SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

# SCHOOL OF BUILDING AND ENVIRONMENT

# DEPARTMENT OFARCHITECTURE

# UNIT – I – Performance of Buildings

# I. Introduction

It is an attribute of a building that expresses how well a building performs, given its climatic location, typology, functionality and systems in it. It is an iterative process in which you continually assess how your building is performing, what is driving that performance, and what you can do to influence it.

Building performance analysis at the early design stage involves implementing an iterative process in which you continually assess how your building is performing, what is driving that performance, and what you can do to influence it.

The traditional energy modeling paradigm is misaligned with the design process, and incapable of delivering on the promise of great performance. This is largely because energy modeling tools were not intended to be architectural design tools. They are useful for designing mechanical systems and performing validation analysis on fully detailed models — and for these uses, the energy modeling paradigm will continue to be a necessary part of the overall design process.

But the energy modeling paradigm is too far removed from the creative, iterative, real-time nature of design. If we want a tool that can meaningfully inform design — that can have significant impact on energy consumption, operating cost, and the capital costs of the HVAC systems; that is useful from Schematic/Conceptual Design through Construction Documents, when architects are actually making design decisions — then the industry needs a new approach. It is a completely different way of thinking about performance.

We analyse the following in various ways in building performance

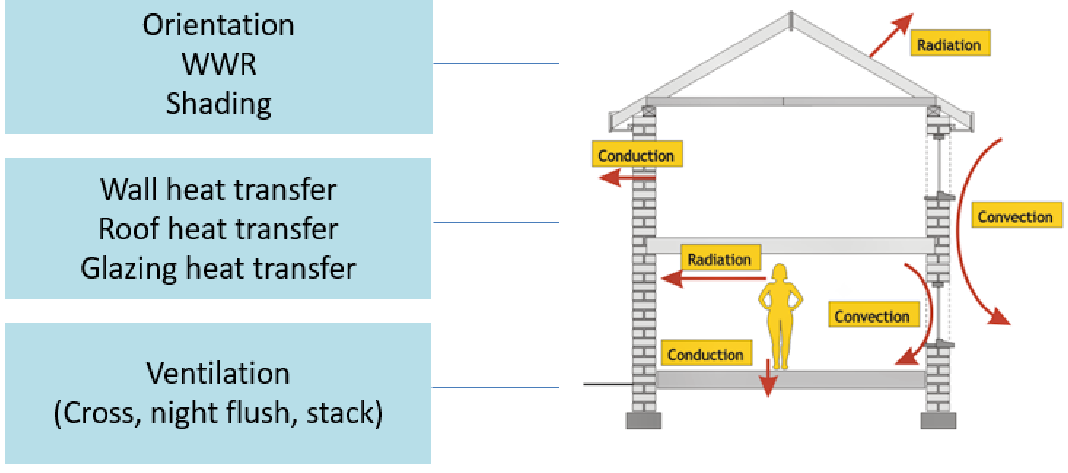



*Figure 1Parameters to be reviewed in a building through various modes of heat transfer: Radiation, conduction, convection*

Lot of advancement in the field of sustainable buildings and neighbourhoods in the last decades,

Development of several rating tools to evaluate their performance.

**PROBLEM:** There is usually "a significant difference between predicted (computed) energy performance of buildings and actual measured energy use once buildings are operational").

The performance of these complex systems is different in theory versus in reality – what came to be known as the **"performance gap".**

The differences in terms of energy performance and indoor environment have been linked to two main causes:

- defects in the building systems and envelope
- the influence of buildings' occupants

**Post-Occupancy Evaluation (POE)-** created for assessing buildings asking users about their needs and experiences in the built environment.

Post-Occupancy Evaluation can be defined as the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time.

## POE can be used in the following:

- POEs focus on building occupants and their needs,
- provide insights into the consequences of past design decisions and the resulting building performance.
- This knowledge forms a sound basis for creating better buildings in the future

## Six major phases of the building delivery

This framework defines the building delivery cycle from a designer's perspective, showing its cyclic evolution and refinement toward a moving target of achieving a better quality as perceived by the building occupants and a better overall performance

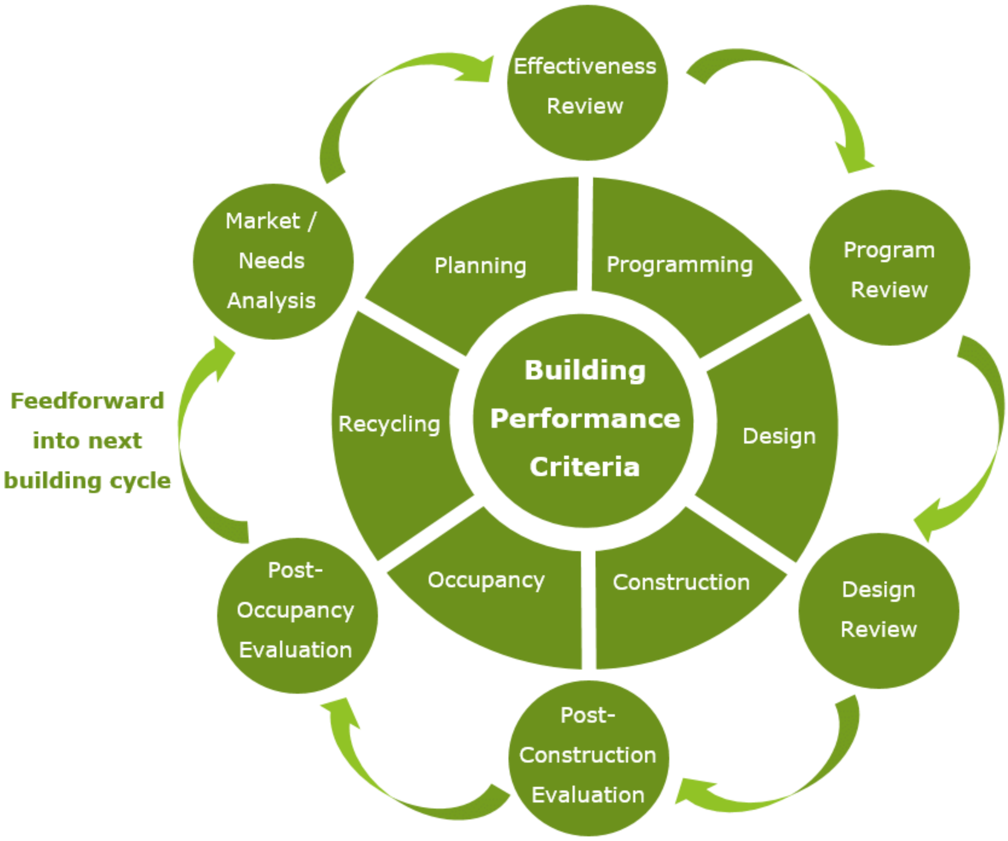



*Figure 2 Six major phases of building delivery*

**Architects and building performance**

**Architects wanted to know:**

- **What's important?** What elements of the design should they focus on? Where are the biggest opportunities to have an impact on performance? Is it a tighter envelope, preventing solar gains, or providing good daylight?
- **What are the constraints?** Designers want to know the constraints and boundaries of the problem. If they know early on that south shading is critical, or that a 55% glazing ratio is ideal, or that a 50-to-60-foot floor plate provides a great balance of daylighting and energy performance, they can use these as meaningful constraints to inform the design.
- **Is it possible to do X?** Can the design be naturally ventilated? Could passive solar address most of the heating needs? Could we meet all energy needs from on-site renewables?
- **How does my design compare?** — to other design options, to typical buildings in my area, to an ASHRAE 90.1 baseline, to 2030 Challenge goals? When exploring the design space, comparisons are critical.

