurements are a simple and practical tool that allows both qualitative and quantitative analysis of physical parameters—such as light, heat, and sound—inside or outside a building. They make it possible to characterize the indoor environment and obtain accurate values for temperature, noise levels, lighting, luminance, and more. A wide range of measurements can be carried out, including:

- Measurements related to occupant well-being (handling complaints, conducting questionnaires, assessing thermal comfort, etc.).
- Ventilation-related measurements (air permeability of the building envelope, airflow rates, indoor air quality, etc.).
- Acoustic measurements (sound level, reverberation time, airborne noise insulation, impact noise insulation, etc.).
- Lighting measurements (illuminance, luminance, glare, etc.).
- Assessment of the thermal insulation of building components.
- Energy consumption measurements (energy use, energy expenditure index, energy signature, etc.).

For diagnostic measurements to be effective, it is essential **to** first define the objectives of the study and the information to be collected, while ensuring that the selected measurements will provide all the necessary data. It is also recommended to establish the interpretation method before beginning any experiment or taking measurements. When conducting on-site measurements, it is equally important to use appropriate instruments, such as:

(1) A lux meter (to measure illuminance),
(2) A luminance meter (to measure luminance),
(3) A digital thermal camera (to measure surface temperatures), and
(4) A multifunction thermometer (to measure air temperature, wind speed, and relative humidity) (see Figure 19).

(1) Lux meter

(2) Luminance meter

(3) Digital thermal camera

(4) Multifunctional thermometer

Figure 22. In-situ measurement equipment (Author, 2019)

The use of this tool can be understood within two limitations.

- First, on-site measurements can only be performed after the building has been constructed, which excludes their use during the design phase.

- Second, the measurements are strongly dependent on climatic conditions, which can influence the accuracy and representativeness of the results.

2.2.2. Simplified calculation methods

Simplified calculation methods are tools that allow the preliminary estimation of natural lighting conditions. These tools take the form of simplified algorithms, tables, nomograms, diagrams, and similar resources, available either in digital or paper form. They are used to calculate illuminance, daylight factor, heat gains, heat losses, noise levels, cooling loads, energy consumption, and other environmental performance indicators.

2.2.2.1. Empirical methods for calculating lighting

The International Commission on Illumination (CIE) has developed a method, based on formulas and diagrams, to estimate the daylight factor (DF) inside a room under overcast sky conditions. These methods are generally used by designers during the preliminary sketch phase of a lighting project, as they provide approximate illuminance values for a space, giving an initial indication of its natural lighting performance. However, their limitations become evident when more detailed tasks are required, such as visualizing the interior ambiance, evaluating visual comfort, or analyzing complex lighting configurations. In such cases, other preliminary tools must be used. Several simplified methods exist for calculating indoor lighting based on artificial and natural light sources. These include, among others:

- The Nomogram and Graphical Methods: Tools such as charts, diagrams, and nomograms that help estimate daylighting performance, window sizing, or illuminance distribution without detailed calculations. The Waldram diagram method (see Figure 20) is based on a system that projects the sky onto a grid in which each element represents the (equivalent) contribution of a portion of the sky to the illumination at the point being studied. Several diagrams exist for different sky types, allowing calculations to be performed under various outdoor lighting conditions.

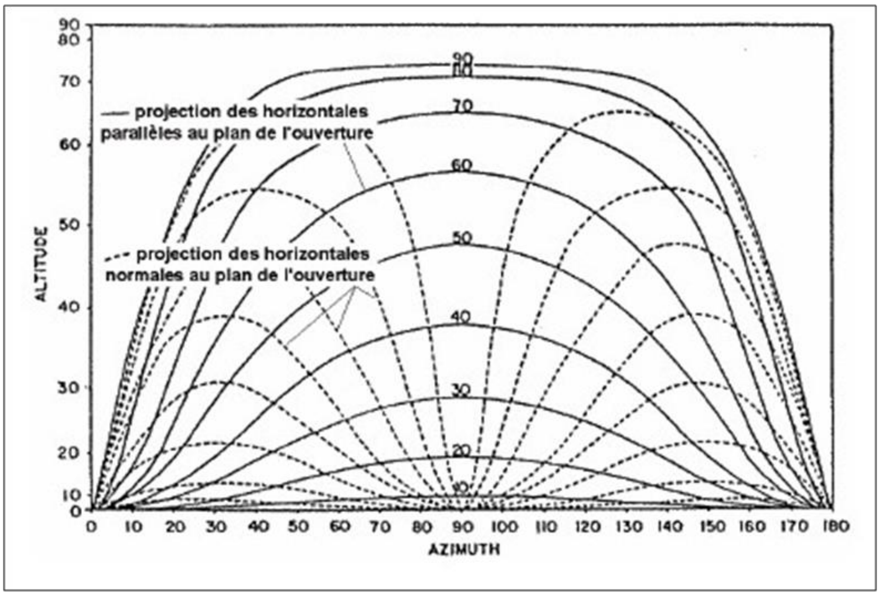


Figure 23. Waldram diagram (Source: Francis Miguet, 2000)

- The BRS Method. Developed by the BRE (Building Research Establishment – United Kingdom), this method calculates daylight factor (DF) values under an overcast sky at a specific point inside a building, based on its floor plans and the type of sky. This relatively simple method also accounts for external obstructions. It relies on the use of disks which, when applied at the correct scale to building cross-sections, determine the direct component of daylight. Different disks allow the calculation of daylight under different sky conditions.
- The NBN L 13-002 Standard for calculations relating to natural light. It is used to determine the illuminance component due to natural lighting inside buildings based on the direct contribution of the sky and reflected light (direct component, externally reflected component, and internally reflected component) under overcast sky conditions.
- The NBN L 14-002/A1 Standard for artificial lighting calculations. This standard allows point-by-point calculation of illuminance values under artificial lighting conditions.
- The Lumen Method (or Utilization Factor Method): Used to calculate the average illuminance in a room based on the light output of luminaires, their number, and their efficiency. It is mainly used for artificial lighting design.
- The Point-by-Point Method: This method determines the illuminance at specific points within a space using the inverse-square law and cosine law. It is more precise but requires more calculations.

- The Daylight Factor (DF) Method: Widely used to predict natural lighting under overcast sky conditions. It estimates the ratio between indoor illuminance and the simultaneous outdoor illuminance.

2.2.2.2. Empirical methods for calculating heat loss

Calculating a heat balance makes it possible to accurately determine the amount of energy required to heat or cool a building. Several factors must be considered, such as the type of building, its exposure, and the surface area of its walls, windows, ceilings, and floors, which are multiplied by coefficients that vary according to altitude, solar radiation, geographical location, etc. Other elements must also be taken into account, including air exchange, thermal bridges, and heat gains that affect the calculation, such as human occupancy and appliances. Two methods are used to evaluate heat losses.

- **Calculation method using the G coefficient**: The G coefficient represents the building's volumetric heat loss, expressed in watts per cubic meter per degree Celsius ($W/m^3\cdot°C$). Although this coefficient is gradually being replaced by the UBAT coefficient, calculations using G remain practical, albeit with limited accuracy and reliability.

$$\text{Balance} = G \times V \times \Delta T \qquad \textit{Equation (4)}$$

G: Overall heat loss coefficient ($W/m^3\cdot°C$)

- 0.65 $W/m^3\cdot°C$ – Insulation standard TR 2005
- 0.75 $W/m^3\cdot°C$ – Insulation standard TR 2000
- 0.90 $W/m^3\cdot°C$ – Construction after 1980
- 1.20 $W/m^3\cdot°C$ – Moderately insulated building
- 1.80 $W/m^3\cdot°C$ – Uninsulated construction

V: Building volume (m^3)
ΔT: Temperature difference between the inside and outside

- **Calculation method using the UBAT coefficient:** The calculation of a building's thermal balance (heat loss) is performed using the following formula:

$$\text{Heat losses} = Dp \times (19 - \text{Text base}) \qquad \textit{Equation (5)}$$

Where:

D_p represents the building's **heat loss coefficient** (W/K), calculated as:

$$Dp = UBAT \times Sdep + R \times Vh \qquad \textit{Equation (6)}$$

UBAT: Average total heat loss coefficient of the building (all walls) in W/m²·K. For greater accuracy, it is recommended to calculate UBAT for each wall individually. Empirical UBAT values are:

- 0.3 – House with exceptional insulation (excellent)
- 0.4 – Insulation without thermal bridges
- 0.75 – Conventional insulation (RT 2005), built between 2007–2012
- 0.8 – Conventional insulation (RT 2000), built between 2001–2006
- 0.95 – Houses built between 1990–2000
- 1.15 – Houses built between 1983–1989
- 1.4 – Houses built between 1974–1982
- 1.8 – Not insulated, single-glazed windows

Sdep: Sum of wall areas (m^2)

Vh: Habitable volume of the treated area (m^3)

R: Coefficient depending on ventilation type:

- Self-regulating MVHR: R = 0.2
- Humidity-controlled MVHR: R = 0.14

19: Comfort temperature (°C)

Tbase: Base outdoor temperature of the location

2.2.3. Comfort indicators

Comfort indicators are quantitative or qualitative measures used to evaluate the well-being of occupants in a building. They help assess how well the indoor environment meets human needs in terms of thermal, visual, acoustic, and olfactory comfort. These indicators translate sensory perceptions into measurable values that can guide building design, operation, and renovation. Comfort results from a complex interaction of geographical and climatic conditions, personal parameters, and characteristics of spaces. It can be evaluated using direct indices, indices derived from direct indices (known as Direct Comfort Indices), and empirical indices.

2.2.3.1. Direct indices

Direct Comfort Indicators provide partial information about occupant comfort:

(1) Temperature: This indicator generally provides useful information but can sometimes be misleading if considered alone.
(2) Relative humidity: It becomes significant at extreme values; conditions are considered uncomfortable when humidity falls below 20–30% or exceeds 70–80%.

(3) Air velocity: This indicator must be interpreted in combination with other factors, such as temperature and humidity, to provide meaningful insights into comfort.

2.2.3.2. Direct derivative indices

These indices are derived from direct comfort indices and include mean radiant temperature, equivalent temperature, operative temperature, and wet-bulb operative temperature.

(1) Mean Radiant Temperature (MRT): This is the weighted average of surrounding surface temperatures, representing the uniform temperature of a hypothetical black body with which a person would exchange the same amount of heat as with their actual environment.

(2) (2) MRT can be measured using a black globe thermometer or a black globe temperature sensor (Tg), together with the dry-bulb temperature (Ts) and air velocity (va).

Tmr: Tg + 0.24(Tg - Ts)va1/2 ***Equation (7)***

The wet-bulb operative temperature represents a variation of the operative temperature that accounts for a state of air saturation, so that heat exchanges occur not only through convection and radiation but also through evapotranspiration.

Table 3. Example of comfort conditions inside a building (Source: Bioclimatic Architecture in a Sustainable Environment, F. Javier Neila Gonzalez, p. 233)

Season	Temperature operative (°C)	Average speed air (m/s)	Humidity relative (%)
Summer	23…25	0.18…0.24	40…60
Winter	20…23	0.15…0.20	40…60

The operative temperature represents the temperature of a parcel of air from which all water vapor has been removed through an adiabatic process. Atmospheric air is humid, composed of dry air and water vapor. Consider a small volume of humid air at a temperature T and a mixing ratio r. If this air is completely dried through condensation, the removal of water vapor causes the air temperature to rise, depending on the latent heat of condensation.

A simplified approximation of the operative temperature can be expressed as:

$$Toperating = \frac{\text{Tair+ Twall}}{2}$$ ***Equation (8)***

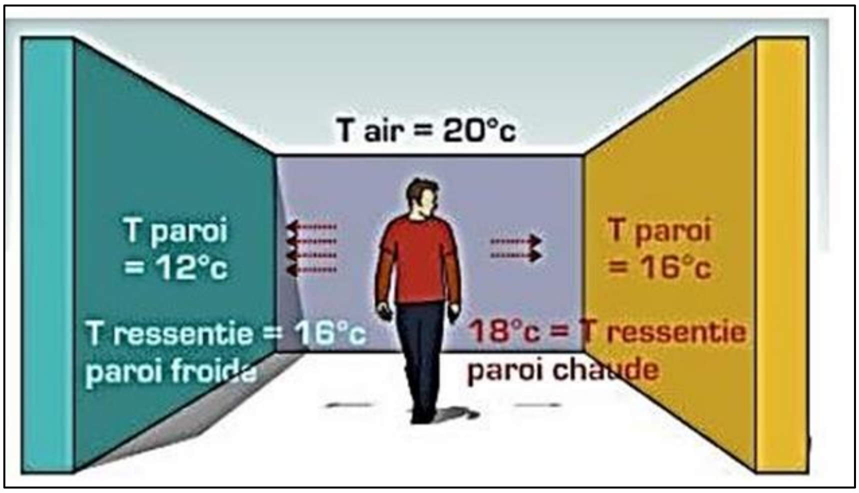


Figure 24. The operative temperature
(Hygrothermal comfort and reduction of energy consumption, 2014)

2.2.3.3. Empirical indices

There are numerous empirical indices used to evaluate the concept of comfort, including: Effective Temperature, Wind Chill Index, Observed Degree of Satisfaction (ODS), Expected Degree of Satisfaction (EDS), Percentage of Satisfied People (PSP), and others. One of the most widely used indices is the Predicted Mean Vote (PMV), which reflects the average opinion of a large group of people regarding their perceived thermal comfort. The PMV is interpreted on the following scale:

(1) A PMV value of 0 indicates optimal thermal comfort.
(2) A negative PMV value signifies that the temperature is lower than the ideal.
(3) A positive PMV value indicates that the temperature is higher than the ideal.

Several factors influence the calculation of the PMV, including:

- Activity and metabolic rate (W/m²)
- Work rate (W/m²)
- Ratio of clothed to unclothed body surface area
- Air temperature (°C)
- Mean radiant temperature (°C)
- Vapor pressure (Pa)
- Convective heat transfer coefficient (W/m²·°C)
- Surface temperature of clothing (°C)
- Thermal resistance of clothing (m²·°C/W)

2.2.3.4. PMV/PPD analysis of the sensation of hygrothermal comfort

The Predicted Percentage of Dissatisfied (PPD) index estimates, based on the PMV value of a specific thermal condition, the percentage of people likely to be dissatisfied with that environment. Once the predicted mean PMV is known, the PPD can be directly evaluated using standard charts. The thermal comfort zone is generally defined as the range from a sensation of slight coolness (-1) to slight warmth (+1), i.e., PMV values between -1 and +1. Within this range, the majority of occupants are considered to feel thermally comfortable.