Performance analysis of buildings need to be done during or before the pre-design stages (step 0 in the image below). Performance evaluation of buildings need to be done during or after the construction stages (step 4)

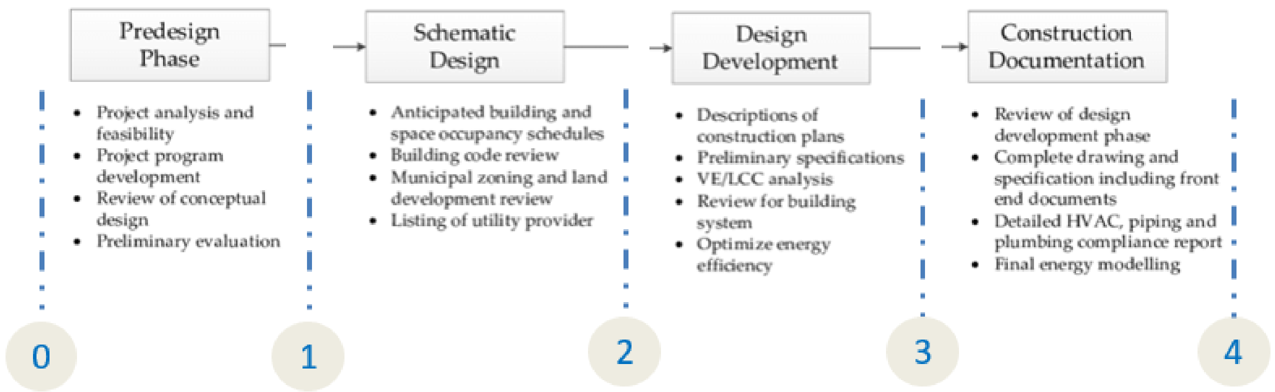



*Figure 3 Stages involved in building design and implementation*

**How to integrate these with design?**

The alternative to energy modeling is a real-time, multiple-options-at-a-time, results-first paradigm in which seamless performance feedback informs design decisions throughout the design process.

This form of building performance analysis aims to be part of the design process. Feedback can't depend on a finished design — instead, the feedback needs to be continuous, helping designers explore the design space, understand their options, and make informed decisions.

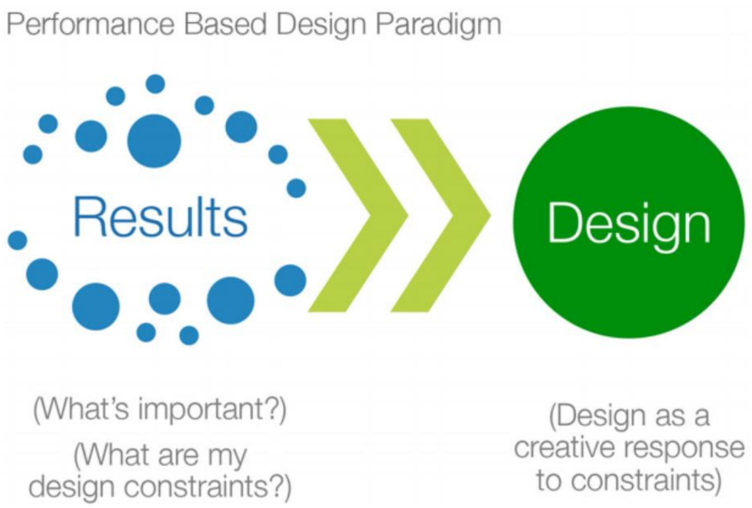



*Figure 4 Performance based design paradigm*

Need for performance analysis of buildings are as follows:

- challenges in defining an ultimate list of the performance aspects that need to be considered,
- challenges in terms of the evaluation process itself, and
- challenges with the goals and ambitions of building stakeholders.

Various frameworks can be used. Some frameworks attempted to provide a generic framework of building performance aspects, such as the

- Total Building Performance Framework
- the ASTM Standard on Whole Building Functionality and Serviceability
- the  Whole Building Design Guide

## Soft computing and simulations

Energy simulation is a computer-based analytical process that helps building owners and designers to evaluate the energy performance of a building and make it more energy efficient by making necessary modifications in the design before the building is constructed. Use of energy simulation software is necessary to show compliance with Indian Energy Conservation Building Code (ECBC) via “Whole Building Performance Method.”

The energy performance of a building depends on how a building has been designed from an energy efficiency perspective and how well the system integration issues have been addressed. The way a building behaves and performs is governed by envelope design (walls, windows, roofs, etc.), selection of building materials, and design and selection of building systems (lighting, cooling, heating, ventilation, etc.) to meet the thermal and visual comfort of occupants and other functional requirements. A building interacts with its external as well as internal environment. A good building designer needs to account for the external factors such as air temperature, humidity, solar radiation, wind speed and direction, etc., which may vary significantly throughout the year, and balance it with thermal and visual comfort requirements, internal heat gains, etc. For example, a designer may decide to have large glazed façade for better aesthetic value and to increase the amount of daylight entering the building. This can lead to reduced lighting load but may increase the cooling load on Heating Ventilation and Airconditioning (HVAC) system due to higher heat gains through glazing. In real practice, understanding and analyzing the total energy performance of a building is very complex and the building designers find it extremely difficult to establish energy performance with reasonable accuracy through conventional computation methods. Usually “rules of thumb” deployed by consultants and the "expert advice" of equipment suppliers play a major role in selection and sizing of building components and systems. This may not be the most effective way to design large complex commercial buildings and may lead to poor energy performance throughout the life of the building. Just like prevention is better than cure, it is easier and more cost-effective to incorporate energy-efficient issues at the time of new construction than through a retrofit process.

Technological advancements in computer software have provided several tools that can help the designers to predict and analyze the energy performance of a building with good accuracy and with substantial reduction in effort. Such programs allow for sensitivity analysis of various design options and decisions— from the conceptual and schematic phases to the detailed specification of building components and systems

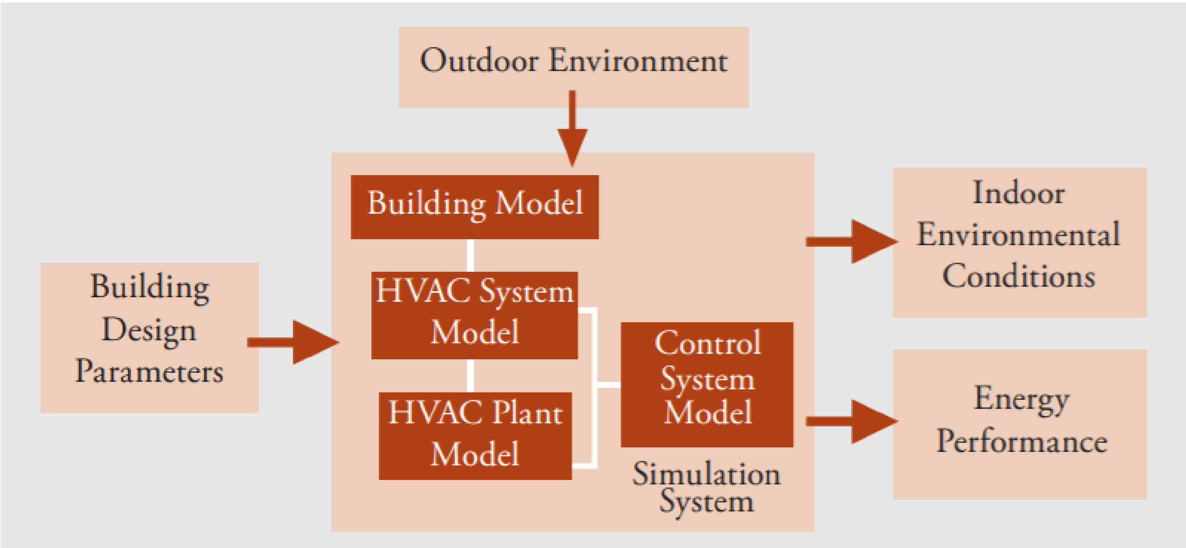



*Figure 5 Building design parameters affecting the outdoor environment, indoor environment and energy performance*

These computer-based energy simulation programs model the thermal, visual, ventilation and other energy-consuming processes taking place within the building to predict its energy performance. A simulation program takes into account the building geometry and orientation, building materials being used, building façade design and characteristics, climatic parameters, indoor environmental conditions, occupant activities and schedules, HVAC and lighting systems and other parameters to analyze and predict the energy performance of a building. Data required for energy modelling are as follows:

| Category | Purpose | Source |
|---|---|---|
| Geographical location (climate) | Accurate load calculation based on external environment | Weather file |
| Geometry<br>• Plan<br>• Section<br>• Elevation | Model geometrical attributes of buildings and any site specific features (shading, reflection by tree or building) | Architectural drawings |
| Construction<br>• Wall<br>• Roof<br>• Window<br>• Overhangs | Model building envelope attributes for thermal load and daylighting calculations | • ECBC<br>• ISHRAE<br>• CBRI<br>• Software library<br>• Vendors<br>• ASHRAE |
| Daylighting and lighting<br>• Layout<br>• Technology and controls | • Visual comfort<br>• Reducing LPD<br>• Integration with daylight | • Lighting consultant<br>• Vendors<br>• ISLE/IES |
| Internal Load<br>• Usage (e.g. number of hours)<br>• Schedule<br>• People, equipment, lighting | Accurately capture sources of internal heat gain within building | • Client<br>• Energy modeler<br>• Benchmarking data<br>• Nameplate data |
| HVAC (type and controls)<br>• Component specification<br>• Control strategy<br>• Layout and distribution | • Sizing the system<br>• Design optimization<br>• Comfort satisfaction | • HVAC consultant<br>• ASHRAE/ISHRAE<br>• ARI<br>• ECBC |

*Table 1 1Data required for energy modelling*

Integration of energy simulation steps with architectural design stages:

| Stage | Architecture Design | Energy Simulation Integration |
|---|---|---|
| Concept Design/ Programming | Climate, desired indoor conditions for comfort | Weather data |
| | Orientation, shape and site conditions | Sun path diagram, Solar analysis |
| | Building massing | Mutual shading analysis |
| | Building operation schedule, ventilation rates | Proper zoning |
| Simple model geometry rule of thumb calculations, % opening (WWR) | Basic equipment options, peak load calculations, schematic system design | Monthly/annual simulation |
| Schematic Design/ Design Development | Geometry: Walls (façades)/openings/ projections/volumes/design elements | Sensitivity analysis: Zoning the building by system types with surface information, integration of loads, advanced fenestration calculations, full interior and exterior solar distribution |
| | Services: Types and placement of systems (structure design, HVAC design/selection, electrical/ lighting, plumbing) | |
| | Programming schedule: Activity type/ occupancy levels, controls | Hourly simulation |
| Construction | Tender drawings, system specifications, material selection, working drawings | Energy Conservation Measures (ECMs) and payback |

*Table 2Integration of energy simulation steps with architectural design stages*

## Investigation and assessment: Auditing

**An Energy Audit,** or Review, is an investigation of all facets of an organisation's historical and current energy use with the objective of identifying and quantifying areas of energy wastage within the organisation's activities. It is best carried out by an Accredited Energy Auditor

The energy audit in a building is a feasibility study. For it not only serves to identify energy use among the various services and to identify opportunities for energy conservation, but it is also a crucial first step in establishing an energy management programme. The audit will produce the data on which such a programme is based. The study should reveal to the owner, manager, or management team of the building the options available for reducing energy waste, the costs involved, and the benefits achievable from implementing those energy-conserving opportunities (ECOs). The energy management programme is a systematic on-going strategy for controlling a building's energy consumption pattern. It is to reduce waste of energy and money to the minimum permitted by the climate the building is located, its functions, occupancy schedules, and other factors. It establishes and maintains an efficient balance between a building's annual functional energy requirements and its annual actual energy consumption.

**It aims at**

i. Assessing present pattern of energy consumption in different cost centres of operations

ii. Relating energy inputs and production output

iii. Identifying potential areas of thermal and electrical energy economy

iv. Highlighting wastage in major areas

v. Fixing of energy saving potential targets for individual cost centres

vi. Implementation of measures of energy conservation and realisation of savings

The study should reveal to the owner, manager, or management team of the building the options available for reducing energy waste, the costs involved, and the benefits achievable from implementing those energy-conserving opportunities (ECOs). Other parameters to be audited:

- Climate and location
- Building details (materials, insulation values)
- Occupancy schedules
- HVAC specs and chiller efficiencies
- Building typology
- Lighting schedules
- Equipment schedules
- Building working timings
- records of utility and fuel expenditures.

**Stages of auditing**

There are 3 stages in energy auditing

- Surveying
- Measurements
- Modelling

**Stage 1: Surveying**

Surveying involves the following:

**a. Preliminary survey**

Prior to the walk-through survey, the auditor may need to know the building and the way it is used. The information can be obtained from:

- architectural blueprints,
- air-conditioning blueprints,
- electrical lighting and power blueprints,
- utility bills and operation logs for the year preceding the audit,
- air-conditioning manuals and system data, and
- building and plant operation schedules.


*Figure 6 Preliminary survey requirements: blue prints, energy bills*

### Walk-through survey

Thus having familiarized with the building, the walk-through process could be relatively straightforward, if the blueprints and other preliminary information available describes the building and its operation accurately. The process could begin with a walk around the building to study the building envelope. Building features such as building wall colour, external sun-shading devices, window screens and tint, and so on are noted as possible ECOs. If a model analysis is included in the study, the building must be divided into zones of analysis.

*Figure 7 Image depicting a walk-through*

The survey inside the building would include confirmation that the air-conditioning system is as indicated on plans. Additions and alterations would be noted. The type and condition of the windows, effectiveness of window seals, typical lighting and power requirements, occupancy and space usage are noted. This information could be compared against the recommendations in the relevant Codes of Practices. System and plant data could be obtained by a visit to the mechanical rooms and plant room. Nameplate data could be compared against those in the building's documents, and spot readings of the current indicating panels for pumps and chillers recorded for estimating the load on the system

**b. Operators' inputs**

*Figure 8 Image depicting energy professional and facility manager/ operator discussion*

The auditor may discuss with the building maintenance staff further on the operating schedules and seek clarification on any unusual pattern in the trend of the utility bills. Unusual patterns such as sudden increase or decrease in utility bills could be caused by changes in occupancy in the building, or change in use by existing tenants. It is not uncommon for tenants to expand their computing operations that may increase the energy use significantly.