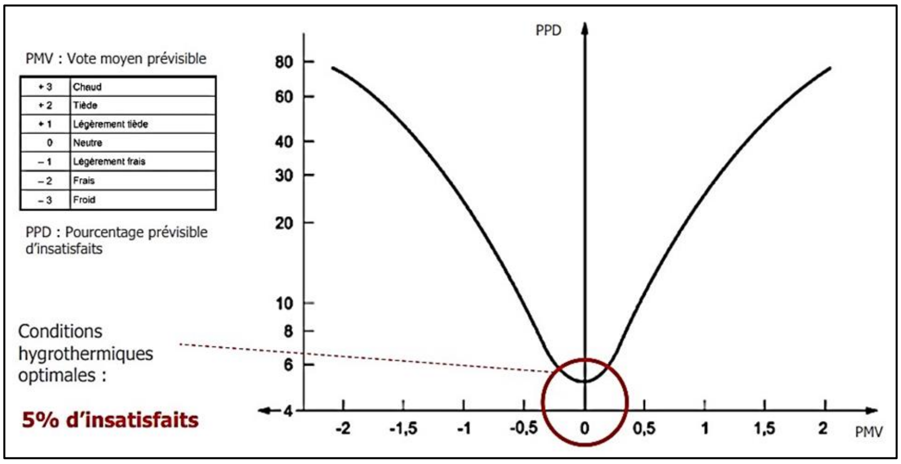


Figure 25. PMV/PPD analysis of the sensation of hygrothermal comfort
(Hygrothermal comfort and reduction of energy consumption, 2014)

2.2.4. Numerical simulation

It is now well established that information technology has become an essential tool for architects in both their current and future practice. From project design to communication, the use of computers offers greater precision and time-saving efficiency.

2.2.4.1. Computer methods

Computer-based methods are widely used during the design and modeling phases of lighting, heating, ventilation, and air-conditioning systems for both new and existing buildings, in order to optimize their performance. With the evolution of information technology, software simulations now make it possible to predict and calculate comfort parameters inside buildings. These simulations can assess lighting conditions, thermal performance, acoustics, energy consumption, and even wind behavior at the urban scale.

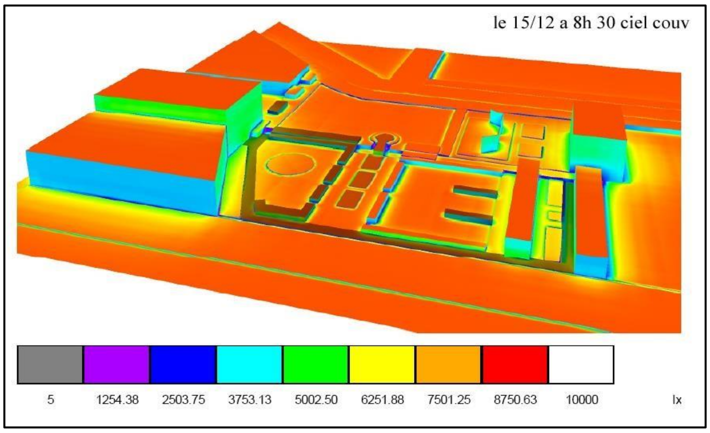


Figure 26. Thermal simulation at the urban scale (Author, 2010)

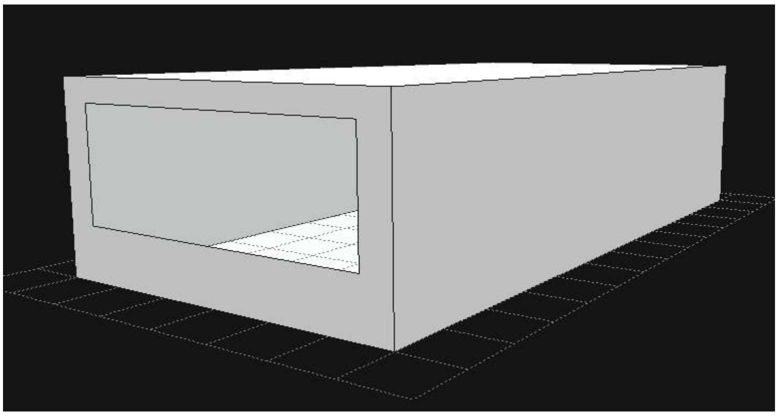


Figure 27. Numerical model for simulation (Daich, 2011)

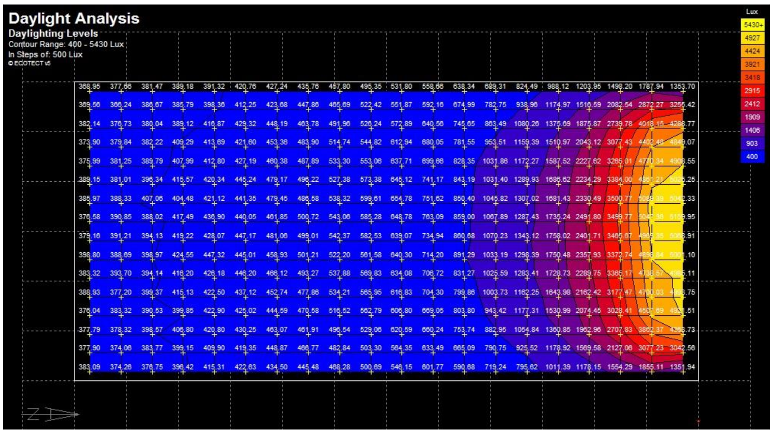


Figure 28. Architectural scale lighting simulation (Daich, 2011)

The parameters required to simulate a physical phenomenon in a building are based on both constant and variable factors. The constant parameters include:

- Geographical location (latitude, longitude, and altitude).
- Type of area: urban or rural.

- Sky conditions: intermediate, overcast, or clear.
- Simulation software used.
- Room geometry, including: Room dimensions (width, length, height) and Window characteristics (width, height, ceiling height, and sill height).
- Material properties, including:
  - Walls (interior walls).
  - Floor slab (interior).
  - Ceiling (interior).
  - Light shelf (internal part).
  - Glazing.

The structural grid is used to divide the space into a series of cells, and then into measurement points. These points can be coded either numerically (1, 2, 3, …) or alphanumerically (a1, a2, b1, b2, …). The grid used in the simulation was positioned 0.9 m above the floor, representing the height of the work plane. To observe variations in natural light levels from the window toward the back of the space, an additional vertical grid is also proposed.

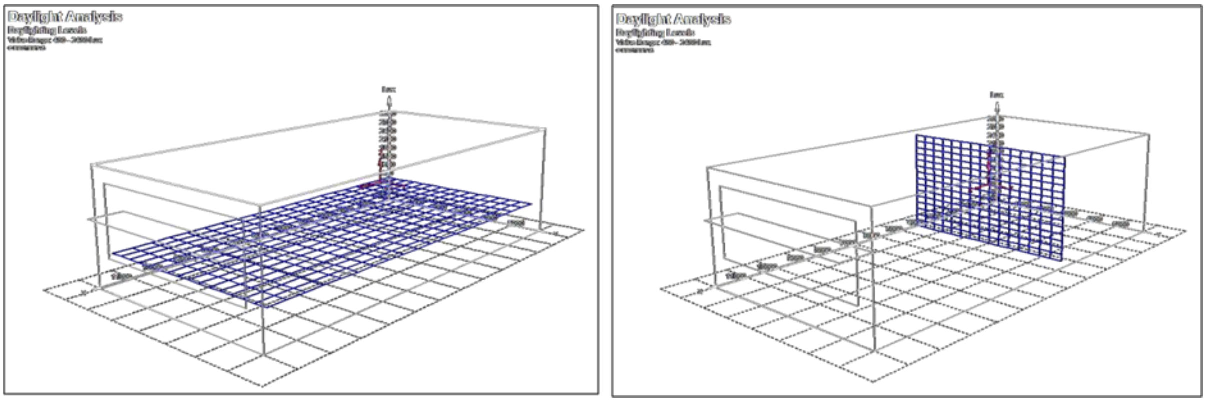


Figure 29. The structural grid: on the left, horizontal structural grid; on the right, grid vertical structure (Daich, 2011)

2.2.4.2. Advantages and Role of Simulation Tools in Environmental Quality Projects

1. Assistance in drawing the geometry of rooms (grid, etc.), sizing glazed surfaces, and selecting solar protection devices and interior finishes.
2. For certified projects, in accordance with standards that require performing natural lighting calculations.
3. For educational purposes, to help explain certain design choices to the project owner.
4. In professional practice, to provide design support for interior space layout.

2.2.5. Physical simulation

During the architectural design process, architects often use physical models. These are scaled-down replicas of reality that preserve the geometric properties of the actual building. This physical model helps architects make decisions regarding form, structure, and façade geometry. It also allows them to study natural phenomena such as light, acoustics, and wind behavior, while thermal phenomena and artificial lighting remain more difficult to model accurately.

2.2.5.1. Physical models for lighting studies

Light models can provide highly accurate qualitative and quantitative results. When human visual perception is taken into account, no visual difference can be detected between reality and a scale model. If a room model is built with precision—respecting its geometry, the characteristics of its interior surfaces (colors, materials, etc.), and its furnishings—the quantity and quality of light will be identical to those in the actual room (under the same sky conditions). The resulting visual impression will therefore be very close to that experienced in the real space.

Figure 30. Physical model at ¼ scale (Daich et al, 2016)

The choice of scale for the model varies depending on the type of study. This scale can range from 1/500 up to full scale. Three main types of models are commonly used:

- **Mass models**, generally at a scale of 1/200, or sometimes 1/100.
- **Models for studying building performance**, typically at a scale of 1/50.
- **Models for examining the efficiency of control elements and new materials**, as well as for simulating opening details, which are built at smaller scales ranging from 1/10 up to full scale and require greater construction precision.

The size of the scale model can also be determined by the type of visualization required, the size of the measuring equipment, and the size of the artificial sky. When integrating a camera into the model, several factors must be considered: the center of the lens should be at eye level, between 1.5 and 1.7 meters in real scale. The dimensions of light-measuring sensors or lux meters must also be taken into account. For photography, macro lenses with a focal length of less than 28 mm are generally used, as they allow for sharp images at very close distances. As a result, the model must have a minimum ceiling height of 15 cm and a minimum room depth of 30 cm.

Figure 31. Physical model at ¼ scale (Daich, 2011)

For the construction of scale models, almost any material commonly used in architecture can be employed. Foam board is generally used for modeling walls. This material is at least 1 cm thick and composed of several layers, making it easy to cut. Its only drawback is a slight translucency. Light may pass through the model walls due to imperfections in their opacity or gaps at the joints, which can lead to significant measurement errors—especially in rooms with low daylight levels. To ensure the model's opacity, black tape should be applied along all the intersections between the different components of the model.

Figure 32. Modeling of walls at 1/4 scale (Daich, 2019)

There are three well-known methods for checking the light proofing of a scale model:

- **The first method** consists of placing the model under direct sunlight to ensure that no light passes through the walls.

- **The second method**, which is the opposite approach, involves placing the model in a dark room and turning on a light source inside it. If no light is visible from the outside, the model is considered sufficiently opaque.

- **The third method**, which is the most accurate, consists of blocking all the model's openings and measuring the luminance inside the room. If any light enters the model, it indicates a defect in opacity.

Therefore, constructing the walls of a scale model requires great precision. The walls must be tightly connected to prevent any light leakage. Internal partitions significantly affect the distribution and quantity of light within the room. Thus, it is essential to model them, especially in areas where modifications are planned. Experience shows that using pins provides excellent flexibility for making adjustments.

Figure 33. Leak test (Daich, 2019)

Modeling furniture is crucial for both quantitative and qualitative analyses of lighting in scale models, and it typically requires more effort than modeling partitions. The layout, color, and materials of the furniture significantly influence the distribution of light within the room. Light-colored furniture reflects light and helps distribute it throughout the space, thereby affecting the overall lighting atmosphere—particularly when assessing the quality of the interior environment. Additionally, furniture must be fixed in place within the model to prevent any movement during simulations. Accurate modeling of furniture is therefore essential to obtaining reliable and precise lighting results.

Figure 34. Left: Furniture modeling; right: Interior ambiance (Daich, 2019)

It is essential to carefully select modeling materials that closely replicate the actual materials, especially for lighting studies, to achieve accurate and realistic results. The material's reflectance coefficients and the nature of its reflection must match those of the real surfaces. Other external factors, such as dust, dirt, and surface texture, can also affect results by reducing reflectance.

The choice of material will further depend on the photographic analysis method. For color photography, the modeled surfaces must have the same color as the real surfaces to achieve a realistic perception of the space. For black-and-white photography, only the reflectance coefficient needs to correspond to that of the real surface.

The following table shows the reflectance coefficients of various types of cardboard used in constructing a scale model.

Table 4. Reflectance coefficients of selected materials (Source: Bodart & Deneyer, 2008)

Type de surface	Couleur surface	Y Coeff réflexion (%)	Carton correspondant Marque Canson	Y Coeff réflexion (%)	Couleur carton
Table	beige clair	76.33	Mi teinte 100	75.45	Vert clair
Tapis	vert-gris	13.46	Mi teinte 448	11.53	Vert
Mur - paroi	beige clair	67.68	Mi teinte 104	67.83	mauve clair
Tablette dessus armoire	beige clair	75.52	Mi teinte 100	75.45	vert clair
Paroi armoire	noir	7.97	Mi teinte 503	8.73	bordeau
Porte avant armoire	noir	8.74	Mi teinte 503	8.73	bordeau
Porte 1	brun clair	51.27	Mi teinte 470	56.92	ocre
Porte 1 bis	brun clair	51.85	Mi teinte 470	56.92	ocre
Châssis porte int 1	gris peinture	28.34	Mi teinte 431	25.59	gris
Châssis porte int 1 bis	gris peinture	28.24	Mi teinte 431	25.59	gris
Tablette sous fenêtre	gris peinture	28.76	Mi teinte 431	25.59	gris
Mur sous fenêtre	blanc	68.03	Mi teinte 407	68.17	beige
Plinthe sous fenêtre	brun clair	38.16	Mi teinte 354	38.79	gris
Mur sous fenêtre latérale	gris peinture	27.28	Mi teinte 431	25.59	gris
Tissus fauteuil	vert	11.61	Mi teinte 448	11.53	vert
Plafond troué 1	beige	60.71	Mi teinte 400	60.06	jaune
Plafond troué 1 bis	beige	60.56	Mi teinte 400	60.06	jaune
Socle porte manteau	noir	6.00	Mi teinte 425	3.89	noir
Feuille présentoir	blanc	78.63	Mi teinte 101	79.46	jaune clair
Feuille porte	blanc	67.26	Mi teinte 104	67.83	Mauve clair
Latte horizontale plafond	beige	76.36	Mi teinte 100	75.45	Vert clair
Bois du plateau	brun foncé	13.38	Mi teinte 448	11.53	Vert

External obstructions, such as neighboring buildings, trees, hills, and other structures, have a significant impact on the amount of light a room receives and must therefore be modeled with accuracy. For instance, if a neighboring building is taller than the building being modeled, it will cast a shadow, reducing the amount of daylight entering the room. Conversely, if the neighboring building has reflective surfaces, it can redirect light back into the modeled building, increasing interior illumination. Consequently, when modeling external obstructions, it is essential to consider their size, color, material, and especially their reflectance.