**c. Report**

- At this stage, ECOs could be found in measures such as:
- Reduce system operating hours,

- Adjust space temperature and humidity,
- Reduce building envelope gain,
- Adjust space ventilation rates and building exfiltration,
- Review system air and water distribution,
- Adjust chiller water temperatures, and
- Review chiller operations.

The benefit from adopting each ECO should be compared against cost of implementation. Caution should be exercised in the cost-benefit analysis given the wider range of certainty of the projections made. However, a survey at this level may be sufficient for small buildings.

**Stage 2: Measurements**

*Figure 9 Image depicting on-site measurements*

The capability of the energy auditor and the scope of an audit could be extended by the use of in place instrumentation and temporary monitoring equipment. In-place instrumentation refers to existing utility metering, air-conditioning control instrumentation and energy management systems (EMS). The use of in-place utility metering and temporary monitoring equipment in energy auditing can yield valuable information about the building systems such as:

- Energy signature and end-use consumption analysis,
- Discovery and identification of ECOs,
- Quantification of energy use and misuse,
- Establishing bounds for potential energy reduction, and
- Data acquisition for further calculation and analysis.

**A. Existing information**

Existing instrumentation such as utility meter readings, and energy billings could be used to establish energy consumption patterns for the building. The regularity of consumption pattern is an indicator that no significant change in consumption occurred prior to the audit. This can also be used to check the validity of projections based on extrapolated short-term monitored data.

*Figure 10 Energy meters*

*Figure 11 Water meters*

Utility data could be used to establish useful indices such as kWh/m2/year to compare relative energy performance of buildings. Air-conditioning control instrumentation such as chilled water temperature probes, water flow meters could be used to estimate cooling load demand and plant operation. For example, chilled water temperature outside the designed range may indicate that cooling coils may be operating under off design conditions.

**b. Short term monitoring** The building may not be equipped for monitoring energy consumption and it may be necessary to install temporary measurement devices such as instantaneous recorders (strip chart, data loggers, etc) and totalizing recorders (kWH meters) to obtain data over the period of a week for the study.


*Figure 12 Image representing measurements and software*

Monitored data is also useful for completing the energy model of a building for use in some building energy simulation software. For example the total building energy consumption would include energy used in the vertical transportation system and potable water pumps which are not modelled in the software. An estimate for annual consumption is extrapolated from the typical week consumption profile. Regularity of the weekly consumption profile means that the annual consumption could be estimated with confidence and the value used to cross check with the annual energy bills.

The image below is a sample of an analysis and graphical observations put forth. This sample graph is to illustrate how short term monitoring of data can be plotted in a graph along with predictions for the rest of the year annually.

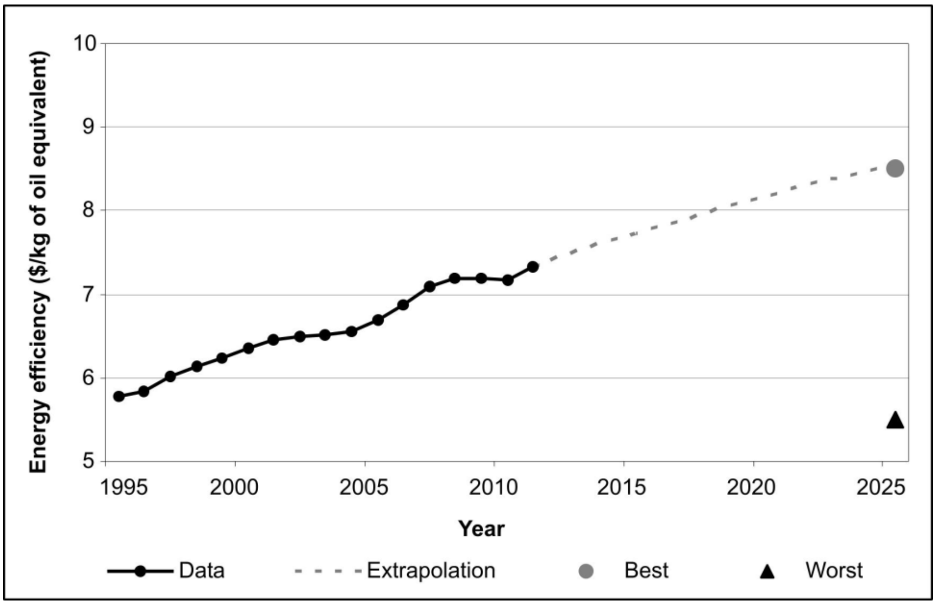



*Figure 13 sample of an analysis and graphical observations*

Building energy consumption = rate of consumption X period of operation

= Kw X h  = kWh

In lighting systems – easy to determine energy consumption manually with precision as it does not interact with other consumption variables.

**Stage-3: Modelling**

Building energy consumption in simplest terms is just the product of rate of consumption of a system and the period of operation. In lighting systems, its energy consumption could be determined manually with precision as it does not interact with other consumption variables. Energy consumption of cooling systems, however, is many times more complicated as it is affected by the internal heat gain within a building as well as weather variables, which varies in a complex manner over time. Building model analysis using computers offers several improvements over manual calculations. These include:

- Precise schedule of building parameters,
- Precise determination of weather impact,
- Specification of part load performance of plant and equipment, and
- Consideration of parameter interactions such as lighting load on air-conditioning consumption.

**a. Software**

Some software permit hour-by-hour calculations of building consumption for the entire 8760 hours of the year, but require thorough knowledge of the software to carry out accurate and meaningful analysis.

*Figure 14 Energy simulation software*

Simplified software based on consumption analysis on characteristic days may also be considered.

**b. Analysis**

ECMs could be considered singly or in combinations to determine interactions between them. The results of the energy savings in each analysis should not be taken as absolute but rather taken to be relative to the base run so as to give an indication of the order of magnitude of savings. Thus those ECMs which shows significant gains would be implemented.

The general procedure for an analysis would be to establish a model giving an annual consumption within 10% of the measured data. This establishes the base model. The impact of ECMs on energy consumption would be compared against the base model.

## Modelling systems

### a. Cognitive modelling

These modelling have a strong influence on building energy consumption. it is ultimately the building occupant who consumes energy through his or her behavior. Understanding this type of behavior is therefore critical to limiting the energy consumption of buildings.

Cognitive modeling is an area of computer science that deals with simulating human problem-solving and mental processing in a computerized model. Such a model can be used to simulate or predict human behavior or performance on tasks similar to the ones modeled and improve human-computer interaction.

Types of cognitive models:

Some highly sophisticated programs model specific intellectual processes. Techniques such as discrepancy detection are used to improve these complex models. Discrepancy detection systems signal when there is a difference between an individual's actual state or behavior and the expected state or behavior as per the cognitive model. That information is then used to increase the complexity of the model. According to Forsythe, the cognitive machines they've created have the capacity to infer user intent -- which is not always consistent with behavior -- store information from experiences similarly to human memory, and call upon expert systems for advice when they need it.

Another type of cognitive model is the neural network. This model was first hypothesized in the 1940s, but it has only recently become practical thanks to advancements in data processing and the accumulation of large amounts of data to train

**b. Empirical modelling**

Empirical models are focused on describing the data with the specification of very few assumptions about the data being analyzed. This type of modeling is particularly helpful when parametric models, due to various reasons, cannot be constructed.

Empirical models are focused on describing the data with the specification of very few assumptions about the data being analyzed. This type of modeling is particularly helpful when parametric models, due to various reasons, cannot be constructed. Based on different methodologies and approaches, empirical modeling allows the analyst to obtain an initial understanding of the relationships that exist among the different variables that belong to a particular system or process. The results from empirical models can be used in order to make decisions about those variables, with the intent of resolving a given problem in the real-life applications.

**c. Analytical modelling**

A mathematical modeling technique used for simulating, explaining, and making predictions about the mechanisms involved in complex physical processes. Quantitative in nature, and used to answer a specific question or make a specific design decision. Different analytical models are used to address different aspects of the system, such as its performance, reliability, or mass properties. Analytical models must be expressed with sufficient precision that they can be formally analyzed, which is typically by a computer.

**Analytical models** can be further classified as:

- **Static** – **static model** represents the properties of a system that are independent of time, or true for any point in time
- Eg: Length, mass etc
- **Dynamic** – dynamic model is an analytical model that represents the time-varying state of the system, such as its acceleration, velocity, and position as a function of time.
- Eg: Accelerator, velocity etc

**Relationship of modelling systems with simulations:**

A simulation is composed of a model (which may be composed of other models) that is executed by a simulation engine based on a set of initial conditions.

The simulation engine creates an instance of the model in the simulation environment, applies the initial conditions to that instance, and then uses the equations expressed by the model to determine the change of state of that instance as a function of time

**Parametric simulations:**

This is a computer aided design (CAD) modelling method/ tool. It saves time. Eliminates the need for a design engineer to constantly redraw a design every time one of the design's dimensions change. It allows designers to modify the entire shape of their design at once, not just individual dimensions one at a time.

Parametric design is based on the sketches of your model. These sketches contain:

(1) dimensions,

(2) constraints and

(3) relationship between the elements of your drawing.

The advantage of setting the parameters early in the design process is that you can then go back to your sketches to automatically modify the features of your final design.

Parametric modelling, geometric preparation and analysis preparation should be streamlined and connected to performance analysis. This would combine parametric control of building geometry and building systems with analysis and visualization of results. The images below show the methods for integrating parametric design with building performance analysis

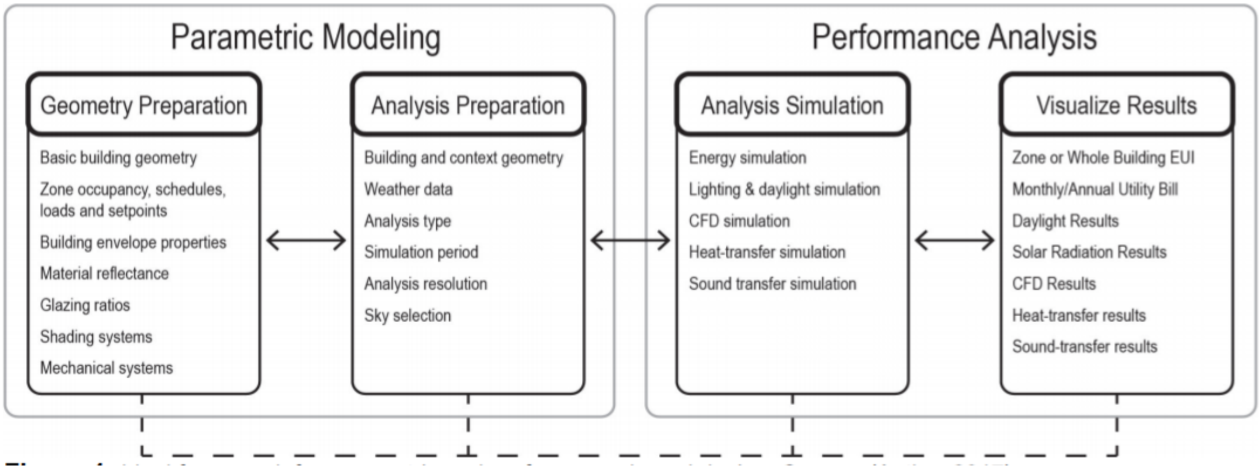



*Figure 15 Parametric modeling and performance analysis parameters*

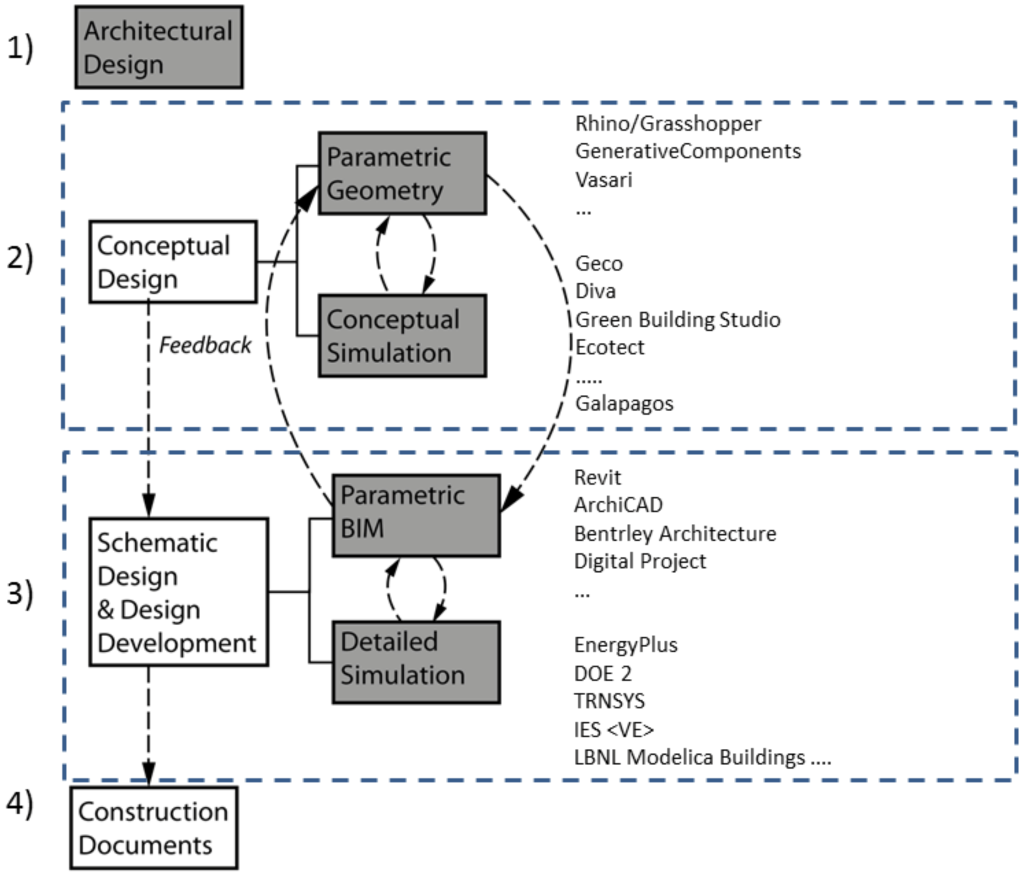



*Figure 16 Software available for various stages of a building from Architectural design to construction*

Parametric design can also be used to give parameters to features you want to control. An example is as shows below. If a model or cube for example that has 1 big void in each surface now needs to be divided into multiple voids in each space, then the parameters to be changed are Size of cube, Thickness of grid, Size of opening. Only these parameters need to be changed and the rest can stay in tact. Performing various permutations and combinations for this is known as Parametric modelling.