Studying lighting on a scale model requires the use of measuring instruments, such as lux meters and luminance meters. It is therefore necessary to determine and clearly mark the measurement points during the model's construction to facilitate the placement of sensors. Illuminance measurements can be taken horizontally (on work surfaces) or vertically (on walls).

To place the instruments near the measurement points, access to the interior of the model must be provided. There are three possible solutions :

1. Pass the sensors through openings, such as windows, ensuring that the wires do not obstruct openings that will later be removed during the simulation.
2. If no suitable opening exists, design the model so that one wall can be easily and quickly removed and replaced.
3. Create a small hole, approximately 1 cm in diameter, in a vertical wall to allow wires to pass through. This hole must be completely sealed during measurements to prevent light leakage.

Experience shows that, to carry out illuminance measurements accurately and to easily place sensors, as well as to make visual observations, the scale model should include at least one removable wall—either at the facade or the ceiling level—depending on the type of study.

2.2.5.2. Physical models for acoustics studies

The use of three-dimensional acoustic models followed several early attempts to simulate sound propagation in enclosed spaces using physical or analog models. In 1965, to study the acoustic properties of ancient theaters, Canac carried out a series of measurements on scale models (Figure 8) using ultrasound. The frequency of the ultrasound was chosen according to similarity laws, with the wavelength reduced in proportion to the scale factor of the model. Acoustic models can be built at scales ranging from 1:100 to 1:5, depending on the type of study.

Figure 35. Model of the Orange theatre (https://www.canalu.tv/video/cerimes/acoustique_des_theatres_antiques.9038)]

2.3. Energy Diagnostic Methods

Introduction

Preliminary calculations performed during the design phase provide an estimate of a building's expected energy consumption under standard assumptions. However, actual energy use can differ significantly, as it depends strongly on occupant behavior, which may cause variations of up to ±50% compared to average usage patterns. Factors such as occupancy schedules, thermostat settings, window opening behavior, equipment usage, and maintenance practices all influence real energy performance. Measuring actual energy consumption through energy meters, monitoring systems, and utility data enables the identification of discrepancies between predicted and real performance. These measurements help reveal operational faults, such as inefficient equipment operation, poor system control, air leakage, or inadequate insulation. Through careful analysis and interpretation of the collected data, it becomes possible to diagnose the underlying causes of malfunctions, distinguish between design-related and user-related issues, and propose corrective actions aimed at improving energy efficiency, reducing consumption, and enhancing indoor comfort.

2.3.1. Energy diagnostic methods

The energy diagnosis allows to identify the elements and systems responsible for the highest energy consumption or characterized by low efficiency, dispersion and waste. Enertech Solution compiles the results of the analysis into a detailed report and presents a summary of the share of energy used by each system present (lighting, room conditioning, industrial processes, etc.), providing recommendations about the most technically and economically appropriate interventions to resolve inefficiencies. In addition, any available incentives and tax breaks are highlighted, as well as the savings that can be achieved over the years as a result of implementing the interventions.

2.3.2. What does energy diagnosis consist of?

The energy audit is an analysis of the consumption profiles of buildings and facilities, showing the distribution of energy expenditure both in terms of allocation on the different services present and in terms of time. The energy diagnosis report is a report that presents a general and complete picture of consumption, from which it is possible to identify opportunities for efficiency gains and estimate the technical and economic viability of each intervention. The ultimate goal is the reduction of primary energy consumption, the rational use of energy, and the containment of climate-changing emissions into the atmosphere.

2.3.3. Advantages and benefits of energy diagnosis

Even when not specifically required by current regulations, a company can turn to Enertech Solution for an energy diagnosis and thus embark on a path to save on energy costs. Through this choice, the public image will also be improved, as the company will demonstrate a concrete concern for the environment and responsible energy use.

2.3.3.1. Reduces energy consumption

Energy audits make it possible to kick-start a path of progressive facility efficiency that can lead to genuine upgrading. Such interventions make it possible to reduce the consumption of gas, electricity or other energy sources from the very beginning and therefore save on related bills. Often the largest share of consumption can be attributed to a small number of processes: by targeted intervention in these it is possible to achieve a significant improvement in the system as a whole.

2.3.3.2. Provides a database for investment decisions

Enertech Solution's energy diagnoses provide timely data on the costs related to current energy supplies, the investment needed to implement efficiency measures, and the economic savings that can be achieved over the years. Such information is valuable and crucial in the process of planning and allocation of medium- and long-term investments.

2.3.3.3. Improves environmental sustainability

Energy diagnosis is the first step in implementing energy efficiency and upgrading interventions. Through a net reduction in consumption, it contributes to the reduction of pollutant and greenhouse gas emissions into the atmosphere. Enertech Solution also proposes, where possible, the introduction of renewable energy sources, through the installation of photovoltaic, solar or biomass systems. These choices trigger a virtuous mechanism of sustainability and produce positive results on multiple levels.

2.3.4. Methods of Energy Diagnosis in Buildings

Energy diagnosis aims to assess, quantify, and improve the energy performance of buildings. Energy diagnosis in buildings relies on a combination of regulatory analysis, on-site audits, calculation methods, dynamic simulations, and in-situ measurements to accurately assess and improve energy performance. The main methods can be classified as follows:

2.3.4.1. Documentary and Regulatory Analysis

This method is useful for preliminary assessments and regulatory compliance. It based on the analysis of existing documentation:

- Architectural and technical drawings
- Energy bills and utility data
- Building specifications and materials
- Compliance with national or international energy regulations

2.3.4.2. On-Site Energy Audit

This method is essential for identifying real energy losses and system inefficiencies by using several tools such as : Infrared thermography, Lux meters, temperature and humidity sensors, and Power meters. A field-based inspection of the building, including:

- Envelope characteristics (walls, roofs, windows, insulation)
- HVAC systems and equipment efficiency
- Lighting systems
- Occupant behaviour and operational schedules

2.3.4.3. Static (Simplified) Energy Calculation Methods

Suitable for existing buildings and large building stock. This method is characterized by: Low data requirements, quick implementation, and limited accuracy. Based on steady-state assumptions: (1) Degree-day methods, and Monthly or seasonal energy balance methods. We can find:

(a) Energy Expenditure Index (EEI)

The Energy Consumption Index is obtained by dividing the total annual energy consumption (from all energy sources), expressed in megajoules (MJ), by the gross floor area of the building (including walls). This simple metric is mainly used for statistical and preliminary analysis. By comparing a building's ECI to known statistical benchmarks, it becomes possible to determine whether the building is a high- or low-energy consumer.

(b) Energy signature

Energy Signature: For a more precise assessment, energy consumption must be measured at time intervals shorter than one year. This is done by periodically recording the fuel and/or electricity consumption used for heating. The measurement interval is typically one week for manual readings, but may be shorter (e.g., one hour) for automatic measurements.

The average outdoor temperature during the same interval is obtained either through automatic monitoring or from meteorological data published by the nearest weather station.

For each measurement interval, a point is plotted on a diagram, with the average outdoor temperature on the x-axis and the average power (energy consumed divided by the duration of the interval) on the y-axis. During the heating season, after a sufficient number of measurement intervals, a straight line can be drawn that best fits the scatter of points obtained (Figure 33).

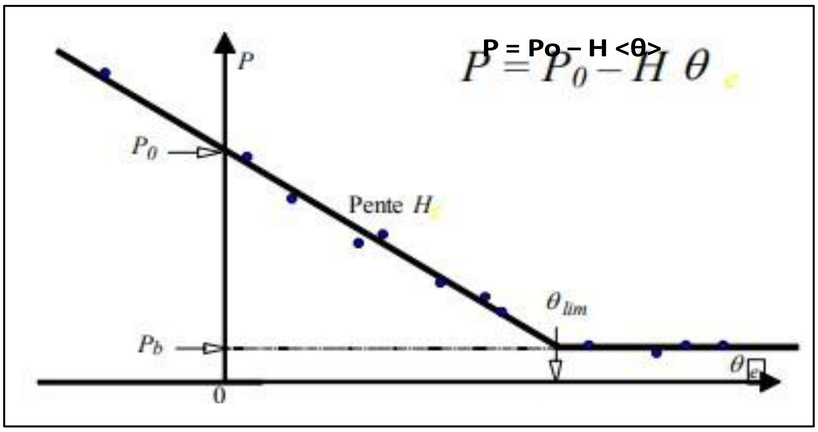


Figure 36. Principle of energy signature (source: Roulet, 2000)

This line is defined by two parameters: $\mathbf{P_0}$, the heating power required when the outdoor temperature is 0 °C, and **H**, the slope of the line, also known as the **energy signature** of the building. The variable **⟨θ⟩** represents the average outdoor temperature during the measurement period.

(c) Hm Method

The dispersion of points in the energy signature can become significant in passive solar buildings because solar gains represent a considerable portion of the heat input. Therefore, solar radiation must be taken into account in the regression. Let us refer back to the building's heat balance equation and compare the signature equation with the building's average heat balance:

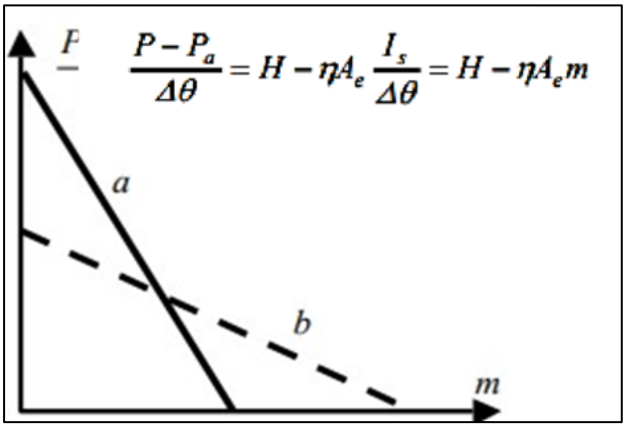


Figure 37. Principle of the Hm method (source: Roulet, 2000)

- Line **a** represents a building with extensive glazing, relatively high heat losses, but significant solar gains.
- Line **b** represents a well-insulated building with low solar gains.
- In this context, **m** is a "meteorological" variable. The regression line has the building's heat loss coefficient as its x-intercept, and its slope, ηA_e, is the product of the effective solar capture area and the utilization factor. This slope represents the building's capacity to harness and utilize solar radiation.

2.3.4.4. Dynamic Energy Simulation (DES)

Hourly or sub-hourly simulation of building energy behaviour. This method is Highly accurate and suitable for design optimisation and research*. It can be used to evalute :*

- Heating, cooling, and electricity demand
- Thermal comfort and indoor conditions
- Impact of climate, orientation, and occupancy

Commonly used tools include dynamic simulation engines such as EnergyPlus, TRNSYS, and Pleiades COMFIE.

2.3.4.5. In-Situ Measurements and Monitoring

Once a building has been completed, or when an existing building is undergoing renovation, measurements become essential to verify whether the building is performing as intended and to monitor its performance over time. These measurements can serve several purposes and may be classified either by their objective or by the type of parameter being assessed. In this section, we present several measurement methods that are particularly useful for evaluating and monitoring the energy performance of a dwelling.

Measuring the amount of energy consumed over a given time interval depends on the type of energy source. For electricity and grid-supplied gas, it is sufficient to read the corresponding meters at the beginning and at the end of the interval. Real-time or long-term monitoring of energy performance:

- Smart meters and data loggers
- Indoor environmental quality sensors
- Continuous performance tracking

2.3.4.6. Thermal Imaging and Envelope Diagnostics

Thermal Imaging and Envelope Diagnostics consists an effective method for diagnosing envelope-related energy losses. Non-destructive testing techniques:

- Infrared thermography to detect thermal bridges
- Air tightness tests (blower door tests)
- Moisture and infiltration detection

2.3.4.7. Life Cycle Energy and Environmental Assessment

This method aims to evaluate the energy use over the building's life span. Is often combined with Life Cycle Assessment (LCA):

- Embodied energy
- Operational energy
- End-of-life impacts

2.3.4.8. Post-Occupancy Evaluation (POE)

Assessment after building occupation aims to improve feedback for future building designs by analyzing how a building actually performs once it is in use. This method, often referred to as post-occupancy evaluation, makes it possible to study:

- Actual energy consumption compared to design predictions
- Occupant behavior and usage patterns and their impact on energy performance
- Thermal, visual, acoustic, and olfactory comfort experienced by occupants
- Indoor air quality (IAQ) and ventilation effectiveness
- Performance of building systems (heating, cooling, ventilation, lighting)
- Operational faults and maintenance issues
- User satisfaction and adaptability of spaces

By analyzing these aspects, post-occupancy assessment helps identify gaps between design intent and real performance, allowing designers and engineers to optimize future building designs, improve energy efficiency, and enhance occupant comfort.

Table 5. A comparative analysis of various energy diagnostic methods

Method	Accuracy	Data Requirement	Typical Application
Documentary analysis	Low	Low	Preliminary diagnosis
On-site audit	Medium–High	Medium	Existing buildings
Static methods	Medium	Low	Large-scale assessments
Dynamic simulation	Very High	High	Design & optimisation
Monitoring & measurement	Very High	High	Performance validation
Thermal diagnostics	High	Medium	Envelope analysis
LCA-based methods	Medium–High	High	Sustainable design
POE	Medium	Medium	Operational feedback

CHAPITER 3

3. SIMULATION AND MODELING SOFTWARE

Introduction

Building performance simulation tools are increasingly used to predict a building's performance, not only in terms of energy consumption reduction but also regarding the enhancement of occupant well-being. These tools play an increasingly important role during the building design phase, helping to demonstrate compliance with regulations. Their use encourages close collaboration between architects and consultants from the very early stages of project development.

3.1. Lighting simulation

Introduction

With the advent of computer tools specialized in lighting, the study of both natural and artificial light in architecture has become much easier. The field of natural lighting in buildings has seen the development of several software programs, such as DIALux, VILUX, ECOTECT, ENERGIE+, RADIANCE, and others. These tools allow for the study of light behavior within architectural spaces, enabling both quantitative analyses—determining illuminance and luminance levels at every point in a room—and qualitative analyses. These software programs are user-friendly and provide results that are very close to reality. Many projects worldwide have been designed using such software.