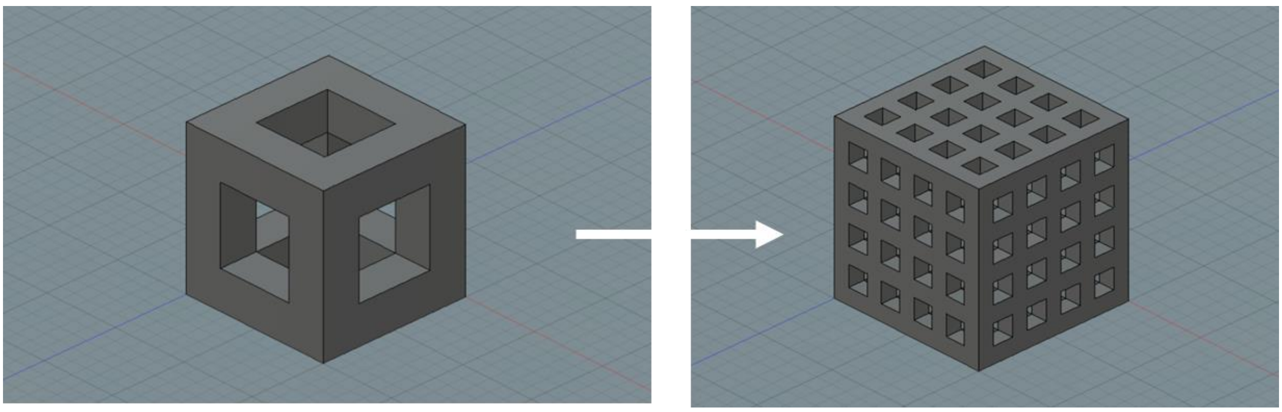


*Figure 17 Parametric design depicted by a cube with changing parameters of various size of voids*

**REFERENCES**


1. https://support.sefaira.com/
2. www.researchgate.net/figure/Building-performance-evaluation-integrative-framework-for-building-delivery-and-life_fig1_326635791
3. https://pearl.plymouth.ac.uk/bitstream/handle/10026.1/13361/10Q%20concerning%20BPA%20final.pdf;jsessionid=76B9D02F1A35DEDE4F8FD3B639E1FB8F?sequence=1
4. https://link.springer.com/chapter/10.1007/978-1-4899-3722-3_12
5. https://kredlinfo.in/EC/Energy_Audit_Methodology.pdf
6. https://www.intechopen.com/books/empirical-modeling-and-its-applications
7. https://www.researchgate.net/figure/Mathematical-modeling-of-temperature-control-in-the-air-conditioning-space_fig2_263395453
8. https://www.sculpteo.com/blog/2017/05/10/save-time-with-parametric-design-for-3d-printing/
9. https://www.researchgate.net/figure/Streamlined-parametric-modeling-BIM-and-building-energy-modeling-Yan-2014_fig1_326440025
10. https://www.nrel.gov/docs/fy08osti/42059.pdf

# UNIT – II – Whole building Energy Simulations

# Introduction

Energy simulation method wherein efficiency of multiple components can trade off with each others' efficiency to result in an overall energy efficient building. This needs to be modelled through simulation software.

There are a lot of simulation tools in the market and below image shows the share of each software/ tool

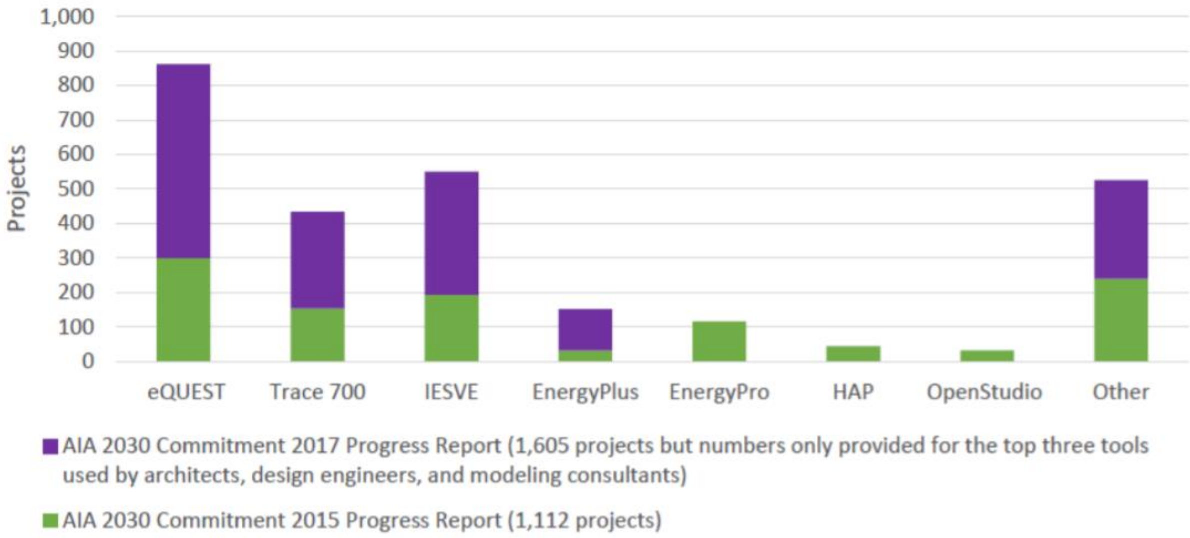



*Figure 18 Simulation tools and total number of projects as per US market*

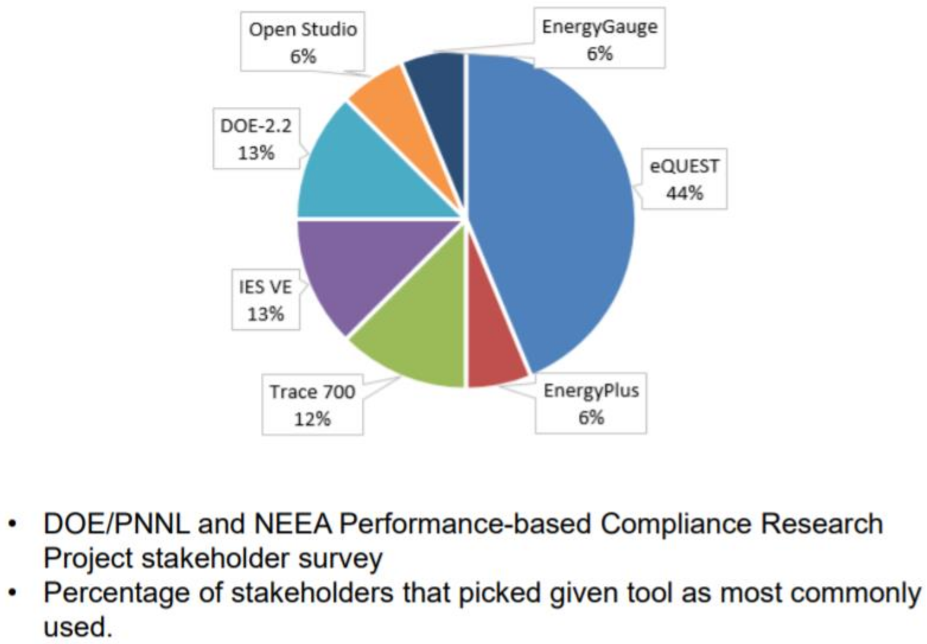



*Figure 19 Share of energy simulation tools in the market*

**Role of energy simulations**

The "Whole Building Performance Method" of ECBC gives the requirements for standard design and proposed design energy simulation models. The purpose is to estimate annual energy consumption of the proposed building and to compare it with the energy consumption of the standard building, then to demonstrate that the proposed building consumes energy equal to or less than that of standard design. The procedure that can be adapted is as follows: • Based on the designs and specifications given by the client, a model is prepared in a simulation program and annual energy consumption is estimated. This is the "AS IS" model.

A standard model is then created and used as a base case; this is based on the requirements given for the standard design as described in Appendix B of ECBC. The annual energy consumption of the standard model is compared with that of the "AS IS" model.

If the "AS IS" model consumes less energy than, or the same amount as, the standard model and it meets all the mandatory requirements of the code, then it is compliant with the code. If it consumes more energy than the standard model, then various energy conservation measures can be applied to evaluate their energy savings potential and a group of such measures, based on their life cycle costs, can be combined to reduce annual energy consumption in the building so that it is equal (or less than) that of the standard. This improved version of the "AS IS" design is called proposed design. Some points to be considered are:

1. The building geometry (except fenestration), schedules and plugloads are the same in both the models.

2. Both the models must meet the mandatory provisions of ECBC.

3. Thermal properties, LPD and HVAC specifications.

4. Benefits of shading, higher efficiency in lighting, HVAC and material properties can be taken in the proposed design.

Once the proposed model and the standard design model are simulated, they are compared to show the final annual energy consumption and the electricity used by various components such as lighting, space heating, space cooling, pumps, equipment, etc. The proposed design should demonstrate better performance than the standard design.

## Modelling the building form

While modelling the building form, thermal zoning is one of the most important concepts. Zoning the spaces or rooms based on the usage patterns, schedules and also based on their exposure to solar radiation is known as thermal zoning. Image below depicts certain common types of zoning

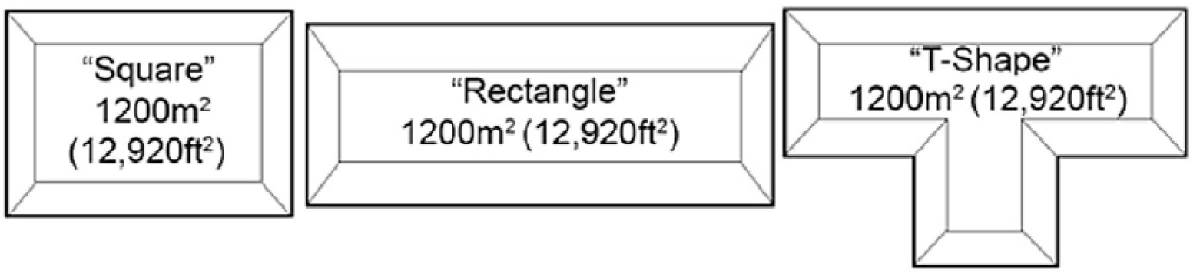



*Figure 20 Thermal zoning types*

Example: consider a space as follows in the image below. The image below that is how it can potentially be zoned.

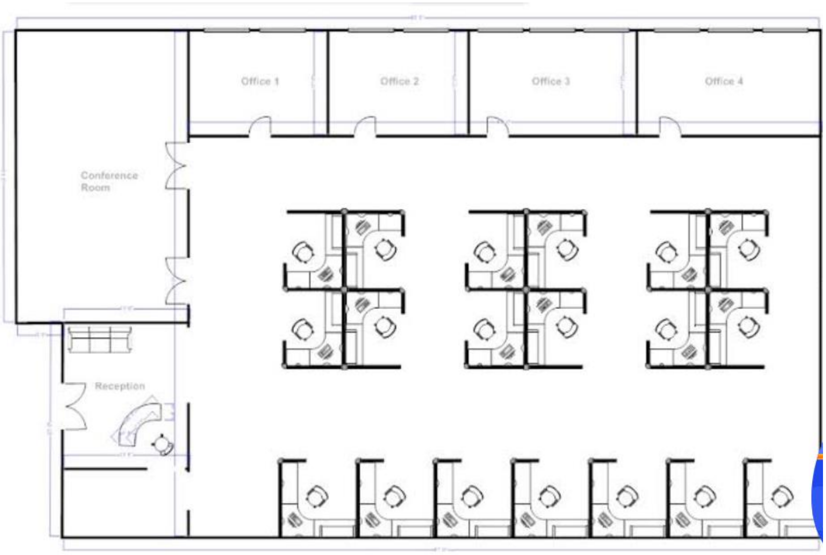



*Figure 21 Building design sample for thermal zoning*

*Figure 22 Sample thermal zoning*

## Factors affecting accuracy of energy models

**Range of simulation capabilities**: An energy analysis program cannot precisely simulate the wide variety of building shapes, equipment, controls, and conditions that exist. The simulation capabilities of energy analysis programs are being expanded continually, but they always lag behind the latest developments in building technology. For example, the major programs only gradually acquired the ability to simulate window shading features, tilted glazing, variable air volume (VAV) systems, temperature reset controls, variable-flow pumping, thermal storage, etc. If the user is an innovator, he/she will not find a program that easily simulates all the configurations that he/ she wants to investigate. Energy analysis programs differ in their strengths and weaknesses. For example, one program may be able to simulate a large range of equipment types, while another provides the most accurate description of thermal characteristics of a wall, and yet another provides the best simulation of complex glazing configurations. It should be ensured that the program chosen is able to simulate the engineering and architectural features that are important for the project

**Accuracy of component simulation:** The user must input the efficiency (input-output) characteristics of each component that uses energy, including part-load performance. This can be done by specifying percentages of maximum output for various percentages of energy input. The designer may have to call the manufacturer's engineering department to get part-load information for the equipment that is being simulated. Some energy analysis programs can assist designers with libraries of efficiency curves for different types of mechanical equipment, such as fans, pumps, chillers, and boilers. However, it is a mistake to rely on generic efficiency curves for major items of equipment, because there are major differences among models. For example, different models of centrifugal chillers differ widely in their part-load behavior and in their minimum loads, which are important factors in their overall energy consumption. Programs developed by equipment manufacturers may have accurate performance data for their own specific models of equipment, but not for the equipment of other manufacturers. The designer may have to manually calculate the efficiency curve for a complex combination, such as a pump driven by a variable-speed drive. In this example, the program may not be able to account for the efficiencies of both the pump and the drive at each percentage of load.

**Number of calculation intervals:** There would be no need for computer energy analysis if the energy loads were constant, or if the loads changed in regular, repeating patterns. In HVAC applications, changing weather conditions make it necessary to use a computer to achieve accurate estimates. The computer achieves accuracy by repeating the entire sequence of calculations for many short time periods. Some energy analysis programs calculate for each hour of the year, assuming a constant load during each hour. This method repeats each calculation 8,760 times, the number of hours per year. This degree of refinement requires relatively long computing times. The newest personal computers may be able to run such simulation in less than one hour per run, and perhaps much less

**Number of zones:** All energy simulation programs are designed to divide the building into zones. They do this as an easy way of dealing with differences in load characteristics. The program user defines the number of zones, and the way the building is divided into zones. This is a major decision that the user has to make at the beginning of input process. A model with larger number of zones provides greater accuracy, but requires more input work. The computer program calculates energy requirements of each zone separately, so more zones means longer computing time. It is conventional to create separate zones for each exterior orientation of the building, along with separate interior zones. For example, the user may divide a simple, single-story building into five zones: north, south, east, west, and interior. All five zones in this example differ in envelope heat gains/losses, daylighting, and they may differ in internal heat gains. User typically defines major space volumes with distinct load characteristics as separate zones. Examples of such spaces are office rooms, computer rooms, large conference rooms, and atriums.