3.1.1. Types of simulators

The study of natural lighting in a room, whether using scale models or full-scale models, can be conducted under either a real or an artificial sky. A real sky is characterized by unstable luminance, significant temporal variability, complex instrumentation, and the difficulty of obtaining comparable measurements. In contrast, an artificial sky is a scientifically validated tool used in several internationally renowned lighting research laboratories, including GRAP (Groupe de Recherche en Ambiances Physiques). It provides a stable lighting environment over time and allows measurements under precisely controlled conditions, enabling comparisons between different projects. This approach is particularly well suited to architects integrating natural lighting strategies, as it ensures a strong connection between the various stages of architectural design and the specific lighting requirements. Various instruments are required for the simulation, including:

3.1.1.1. Mirror box

The Mirror Box, also called a mirror sky, is a cubic chamber measuring over 3 meters on each side. Its interior walls are covered with highly reflective mirrors, and its ceiling is illuminated by 101 fluorescent tubes, masked by a diffusing material. This type of artificial sky offers several advantages: it is a simple and easy-to-use tool for simulating an overcast sky, as defined by the International Commission on Illumination (CIE). The resulting illuminance on the horizontal plane at the base of the cube is 10,000 lux and exhibits excellent uniformity. Measurements are taken using lux meters placed both inside and outside the model. Additionally, a camera equipped with a wide-angle lens is used to visualize the interior lighting, providing a realistic representation of the light distribution, as if the observer were actually inside the building.

The Mirror Box also allows for testing different façade configurations and provides highly precise results. It is very instructive and enables the study of relatively large-scale models in a short time and at a lower cost. The main limitation of the Mirror Box is that it cannot simulate different sky types and does not account for the direct component of sunlight.

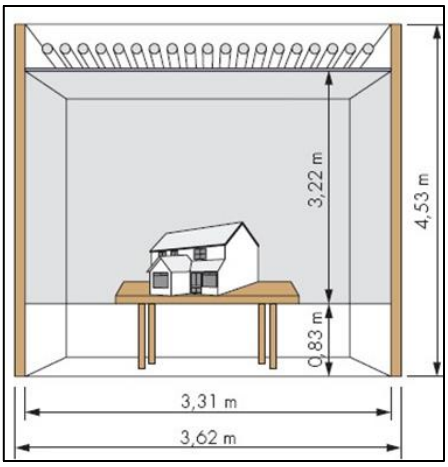


Figure 38. Mirror box model (Deneyer, 2003)

3.1.1.2. Artificial sky with a single lamp

The artificial sky with a single lamp is a more advanced and powerful tool, designed to simulate any type of sky, including those with direct sunlight. It works by subdividing the sky into 145 light disks based on the modified Tregenza theoretical distribution. These disks are positioned side by side to ensure complete coverage of the dome (see Figure 149). The intensity of each disk's light flux can be adjusted to simulate various sky conditions, such as overcast, clear, or partly cloudy skies.

This system allows for precise measurements of natural lighting at any chosen time and under any selected sky type, typically within a short period of approximately 70 minutes. Unlike the Mirror Box, it does not provide a direct view of the interior lighting conditions. However, a view of the environment can be digitally reconstructed by combining the images taken at the 145 disk positions.

The model must be mounted on a solid base extending at least 3 cm beyond its sides and with a maximum height of 3 cm before attachment to the turntable. Furniture and other interior elements must be securely fixed, as the model will rotate at various angles. The total weight of the model should not exceed 15 kg to allow smooth rotation of the turntable and ease of handling.

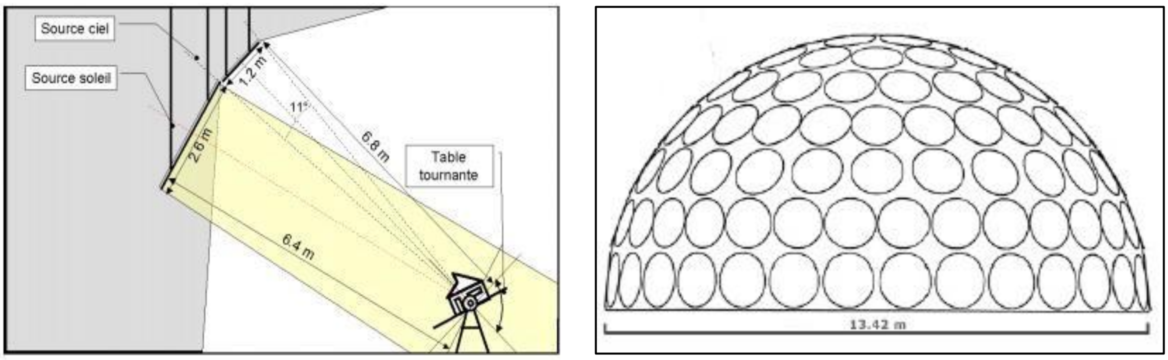


Figure 39. Artificial sky with a single lamp (Deneyer, 2003)

3.1.1.3. Mechanical Sun

The mechanical sun is an educational tool used to visualize the apparent movement of the Sun. It consists of a movable lamp that travels around a scale model, simulating the Sun's path for a specific latitude. During each simulation, the Sun traces a circular path corresponding to the base of a tilted cone, with the cone's main axis inclined at an angle matching the latitude of the location. The length of the cone's side varies depending on the chosen day of the year.

This simulator is not used for measurements; its purpose is solely to visualize the Sun's movement and the resulting shadows or sunspots on the model.

3.1.1.4. Artificial sun with a lamp

The artificial sun with a single lamp is a simulator that enables a more detailed study than the mechanical sun because it allows both observation and measurement. It consists of 91 small halogen lamps mounted on the ceiling. Relative movement is achieved by rotating the model around two independent axes.

This simulator can be used to assess the visual effects induced by sunlight through direct observation. However, these observations must be combined with measurements taken under diffuse skies to reflect real conditions, simulating the combination of clear skies and sunlight. The models are secured to the rotating platform using adjustable clamps, which are adapted to the model's size.

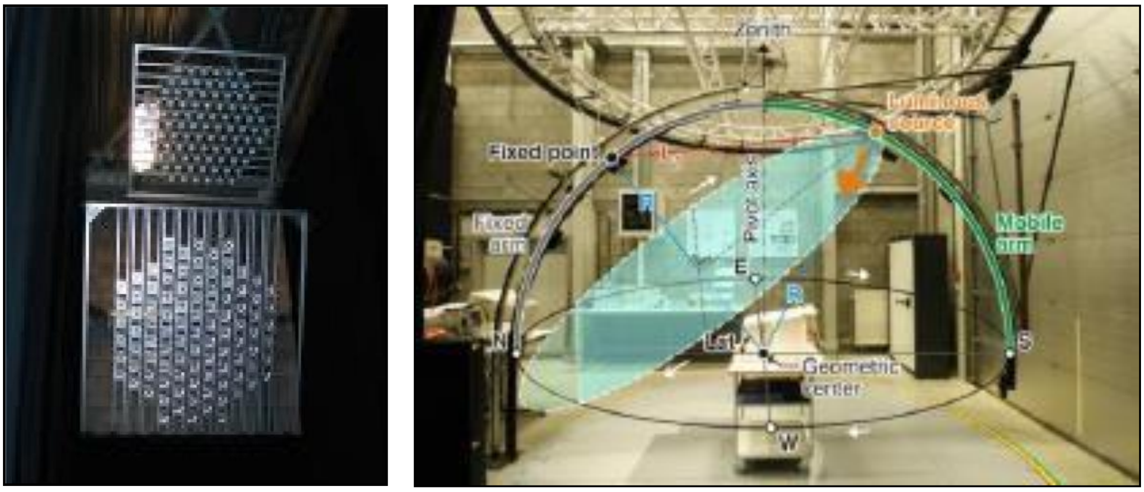


Figure 40. Artificial sun with a lamp: on the left, Sky above and sun below. (Deneyer, 2003); on the right, Mechanical Sun (Source: CSTC Files 2011/3.18)

3.1.2. Building lighting simulation software

Over the past decade, significant advances in computer science have led to the development of new simulation programs that have profoundly impacted the building sector. Architects now use these software tools to predetermine natural lighting in their projects. These tools are generally categorized based on two different calculation methods: radiosity analysis and inverse ray tracing.

The radiosity method focuses on radiative exchanges between perfectly diffusing surfaces forming an enclosed space. Software based on this method typically handles simple volumes illuminated by rectangular openings. However, it does not account for specular surfaces or the spectral aspects of light. To enhance realism, it is often combined with a climate database.

In contrast, the inverse ray tracing method considers all optical phenomena that can be analytically expressed by physical equations. It can simulate specular, semi-specular, diffuse, refractive, or translucent materials and can efficiently handle non-homogeneous textures and infinitesimally small surfaces. Radiance is a prime example of software that uses this method to calculate light propagation.

These programs generally require a steep learning curve and some prior experience, making them primarily suitable for daylighting specialists. They also require detailed modeling of all space elements and can involve relatively long computation times, so they are not typically used at the preliminary or sketch design stage.

The table below provides an overview and detailed description of some lighting simulation software for existing buildings:

Table 6. Different lighting simulation software (Deroisy & Deneyer, 2011)

Logiciel	Editeur	Méthode	Modélisation	Types de ciel	Résultats
Ecotect	Autodesk	*Split flux formula*	Géométries simples Surfaces diffuses Maillage paramétrable	Ciel couvert CIE Ciel uniforme CIE Soleil direct	Eclairements [lux] Facteurs de lumière du jour (%) Visualisation des ombrages
Dial-Europe	Estia	*Split flux formula*	Géométries simples Surfaces diffuses Maillage fixe	Ciel couvert CIE	Facteurs de lumière du jour (%) Visualisation des ombrages
Dialux	DIAL GmbH	*Radiosity* (*raytracing* pour les visualisations)	Géométries complexes Surfaces diffuses Maillage paramétrable	Ciel couvert CIE Ciel intermédiaire Ciel clair CIE (soleil direct)	Eclairements [lux] Facteurs de lumière du jour (%) Luminances (cd/m²) Visualisation des scènes
Relux Pro	Relux Informatik	*Radiosity* (*raytracing* pour les visualisations)	Géométries complexes Surfaces diffuses Maillage paramétrable	Ciel couvert CIE Ciel clair CIE (sans soleil direct)	Eclairements [lux] Facteurs de lumière du jour (%) Luminances (cd/m²) Visualisation des scènes
3DS max	Autodesk	*Radiosity + raytracing*	Toutes géométries Surfaces diffuses, spéculaires ou mixtes Maillage paramétrable	Tout type de ciel	Eclairements [lux] Facteurs de lumière du jour (%) Luminances (cd/m²) Visualisation des scènes
Velux Daylight Visualizer	Velux	*Raytracing + photon mapping*	Géométries complexes (via import fichiers 3D) Surfaces diffuses, spéculaires ou mixtes Maillage non paramétrable	15 types de ciels, dont ciel couvert CIE, ciel intermédiaire et ciel clair CIE	Eclairements [lux] Facteurs de lumière du jour (%) Luminances (cd/m²) Visualisation des scènes
Radiance	LBNL	*Raytracing* (extension *photon mapping* disponible)	Toutes géométries Tout type de surface Maillage paramétrable	Tout type de ciel	Eclairements horizontaux, verticaux, cylindriques, ... [lux] Facteurs de lumière du jour (%) Luminances (cd/m²) Visualisation des scènes

3.1.2.1. Ecotect software

Ecotect 5.5 is a High Environmental Quality (HQE) design software for architects, offering a wide range of simulations and analyses to fully understand building performance. It is a comprehensive yet user-friendly tool that integrates a 3D modeler with solar, thermal, acoustic, and cost analyses.

Ecotect enables designers to work easily in 3D while using all necessary tools for efficient energy management. Its main advantages include:

- Ease of use and intuitive interface.
- Guidance throughout the design process.
- Support for making informed decisions from the initial sketching phase regarding building location, overall shape, orientation, exterior materials, window size, and placement.
- The ability to analyze lighting conditions throughout the year by simply setting simulation parameters such as location, date, time, and sky conditions.

This makes Ecotect 5.5 particularly valuable for architects aiming to integrate energy efficiency, daylight optimization, and environmental performance into the early design stages.

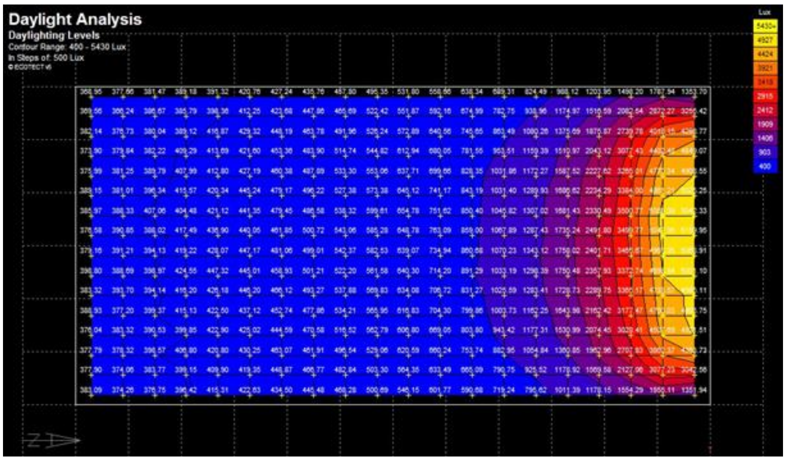


Figure 41. Result of light simulation using Ecotect (Daich, 2011)

Ecotect allows the import of data from various formats, including:

- **3D Studio:** .3DS, .ASC, .PRJ
- **AutoCAD:** .DXF
- **EnergyPlus:** .IDF
- **Windows Bitmap:** .BMP

It also allows exporting to:

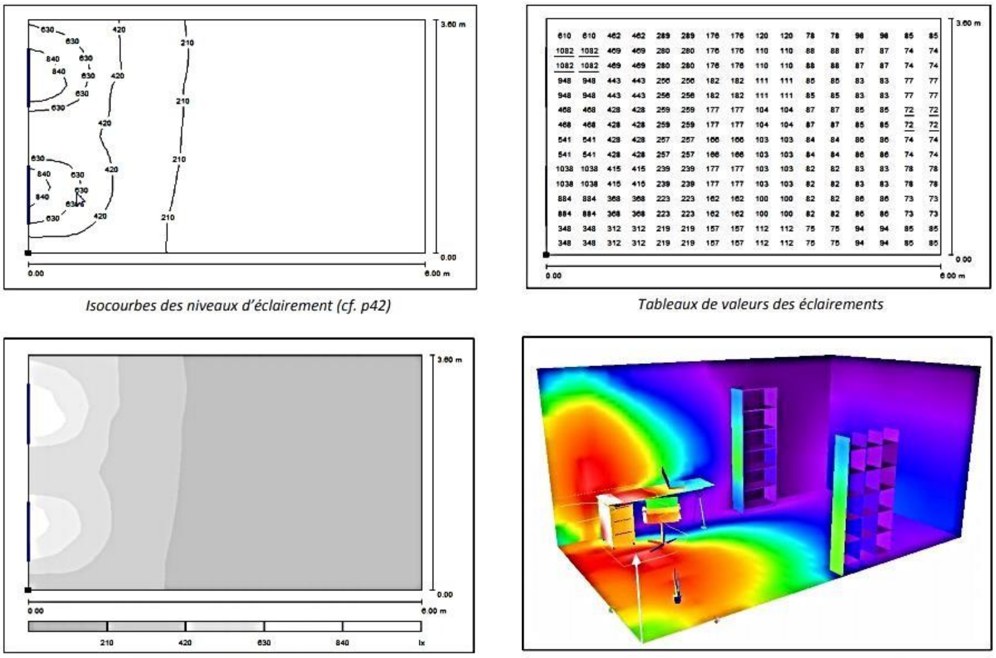
- **DOE-2:** .INP
- **AIOLOS:** .PPA
- **VRML:** .WRL
- **ESP-R:** .CFG
- **WinAIR4 CFD:** .GEO
- **Radiance:** .RAD, .OCT
- **EnergyPlus:** .IDF
- **AutoCAD:** .DXF

Ecotect provides six main functions:

- Visual Impact Function: This function analyzes projection angles, obstructions, and vertical components for any point or surface.
- Solar Radiation Analysis Function: In Ecotect 5.5, this function allows visualization of the impact of solar radiation on windows and calculated surfaces for each season.
- Shadows and Reflections Function: This function simulates shadows and reflections, indicating the sun's position and the sunlight path within the project. It shows how light enters through windows and moves through the space.
- Daylight Function: This function calculates sunlight and natural lighting details, including illuminance levels (lux), daylight factor (%), and internal and external reflections (%), at any point in the model, as well as sky components. Depending on the type of grid (vertical or horizontal), results can be displayed in 2D and/or 3D. It also simulates potential energy savings achieved through designs optimized for natural lighting. This function forms the basis of our work.
- Thermal Performance Function: This function calculates heating and cooling loads for all types of zones, regardless of shape. It also analyzes thermal variations due to building occupancy, internal heat gains, infiltration, and equipment usage.

3.1.2.2. DIAL LUX software

DIALUX has become an essential free tool for lighting design. It not only allows users to select lighting fixtures based on numerous parameters but also helps achieve real energy savings by optimizing new lighting solutions. The software is widely used to design, calculate, and professionally visualize lighting studies for a single room, entire floors, buildings, and outdoor areas. DIALUX allows for the calculation of daylighting under three types of sky, including CIE overcast skies. It can be used at all stages of a project, though its simple geometric modeling tool makes it most suitable for the preliminary design phase. The software offers the ability to model relatively complex geometries and to reuse the same geometry for artificial lighting calculations compliant with AFE standards. It also supports running calculations across multiple rooms simultaneously.



Isocourbes des niveaux d'éclairement (cf. p42) — *Tableaux de valeurs des éclairements* — *Cartographie des niveaux de gris* — *Cartographie en fausse couleur des valeurs d'éclairement*

Figure 42. DIAL LUX output (source: Haubruge and Bodart, 2012)

On the other hand, DIALUX has some limitations. Its input interface can be unintuitive, and certain parameters have little impact on the results. The software does not support the modeling of circular geometries or secondary daylighting sources. While a geometric model can be created directly within DIALUX, .dwg or .dxf files can also be imported to serve as a basis for the design.

3.1.2.3. Dial+ Software

DIAL+ offers excellent ergonomics and fast calculation times. This module allows users to run lighting simulations (RADIANCE) or calculate heating and cooling loads at the room scale. It can generate reports including the following results:

- Daylight factors
- Dynamic diffuse autonomy (percentage and hours)
- Autonomy for Minergie-Eco (Switzerland)
- Illuminance values for electric lighting

- Annual electricity consumption for lighting (SIA 380/4, Minergie)
- Solar diagrams including external obstructions
- Shading studies (sunlight factor, fraction of sky visible)

The cooling module provides access to the following functions:

- Cooling and heating loads (EN 15251, EN 15255, EN 15265, ISO 13791, SIA 382/1, SIA 382/2)
- Airflow rates due to natural ventilation (Cockcroft model)

Thanks to its rapid simulation capabilities and simplicity, DIAL+ is particularly well-suited for conducting parametric studies, which is highly valuable during the preliminary design phase. It enables early decisions to be made at the room level, which can then be applied to the rest of the building. DIAL+ features a highly intuitive interface designed to optimize energy loads at the room scale, allowing non-expert users to easily describe room parameters. As such, it can be used by both architects and engineers and is also well-suited for educational purposes. However, fully utilizing all of its features (lighting and thermal) assumes that the user has a basic understanding of building behavior. DIAL+ includes a simplified 3D modeler that allows modeling of rectangular, L-shaped, or trapezoidal rooms with flat, single-pitched, or double-pitched roofs. Opaque or transparent objects can also be added within the modeled rooms. The average time required to input all room parameters for a classic simulation is less than 10 minutes. Simulation results are displayed as 2D plans and graphs (daylight factor, autonomy, illuminance, etc.) on the work surface or on the walls.

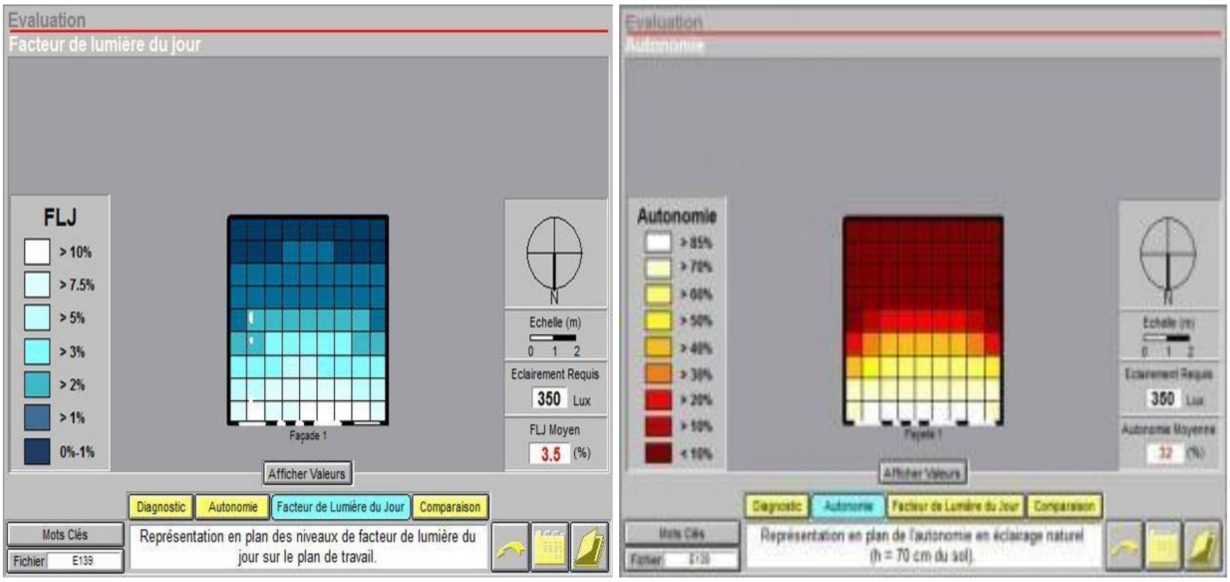


Figure 43. Simulation using DIAL+: Left, FLJ result; right, daylight result autonomy (http://www.behi.fr/outils-societe)

3.1.2.4. ReluxPro software

ReluxPro offers a user-friendly interface with powerful import capabilities for 2D architectural plans or 3D models. Its extensive luminaire database allows for precise positioning of lighting fixtures within a building and provides rapid rendering results. The software calculates illuminance levels, and for each zone within a building, it can determine illuminance values as well as g1 and g2 uniformity indices. This enables calculation of the daylight factor for each room and prediction of natural light distribution throughout the modeled space. Luminance values can also be obtained.

ReluxPro is designed for construction professionals, including architects and lighting designers familiar with computer-aided design tools. It includes intuitive 3D modeling features, allowing the modeling of furniture and luminaires from its extensive database. Window openings and other architectural elements, such as doors, can also be defined in the walls. Additional advantages include good ergonomics, the ability to model complex geometries, the capacity to simulate multiple rooms simultaneously, and relatively fast calculation times. However, ReluxPro has some limitations: it does not provide error messages when issues arise during modeling, and it can be difficult to distinguish which parameters most strongly impact the calculation of natural or artificial lighting.

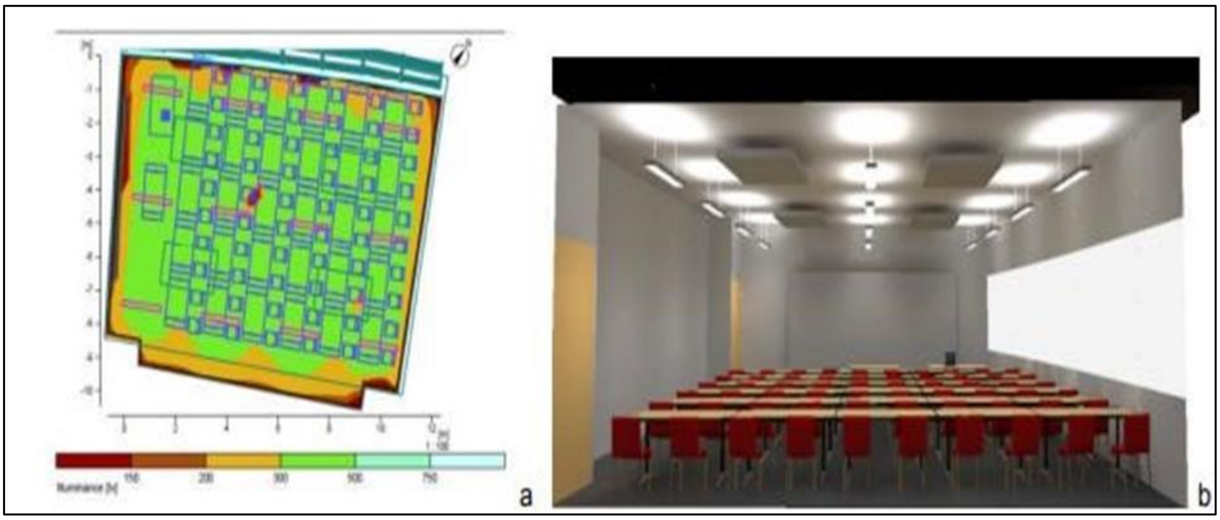


Figure 44. Simulation using RELUX: on the left, outline lines of the artificial lighting; on the right, a rendering of a room under Relux (Yu et al, 2014)

3.1.2.5. IES VE software

Virtual Environment is an integrated suite of applications connected through a common interface and a simple Data Integration Model (DIM). This architecture allows data used in one application to be easily shared and utilized by other applications within the suite. Key examples of available modules include ApacheSim for thermal simulation, Radiance for daylighting analysis, and SunCast for shading studies.

The 3D geometric modeling application, ModelIT, enables users to create the 3D models required by the other components of the Virtual Environment. ModelIT is designed to accommodate varying levels of complexity: during the pre-design or feasibility study phase, basic models can be generated from sketches using simple modeling tools for preliminary assessments or comparative studies. At the final design stage, accurate 2D representations of the building (e.g., from .dxf files) can be imported into ModelIT to serve as the basis for detailed 3D modeling of the spaces.

The Radiance IES interface is fully integrated into the Virtual Environment. Radiance generates two types of images: illuminance renderings and luminance renderings. Illuminance renderings display lux values and can generate iso-contours for lux or Daylight Factor, while luminance renderings are used to evaluate glare indices or produce photorealistic images. The interface is designed to simplify image creation, automatically applying default assumptions wherever possible.

3.1.2.6. Radiance software

RADIANCE is a sophisticated tool for analyzing and visualizing lighting. Using 3D geometric models, it produces physically accurate results and high-quality renderings, including luminance and illuminance values as well as photorealistic images. False-color visualizations or iso-line diagrams allow results to be displayed clearly and intuitively.

RADIANCE is widely recognized as the reference program for daylighting calculations. Simulations can be performed for different sky types (clear, uniform, or overcast) or for any sky defined using the Perez model. An additional plugin allows modeling of the 15 new CIE sky types. The Perez model also serves as the basis for annual daylighting calculations using local climate data. Additional tools are available for calculating glare indices and other lighting performance metrics. RADIANCE is used by architects, designers, and engineers to predict illuminance levels and the visual appearance of spaces under various natural and artificial lighting systems before construction. Researchers also use it to evaluate new lighting products. The software is applicable at any stage of building design and allows for modeling a wide variety of spatial geometries and lighting conditions.

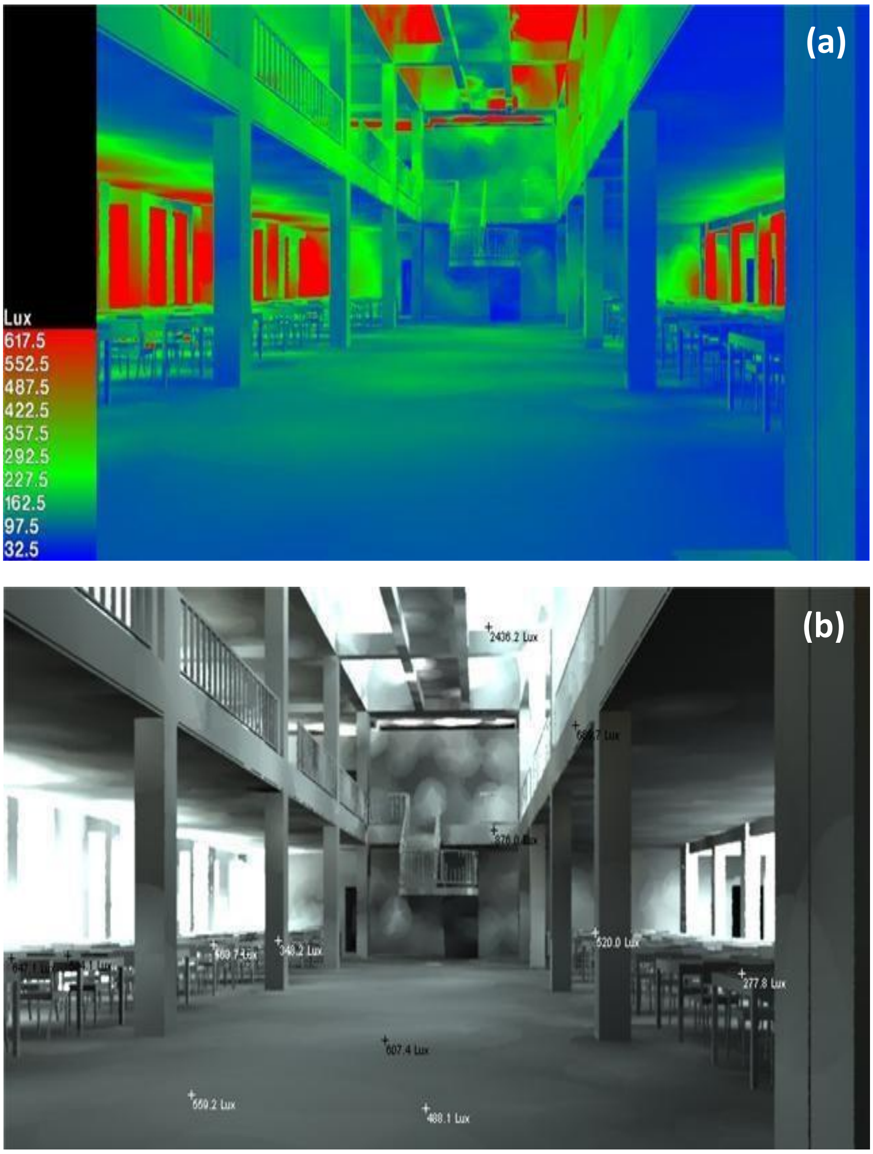


Figure 45. Radiance (a) false color rendering; (b) photorealistic rendering (Author, 2010)

3.2. Thermal and Energy Simulation

Introduction

Thermal simulation tools are increasingly used by all professionals involved in building design, as building analysis software becomes more sophisticated, integrated, and user-friendly, offering opportunities to better understand building performance, particularly in terms of energy optimization. Energy simulation software supports designers in reducing energy costs by precisely identifying the variables that influence building performance and guiding the implementation of effective measures. These programs on the market can be broadly classified into four main categories: performance assessment software for evaluating overall building efficiency, regulatory calculation software to ensure compliance with energy codes and standards, thermal balance software for calculating heating and cooling loads, and dynamic thermal simulation software for detailed, time-dependent modeling of energy flows, thermal comfort, and system interactions.

3.2.1. History of building energy simulation environments

According to the U.S. Department of Energy (2015), over 450 software programs were listed for building energy analysis, reflecting the diversity of tools developed to address thermal and energy concerns. These tools range from simple spreadsheets to complex graphical software, differing in accuracy, outputs, and purpose—some focus on identifying trends, others on optimizing the building envelope, and some on sizing equipment. The evolution of building energy modeling software can be categorized into four generations. The first generation focused on basic energy balance and thermal performance. The second generation (1975–1985) introduced transient, single-zone modeling with hourly simulations, thermal analogies, and sequential programming. The third generation (1985–1995) incorporated mass and energy balances, quasi-static and systematic energy system modeling, causal analysis, and multi-zone modeling. The fourth generation, emerging from 1985 onward, advanced to multiphase modeling at the neighborhood scale, integrating ventilation networks, heat distribution systems, and dynamic system behavior.

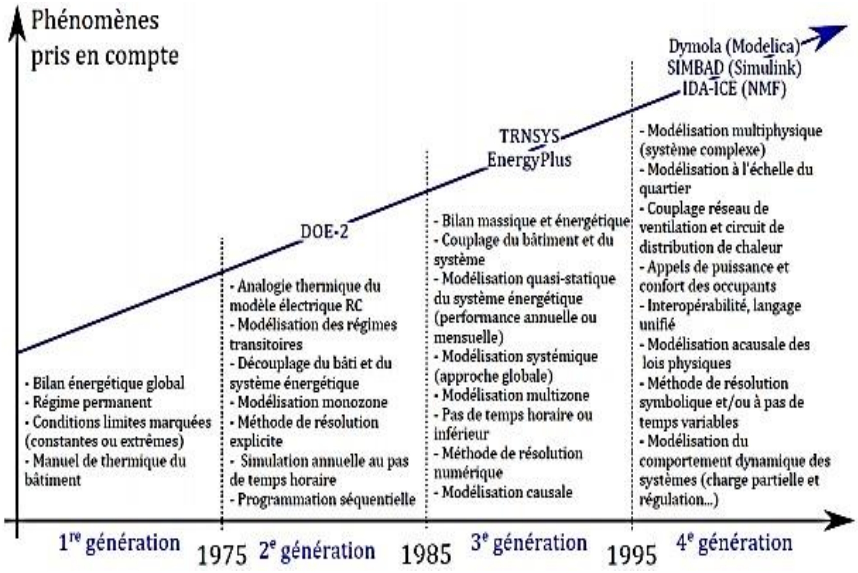


Figure 46. History of building energy simulation environments (H. Blervaque, 2014.)

3.2.1.1. PLEIADES COMFIE (http://www.izuba.fr)

PLEIADES-COMFIE is a software suite developed to model the energy behavior of buildings. PLEIADES serves as the user interface, while COMFIE is the dynamic thermal simulation engine, continuously developed since 1990. The software can be used alongside ALCYONE for data entry and 3D building visualization, METEOCALC for generating and formatting meteorological files for COMFIE, and novaEQUER for environmental analysis. Its main advantages are ease of use and rapid simulation capabilities, making it particularly attractive for engineering firms. However, the lack of access to its source code limits its suitability for research purposes. This dynamic thermal simulation model of buildings anticipates energy consumption and the risk of discomfort in all seasons.

Figure 47. (a) Graphical interface of the software; (b) Example of simulation (https://www.izuba.fr/logiciels/outils-logiciels/)

Comfie is Pleiades' dynamic thermal simulation (DTS) calculation engine. At each time step, the algorithm determines the heating, cooling, humidity and temperature needs in each area of the building. The resulting thermal balance includes exchanges between zones. Thermal inertia is taken into account at the level of each wall. This calculation engine, from the CES (Centre for Energy Efficiency of Systems) at MINES ParisTech, has been validated experimentally (Incas platform, Passys cell) and by inter-software comparison (Bestest from AIE).

The DTS Comfie module also calculates the energy consumption of the equipment (Dynamic Energy Simulation or DES) at each time step with the possibility of recovering heat losses, evaluates several comfort indicators and has a utility to manipulate and generate weather data files.

Comfie is linked to Amapola, which makes it possible to identify the least expensive solutions, anticipate uses and optimise the reliability of forecasts. It is therefore possible to assess energy consumption within the framework of the energy efficiency guarantee with a risk of an overrun of less than 5%.

Pleiades brings together all the tools required for the design of high energy and environmental performance buildings, including:

- Dynamic energy simulation (energy needs and consumption).
- Daylighting comfort and hygrothermal comfort analysis.
- French thermal and environmental regulations (RE 2020, RT 2012, existing building regulations, and EPC/DPE).
- Energy–Carbon experimentation (E+C-).
- Building services system sizing.
- Design optimisation.
- Energy performance guarantees.
- Indoor air quality assessment.
- Life Cycle Assessment (LCA).
- Environmental certification schemes: HQE, BREEAM, etc.

3.2.1.2. EnergyPlus (https://energyplus.net)

EnergyPlus is a free, advanced software for analyzing building energy performance, developed based on the BLAST and DOE-2 engines. It includes modules that integrate various equipment into the building energy balance, supports multi-zone modeling, and allows thermal stratification of large spaces. The software can simulate airflow, including natural ventilation and controlled openings based on external conditions, and monitor water consumption. EnergyPlus can also interface with CAD-generated geometric models and utilize extensive weather station data. However, as it primarily functions as a calculation engine, working directly with its text-based input files can be complex. Therefore, many users prefer graphical interfaces like DesignBuilder to simplify modeling and analysis.

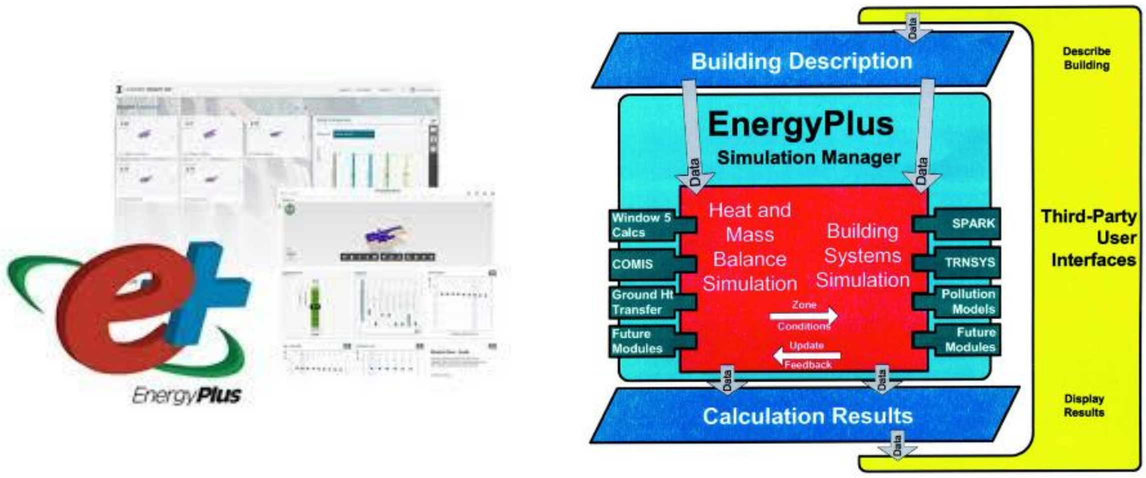


Figure 48. Overall EnergyPlus structure (https://www.researchgate.net)

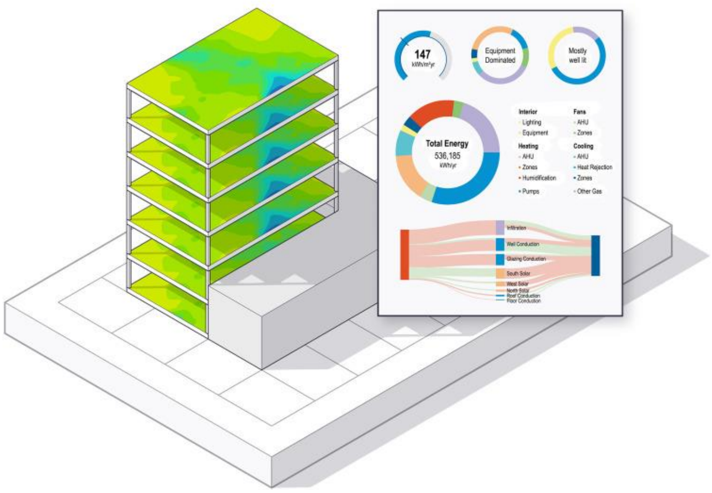


Figure 49. Example of simulation using EnergyPlus (https://www.sciencedirect.com/topics/engineering/energyplus-simulation#definition)

EnergyPlus is an energy analysis and thermal load simulation program that models heating, cooling, lighting, ventilation and other energy flows in buildings and includes some important simulation capabilities such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation [176], multizone air flow, thermal comfort and natural ventilation. In EnergyPlus, a PCM-module is introduced using an implicit conduction finite-difference solution algorithm which includes both phase-change enthalpy and a temperature dependant thermal conductivity.

EnergyPlus implements detailed building physics algorithms for heat transfer—radiation, convection, and conduction—air and moisture transfer, light distribution, and water flows, allowing to model a broad range of building and mechanical system configurations and conditions, and includes advanced simulation features such as subhourly time steps, simultaneous solution of zone conditions and HVAC system actions, a modular HVAC structure, and a runtime scripting language for user-defined control strategies.

- **DesignBuilder:**

DesignBuilder is an EnergyPlus based software tool used for energy, carbon, lighting and comfort measurement and control. DesignBuilder is developed to ease up the building simulation process. DesignBuilder is comparing alternative building designs by using function and performance-based method of comparison results by the various analyzes in a quick and economic manner. It presents several advantages:

- 3D Building Modeling & Energy Simulation: DesignBuilder combines fast three-dimensional building modeling with dynamic energy simulations.
- Ease of Use: The software is regarded as a unique tool for creating and evaluating building designs due to its user-friendly interface.
- Flexible Design Stages: Specially developed modules allow it to be used effectively at any stage of the design process.
- Minimal Input, Maximum Output: Only a few input parameters are required, yet it provides a wide range of opportunities to develop detailed designs.
- Rapid Modeling: Innovative productivity features enable even complex buildings to be modeled quickly.

- Accessible for Non-Experts: The software is suitable for non-expert users without compromising on detail or accuracy.

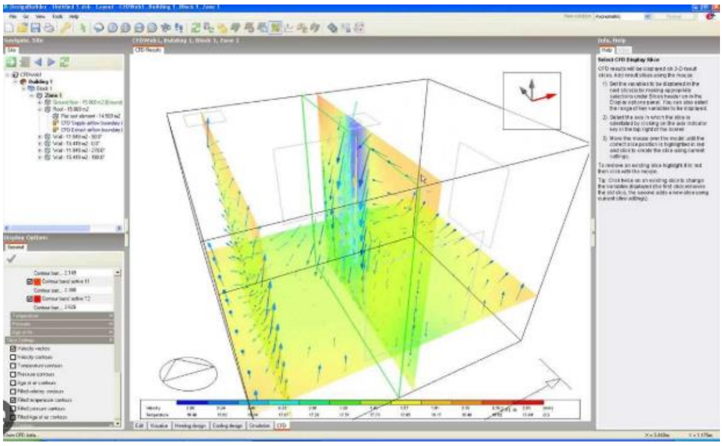


Figure 50. Example of simulation using EnergyPlus (https://www.sciencedirect.com/topics/engineering/energyplus-simulation#definition)

DesignBuilder is also a commercially available CAD software for 3D modelling of buildings for the purpose of energy efficient design and building operation. DesignBuilder is developed allowing the import of BIM data from another computing environment – presumably so that only energy relevant BIM parameters are used. DesignBuilder has been developed to be used by a wide range of professionals such as architects, engineers, building services workers, energy consultants and related departments of universities. Some typical usage purposes are summarized below:

- To evaluate facade options in terms of overheating, energy consumption and shading parameters.
- Evaluation of the optimum use of daylight. Modelling of lighting control systems and determining the savings rate in the corresponding electricity.
- To calculate the buildings in/around temperature, velocity and pressure distribution by using the CFD (Computational Fluid Dynamics) module.
- Visualization of the site plan and shading.
- Thermal simulation in buildings which are ventilated with natural ventilation.
- Determining the capacity of heating and cooling equipment to include the issues to help HVAC design.
- To provide material to design meetings for supporting interdisciplinary communication.
- To be used in universities in energy modeling and simulation courses.

DesignBuilder allows complex buildings to be modeled in a simple fast way even by non-expert users. DesignBuilder is the first and most comprehensive program that creates a graphical interface to a Energyplus dynamic thermal simulation engine. This graphical interface makes the design of the buildings, their energy performance and CFD simulations allow to be displayed in 3D to provide support for examination.

3.2.1.3. TRNSYS (http://www.trnsys.com)

TRNSYS (Transient System Simulation Tool) is a dynamic simulation developed in the mid-1970s by Dr Sanford Klein at the Solar Energy Laboratory at the University of Wisconsin – Madison., TESS, TransSolar (Germany), and CSTB (France). It allows the simulation of complex thermal systems of all types using a block-based approach, breaking down complex models into simpler sub-models. TRNSYS is open and extensible, enabling users to add new components or simulate emerging technologies. It can be coupled with tools such as CONTAM, Excel, Fluent, GenOpt, or Matlab for enhanced functionality. However, it has a steep learning curve, and its graphical interfaces, while powerful, may reduce efficiency for engineering firms due to the large number of parameters to manage.

RNSYS (pronounced 'tran-sis') is a transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results.

The modular nature of TRNSYS gives the program tremendous flexibility, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. TRNSYS is well suited to detailed analyses of any system whose behavior is dependent on the passage of time. TRNSYS has become reference software for researchers and engineers around the world. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells.

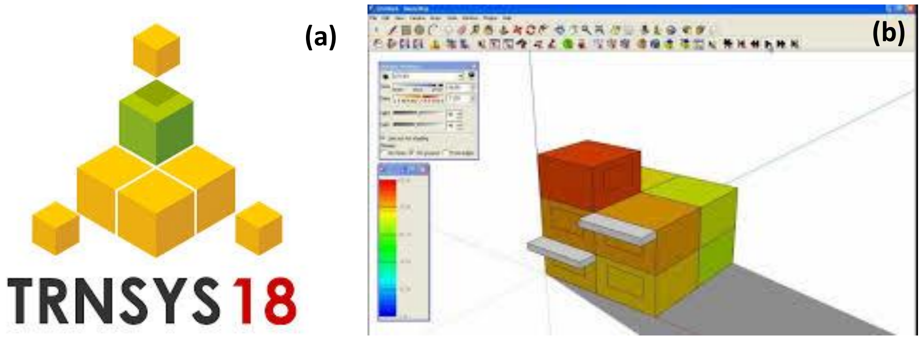


Figure 51. (a)Graphical interface of trnsys software; (b) Example of modeling using trnsys (https://trnsys.org/https://geoflow.com.au/energy-modelling/)

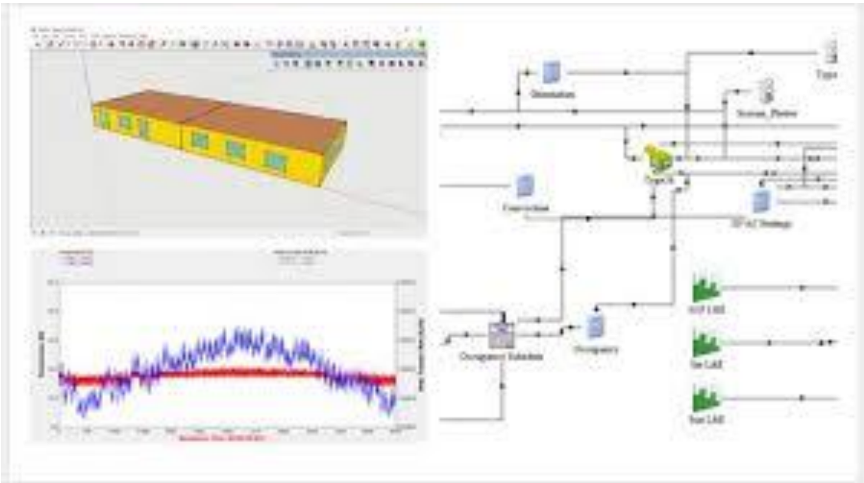


Figure 52. Example of simulation using trnsys (https://www.udemy.com/course/design-an-hvac-system-in-trnsys/3)

3.2.1.4. ESP-r (http://www.esru.strath.ac.uk/Programs/ESP-r.htm)

ESP-r is an open platform for simulating the energy and environmental performance of buildings, integrating heat, air, moisture, and light into a single model. Accurate and flexible, it is key to optimising efficiency and comfort in sustainable projects.

ESP-r, developed by the University of Strathclyde in Glasgow since 1974 and open source since 2002, is a highly flexible building simulation software. It allows users to model the building envelope, energy systems, and control strategies while also enabling the development of new models. ESP-r can simulate heat, air, and moisture transfers, as well as evaluate thermal, visual, and acoustic performance. It supports multizone modeling for heat and airflow and can incorporate CFD (Computational Fluid Dynamics) analysis. With time steps shorter than one hour, it offers detailed simulations, making it particularly suited for research teams rather than typical engineering firms.

ESP-r (Environmental Systems Performance – Research) is an advanced tool for simulating the energy and environmental behaviour of buildings, developed by the University of Strathclyde, in Glasgow. Its approach is based on an integrated model capable of representing heat, air, moisture, light and electrical energy flows with high spatial and temporal resolution. This versatility allows the analysis of complex interactions between different building systems, offering a holistic view of energy performance.

The software is designed for Linux environments, although it can also run on Windows via Cygwin, and is distributed under an open licence, making it accessible for research, consultancy and training. ESP-r uses a finite volume conservation method, transforming building geometry and operating conditions into equations solved dynamically according to climate, occupancy and control systems. Its ability to integrate multiple domains makes it ideal for detailed studies, from energy efficiency to thermal comfort.

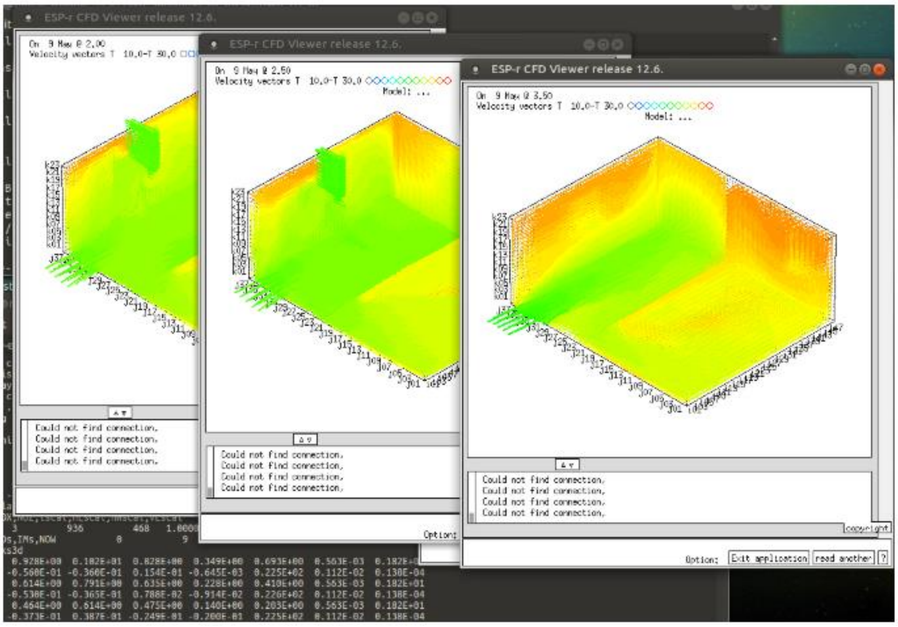


Figure 53. Example of simulation using ESP-r (https://www.esru.strath.ac.uk/Courseware/ESP-r/tour/applications_in_suite.html)

3.2.1.5. Dymola (http://www.3ds.com/products-services/catia/products/dymola)

Dymola (Dynamic Modeling Laboratory), developed by Dassault Systèmes, is a versatile environment for modeling and simulating complex, multiphysics dynamic systems. Initially applied in aeronautical and automotive engineering, it now includes libraries for mechanics, hydraulics, electricity, robotics, and building thermal analysis. Its graphical editor enables intuitive modeling using existing libraries, while the open environment allows users to create new components or extend existing ones. Notably, the Buildings library, developed by Lawrence Berkeley National Laboratory, supports dynamic simulation of building energy, thermal performance, and control systems. Dymola can also be integrated with other tools, such as EnergyPlus, Matlab, and GenOpt, enhancing its flexibility for advanced building simulations.

Below (Table 7) is a comparative overview of different software tools dedicated to sound assessment in buildings:

Table 7. Comparative overview of different sound software

Criteria	PLEIADES COMFIE	EnergyPlus	TRNSYS	ESP-r
Main application field	Building energy performance	Detailed energy simulation	Dynamic multi-system simulation	Integrated thermal simulation
Simulation type	Thermal, energy, regulatory	Thermal, energy, advanced HVAC	Thermal + energy systems	Thermal, energy, airflow
Scale of analysis	Building / district	Building (highly detailed)	Building + energy systems	Building
Dynamic (hourly) calculation	Yes	Yes	Yes	Yes
HVAC system modelling	Medium	Very advanced	Very advanced	Advanced
Thermal comfort simulation	Yes (PMV, temperatures)	Yes (PMV/PPD)	Yes	Yes
Ventilation / airflow modelling	Simplified	Advanced	Possible	Very advanced
BIM integration	Strong (SketchUp, IFC)	Indirect (via OpenStudio)	Limited	Limited

Criteria	PLEIADES COMFIE	EnergyPlus	TRNSYS	ESP-r
User interface	Graphical and intuitive	Simulation engine (no native GUI)	Technical	Technical
Ease of use	Very easy	easy	easy	easy
Target users	Architects, engineers	Researchers, consultants	Researchers, system engineers	Academic research
Software status	Active	Active (global reference)	Active	Active
Main strengths	Regulatory compliance, usability	Accuracy, scientific robustness	Flexibility, system coupling	Thermal–air–energy coupling
Limitations	Less detailed HVAC modelling	Steep learning curve	Complex interface	Limited user-friendliness

- **Comparative Synthesis :**

- PLEIADES COMFIE : A design- and regulation-oriented tool, particularly well suited for architects and early project stages, offering a good balance between accuracy and usability.
- EnergyPlus : The international benchmark for advanced building energy simulation. It provides highly detailed HVAC modelling but requires external interfaces (e.g. OpenStudio) for practical use.
- TRNSYS : A modular and highly flexible simulation environment, ideal for research applications, complex energy systems, renewable energy integration, and coupled simulations.
- ESP-r : A robust academic tool, especially powerful for analysing thermal–ventilation–energy interactions, although its interface is less intuitive for non-expert users.

3.3. Acoustic Simulation

Introduction

In the past, the evaluation of indoor acoustic environments was carried out using physical scale models, with the scale depending on the objective of the study. However, with the advent and availability of advanced simulation software, acoustic studies of listening spaces are now performed using computer programs. These tools allow designers to validate the shape of the listening space and the distribution of materials to optimize sound balance and clarity. Acoustic simulation tools are increasingly used in architecture and building design to predict and evaluate the behavior of sound within spaces. These tools allow designers and engineers to optimize room acoustics, control noise levels, and enhance comfort. Simulations can address various acoustic phenomena, including sound propagation, reverberation, echo, speech intelligibility, and sound insulation.

3.3.1. Acoustic simulation software

Predicting the acoustic performance of building products and systems, particularly for sound insulation, often involves complex, calculation-intensive methods that can be challenging for most acoustics practitioners. To address this, several specialized software programs have been developed to allow users to perform accurate predictions without manual calculations. These PC-based tools are suitable for a wide range of industrial and engineering applications. Some notable examples for calculating and simulating sound phenomena include AcouBAT, Mithra Sound, Ecotect, and CadnaR.

3.3.1.1. AcouBAT software

AcouBAT is a specialized software for predicting the acoustic performance of buildings, tailored for architects, project owners, and engineering firms. It evaluates sound insulation against airborne noise, impact noise, and equipment noise, and can be applied to residential buildings, offices, schools, and healthcare facilities. Developed by the CSTB (Scientific and Technical Center for Building), AcouBAT offers two major advantages:

1. Regulatory compliance: It helps ensure conformity with building acoustic regulations, as well as Qualitel and HQE standards.

2. Comprehensive product database: It includes over 2,000 products and 2,500 acoustic performance values, covering low frequencies in analyses.

- **Software Properties:**

AcouBAT by CYPE enables the calculation of the following parameters used to assess the acoustic performance of buildings:

- Sound insulation against airborne and impact noise between rooms.
- Sound insulation against external airborne noise.
- Reverberation time and minimum required acoustic absorption areas.
- Sound pressure levels generated by building service equipment.

The software's component database is continuously updated, and users can create custom components with specific acoustic properties. Components are classified into 12 categories:

- Traditional masonry
- Concrete partition or slab
- Partition wall
- Lightweight partition
- Floor covering
- Lining
- Door and window
- Technical equipment
- Roofing
- Ceiling and technical floor
- Continuous façade
- Thermal break

This makes AcouBAT a versatile tool for both design and regulatory validation in building acoustics.

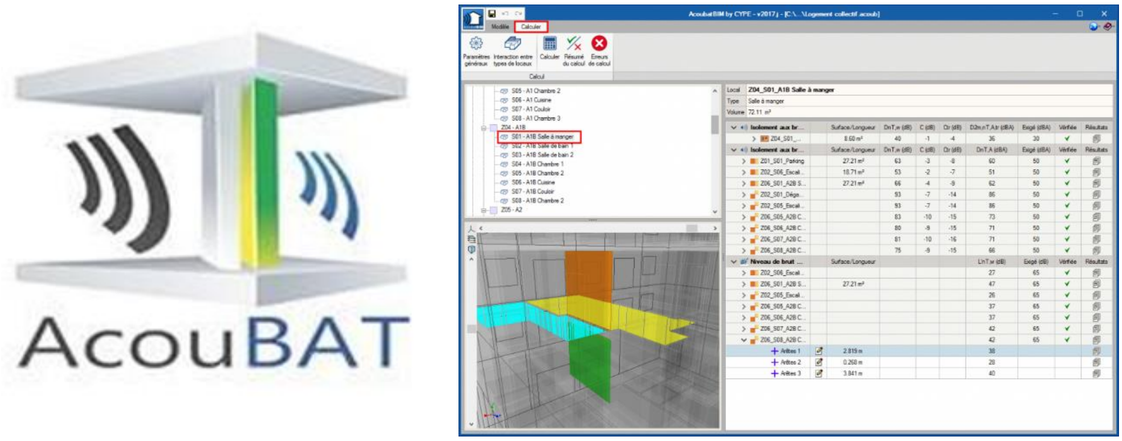


Figure 54. AcouBAT graphical interface (https://www.actu-environnement.com)

3.3.1.2. Mithra Sound software

Mithra Sound is a specialized software tool designed to realistically recreate outdoor soundscapes. It integrates 3D visualization of the modeled site, allowing users to combine quantitative simulation data with immersive auditory experiences. This makes it particularly useful for evaluating the acoustic impact of urban development and comparing different planning scenarios.

The main functions of Mithra Sound include:

- Auditory simulation of urban sound sources: Simulates both fixed and mobile sources, including road traffic, tram noise, and other urban sounds.
- Dynamic traffic modeling: Accounts for traffic lights, priorities, and flow dynamics in noise simulation.
- Flexible urban modeling: Enables rapid simulation of simple configurations via direct input or detailed urban areas using imported GIS data.
- Acoustic propagation analysis: Uses the MithraSIG calculation engine to consider realistic propagation effects of sound across urban environments.

This combination of auditory simulation and urban modeling makes Mithra Sound a powerful tool for planners, architects, and engineers working on urban noise management and environmental impact assessments.

Figure 55. MithraSound graphical interface (https://boutique.cstb.fr/acoustique/549-mithrason.html)

- **MithraSIG software:**

MithraSIG is a GIS-based acoustic simulation software. The Geographic Information System (GIS) provides openness and durability, with a wide-range of formats maintained for both reading and exporting, advanced drawing and editing features, analysis and rendering. The software has a broad scope of application, modelling noise pollution in the vicinity of road, motorway and rail infrastructures, as well as noise from building sites, wind farms, ports and any other neighbourhood noise (point sources, etc.). The tool also determines the proportion of the population.

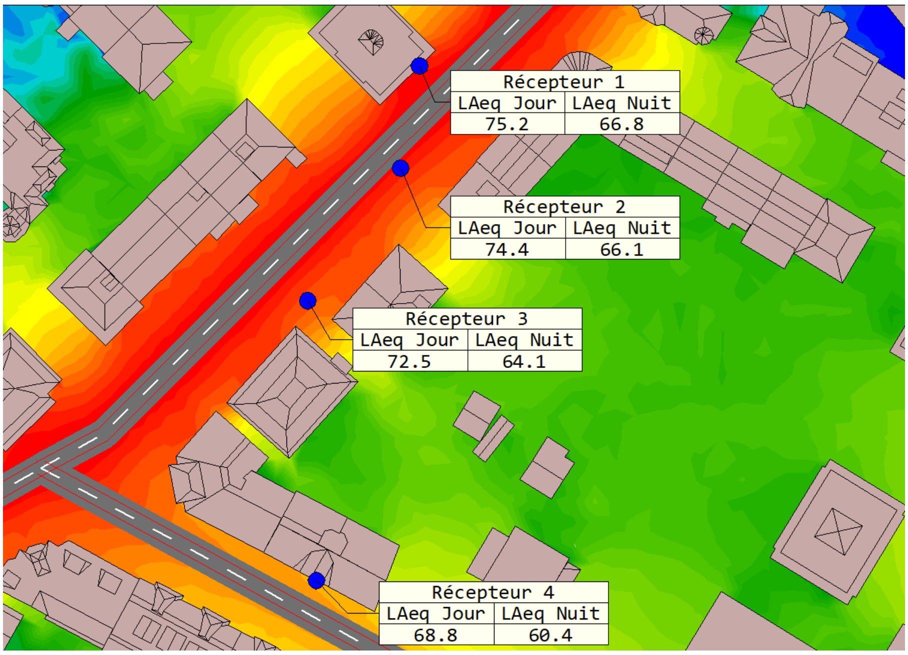


Figure 56. MithraGis graphical interface (source: https://www.geomod.fr/en/expertise/wave-propagation/mithrasig)

- **Main functions :**

Choice of degree of accuracy: beam shot, rays shot, fast ray shot

• Computation of index: Lden, Ldn, Lnight, Levening, Lday or by hour

• Display of labels showing prediction results and measurement campaign data

• Data analysis showing maps before and after implementation of noise reduction procedures, s.g. acoustic barriers or traffic rerouting

• Creation of threshold maps

• Calculation of population affected by noise and calculation of areas by noise levels

• Exploitation of the Imagine database (European Imagine Project) providing more than one thousand of industrial noise sources

• Reading and/or writing of over 160 GIS, CAD, database and graphic formats

Simulation of noise sources: from road, rail (train and tramway) and industry

•Calculation of noise levels conforming to EU directive 2002/49/CE

Choice of calculation method: NMPB2008 (octave and 1/3 of octave), ISO9613, NMPB96 (XP S 31133), Harmonoise (1/3 of octave).

• Creation of dynamic maps: maps on receivers placed by the operator, 2D maps, 3D maps showing noise distribution on building facades and vertical sections. Dynamic maps can also display results "on the fly" as gridded data, equal-loudness curve or polygons.

- **Modularity :**

MITHRA-SIG is organized in 4 modules:

• Road

• Rail (train and railway)

• Industry

• Analysis (labels management, combination of gridded data)

- **3 levels are available :**

• LIGHT : up to 5 km²

• MEDIUM : up to 20 km²

• FULL : unlimited

- **There are 2 levels of functionality:**

• Map Manager: simple functions of creating and editing, for an average experienced professional

• Map Editor: advanced functions of creating and editing for an experienced professional

3.3.1.3. Ecotect software

Ecotect is a comprehensive environmental simulation software that integrates a 3D modeler with solar, thermal, acoustic, and cost analyses. Regarding acoustic evaluation, Ecotect provides a user-friendly tool for assessing the sound performance of a built space. It enables the study of:

- Sound distribution within a room or environment
- Reverberation times and acoustic response
- Effects of materials on sound propagation

The software is designed to support conceptual and early-stage design, offering visual and analytical feedback that helps architects and designers progressively refine acoustic performance. Its highly visual results make it particularly useful for teaching beginners the key principles of indoor and outdoor acoustic design, allowing them to understand how geometry, materials, and spatial layout influence sound.

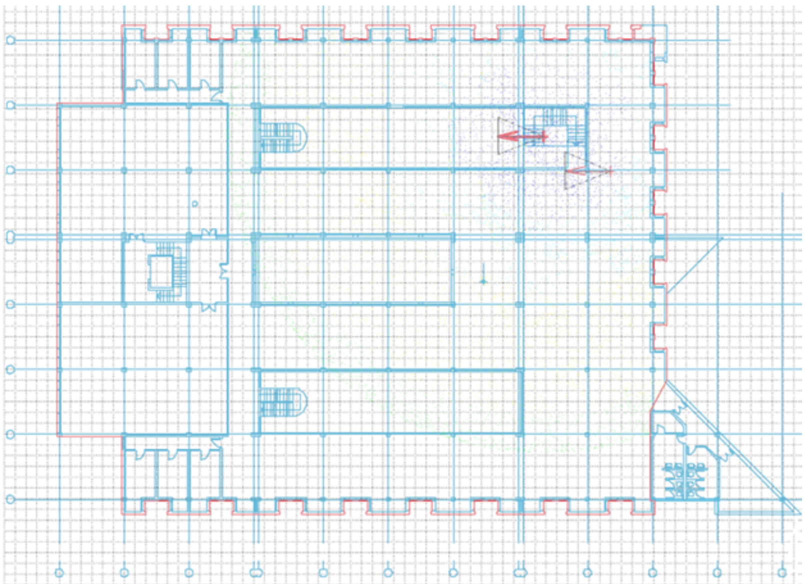


Figure 57. Ecotect software output: Sound study (source: Author)

3.3.1.4. CadnaR software

CadnaR is a specialized and powerful software program for indoor acoustic prediction that allows detailed simulation and analysis of sound within spaces. CadnaR enables users to carry out on-site acoustic simulations, making it the ideal tool for noise issues in the workplace and for room acoustics optimization as well. It is based on exactly the same software interface as CadnaA, the noise prediction software for outdoor use.

It is particularly suited for workplaces, offices, and industrial environments where noise control and room acoustic optimization are critical. Its key features include:

- Modeling rooms with complex geometries, accounting for walls, ceilings, and obstacles
- Modeling noise sources as points, lines, areas, or parallelepipeds
- Defining machine emission levels and directivity of point sources to reflect realistic sound propagation
- Support for selecting absorbent materials via a comprehensive materials library
- Evaluation of acoustic solutions, including effectiveness assessments of modifications
- Scenario analysis, allowing comparison of alternative solutions by calculating noise level distributions on 2D or 3D meshes

CadnaR is ideal for predicting and controlling indoor sound levels, helping engineers and designers make informed decisions to meet acoustic standards and optimize the sound environment.

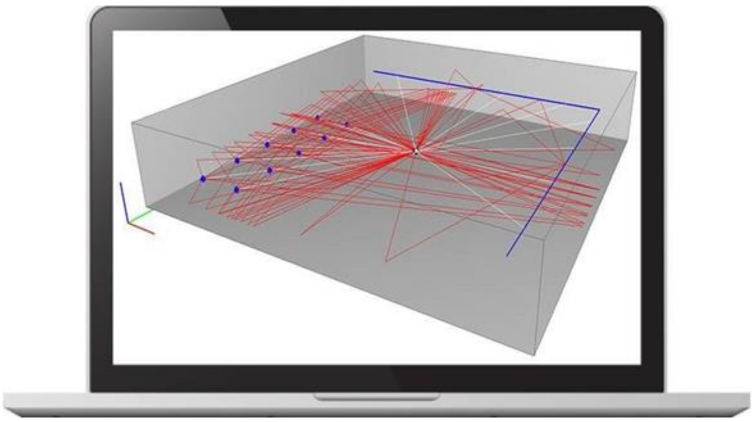


Figure 58. MithraSound graphical interface (source: https://www.01db.com/fr/nossolutions/our-products/indoor-acoustic-assessment-software/)

CadnaR offers several methods for simulating sound propagation within indoor spaces, each suited to different types of acoustic studies:

1. Mirror Image Method :
    - Models reflections on room surfaces, obstacles, and reflective sources as individual rays.
    - Each ray path is traced, accounting for reflections on all obstacles up to a specified reflection order.
2. Particle Model Method :

- Simulates a large number of "particles" emitted randomly from each source in all directions.
- Considers the reflective properties of obstacles and surfaces, with reflections modeled up to the chosen order.

3. <u>VDI 3760 Method :</u>

- Based on the mirror image method and defined by the German standard VDI 3760.
- Includes diffraction and damping effects, following the approaches of Kuttruff and Jovicic.

4. Diffuse Field Method

- Calculates sound pressure levels using statistical approaches based on Sabine's theory of room reverberation.

These methods allow flexible and accurate simulation of indoor acoustics, from precise ray-tracing for complex reflections to statistical modeling for reverberant spaces.

- **Data import and export:**

- Data editing in the library (spectral data: sound power level and absorption coefficients)
- Import/export directivity data from occasional sources
- Import coordinates of receiver points
- Import bitmap file to represent the background of the room studied
- Export object geometry and calculation mesh in dxf format
- Extensive printing options (printing protocol, printed report, printed graphics using Plot-Designer).

- **Applications:**

- Noise level assessment in workplaces and workshops
- Calculation of noise distribution in lecture halls and conference rooms
- Optimization of acoustics in catering establishments, recreation rooms, game rooms, sports halls, etc.
- Calculation of the benefits of acoustic walls or panels, with different levels of absorption depending on location

- Verification of the compliance of industrial premises with health and safety directives and legislation
- Assessment of parameters describing the quality of room acoustics and other psychoacoustic parameters related to music and / or speech performances
- Planning of different audio setups in multi – purpose halls according to uses (concerts, conferences, etc.) in just one file with different variants.

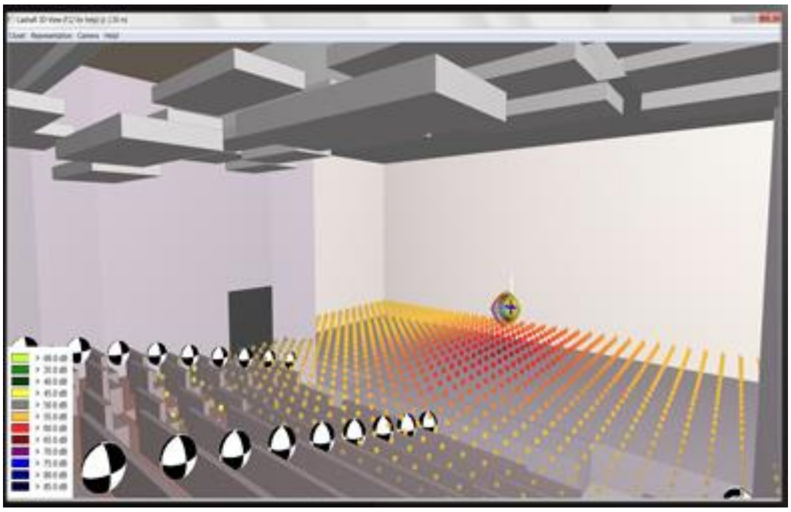


Figure 59. MithraSound graphical interface
(source: https://www.acoem.com/en/products/noise-vibration-softwares/cadnar/)

Below (Table 8) is a comparative overview of different software tools dedicated to sound assessment in buildings:

Table 8. Comparative overview of different sound software

Criteria	Mithra Sound (MITHRA-SIG)	CadnaA	Ecotect Analysis	AcouBAT (by CSTB / CYPE)
Main field	Environmental acoustics	Environmental acoustics	Building environmental analysis	Building acoustics
Noise types handled	Road, rail, industrial, aircraft	Road, rail, industrial, aircraft	Simplified noise (secondary)	Airborne noise, impact noise, building services
Scale of analysis	Urban / territorial	Urban to regional	Building (conceptual level)	Building (detailed level)
3D modelling	Yes (GIS + 3D)	Yes (very advanced)	Yes (basic)	No (analytical calculations)
Noise mapping	Yes (2D / 3D)	Yes (international reference)	No	No
Integrated standards	ISO 9613, CNOSSOS-EU, NMPB	ISO, CNOSSOS-EU, DIN, CRTN, NMPB	Indicative approach	EN ISO 12354

Criteria	Mithra Sound (MITHRA-SIG)	CadnaA	Ecotect Analysis	AcouBAT (by CSTB / CYPE)
Main outputs	Noise maps, SPL levels	Noise maps, isophones, Lden, Ln indicators	Global environmental indicators	DnT,w, L'nT,w, RT indices
GIS / BIM integration	Strong (native GIS)	Possible (import/export)	Limited	Strong (BIMserver.center)
Target users	Local authorities, urban planners, researchers	Acoustic consultancy firms	Architects (early design stage)	Acousticians, building engineers
Accuracy level	High	Very high	Medium	Very high
Strengths	GIS integration, territorial-scale analysis	Power, standards, reliability	User-friendly, educational	Regulatory compliance for buildings
Limitations	Less building-oriented	Steep learning curve	Obsolete	No urban noise mapping

- **Comparative Interpretation :**

- CadnaA is the international benchmark for strategic noise mapping, particularly for large infrastructures and urban environments.
- Mithra Sound (MITHRA-SIG) is highly relevant for territorial and environmental analyses, especially when combined with GIS tools, making it suitable for climate–environment–planning studies.
- Ecotect Analysis was useful during the conceptual design phase, but it is now obsolete following its official discontinuation by Autodesk.
- AcouBAT is best suited for building acoustic compliance, offering robust calculation methods based on EN ISO 12354 standards.

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TRNSYS | TRNSYS

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