**Equipment defects and unpredictable behavior:** The program's simulation results may differ substantially from real performance because components are not ideal. For example, some energy analysis programs calculate theoretical thermal characteristics of walls in excruciating detail. Real wall construction includes sloppy insulation, thermal short circuits through studs, air infiltration, and other factors that substantially degrade thermal performance. Sophisticated program users try to compensate for such predictable flaws by adjusting the input, but it is not possible to predict the performance of bricklayers and carpenters with a great deal of accuracy.

**Program errors:** There are only a few energy analysis programs in existence that have proven to be reasonably reliable, and all have limitations and flaws. These programs have bugs for the same reasons that all large computer programs have bugs. A common bug in energy analysis programs is failure of the program to accurately simulate the way equipment behaves. This is a continuing problem. Few people have a good understanding of energy behavior of systems, not many of them write energy analysis programs, and those who do may not remain involved with the program to upgrade and debug it.

**Input errors and misunderstandings:** The computer cannot read the designer's mind to determine what the designer really means, and it will not fix the designer's input errors. The computer is completely literal in reading the input. Typically, analysis requires hundreds or thousands of input numbers. An error in any single number will cause an error in the output. Therefore, all inputs need to be meticulous. Some programs can flag input data that falls outside a normal range. This is helpful in catching gross input errors, but errors can still slip through this screen.

## Thermal performance criteria of buildings and

## Envelope considerations, climate analysis and weather data

These have been broadly defined to allow all capable programs to be considered for approval by the adopting authority, while eliminating programs that would not be able to adequately account for the energy performance of building features under the ECBC.

Minimum hours per year: Programs must be able to model energy flows on an hourly basis for at least 1,400 hours per year. Many programs model for the full 8,760 hours in a year; others use representative days for the different months and seasons.

Hourly variations: Building loads and system operations vary hour-byhour, and their interactions have a large influence on building energy performance. Approved programs must have the capability to model hourly variations, and to establish separately designed schedules of operation for each day of the week and for holidays, for occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation.

Thermal mass effects: A building's ability to absorb and hold heat varies according to type of construction and system and ventilation characteristics. This affects the timing and magnitude of loads handled by the HVAC system. Simulation programs must be able to model these thermal mass effects.

Number of thermal zones: There are multiple thermal zones in all buildings, and they experience different load characteristics. Approved programs must be able to model at least 10 thermal zones; many simulation programs can handle a far greater number of zones.

Part-load performance: A building's mechanical system rarely experiences full-load operating conditions, so understanding the performance of equipment under part-load conditions is important. Approved programs must incorporate part-load performance curves in their calculations.

Design load calculations: Approved programs must be capable of performing design load calculations to determine required HVAC equipment capacities as per ECBC norms. The Standard Method of Test can be used for identifying and diagnosing predictive differences from whole building energy simulation software that may possibly be caused by algorithmic differences, modeling limitations, input differences, or coding errors. An overall validation methodology, according to ANSI/ASHRAE Standard 140-2004, consists of three parts:

A. **Comparative Testing** - in which a program is compared to itself or to other programs
B. **Analytical Verification** - in which the output from a program, subroutine, algorithm, or software object is compared to the result from a known analytical or quasi-analytical solution for isolated heat transfer mechanisms under very simple and highly constrained boundary conditions

C. **Empirical Validation** - in which calculated results from a program, subroutine, algorithm, or software object are compared to monitored data from a real building, test cell, or laboratory experiment.

**Modeling of Glazing:** The ability of the programs to model glazing correctly with angular dependence (refer Window 5 and NFRC IDGB glazing database used by EnergyPlus, eQUEST and DOE2.1E)

**Building envelope:** The basic rule for modeling the building envelope in the design energy calculations is to use the design shown on the final architectural drawings, including building shape, dimensions, surface orientations, opaque construction assemblies, glazing assemblies, etc. Any simulation program necessarily relies on a somewhat simplified description of the building envelope. It is usually too time-consuming and difficult to explicitly detail every minor variation in the envelope design, and if good engineering judgment is applied, these simplifications won't result in a significant decline in accuracy

## Heating and cooling systems modelling

The basic rule for modeling an HVAC system is to base the model as completely as possible on actual system design. This includes the system type, equipment capacities and efficiencies, controls, and other ancillary features (such as economizers). The equipment efficiencies may need to be adjusted to meet the needs of the simulation program. Some special cases related to HVAC systems need to be considered:

1. **Complete existing HVAC system:** An example might be an existing speculative building that is being built for a tenant. The subject of the building permit is primarily the interior construction and lighting system and does not include the HVAC system because it had already been built and permitted. In a case like this, the design and budget energy cost models are based on the existing HVAC system. It would also include the existing building envelope, plus the new lighting system and any other new energy features.
2. **No existing heating system**: If no heating system exists, a default heating system must be assumed and modeled. It should be a simple, fossil-fueled heating system with sufficient capacity to meet the design heating loads for the building.
3. **No existing cooling system**: If no cooling system exists, a default cooling system must be assumed and modeled. It should consist of one air-cooled singlezone system for each thermal block (a thermal block is a collection of one or more HVAC zones grouped together for simulation purposes and need not be contiguous)

An HVAC zone is physically determined by the design of the HVAC system. It includes some number of thermodynamically similar spaces whose loads can be satisfied through use of a single thermostat. The duct outlets or other terminal units controlled by a single thermostat serve the zone. Thermal zoning requires engineering judgment to avoid modeling error and to ensure that it can be reasonably determined. For example, the interior spaces of a multi-story building may be physically separate spaces on each floor, but they may often be reasonably combined into a single thermal zone in the simulation model of the building because they have similar loads and are served by similar systems. However, a cafeteria or computer room in an office building would need to be modeled separately, as would lowerfloor retail uses. The basic rule is that thermal zone must be defined identically for the standard building design and the proposed design. Zones may be combined, or multipliers may be used, if all the following conditions are met:

• All of the space use classifications must be the same throughout the thermal zone. This ensures that they have the same load and schedule characteristics.

• For exterior HVAC zones with glazing, the glazing for each zone must have the same orientation, or their orientations must be within 45 degrees of each other. This ensures that they have the same solar heat gain characteristics. This is not to say that zones may not have two or more glazing orientations (a corner office could easily have two), but that zones must have similar orientations. It would be acceptable, for example, to group all of the northeast corner offices on the intermediate floors of an office tower into a single thermal block. • All of the HVAC zones must be served either by the same HVAC system or by the same kind of HVAC system. The configuration of the thermal zones must be assumed if the HVAC system is not designed at the time of simulation modeling. This situation is quite common in commercial buildings where the future tenants will determine the zoning of spaces in the building. Things to consider are:

• Separate interior and perimeter spaces: If the HVAC zones are not yet designed, the space should be divided into two kinds of thermal zones: perimeter zones for interior spaces located within 15 feet of the external wall, and core zones for spaces located more than 15 feet from the external wall.

• Separate orientations with glazing: Glazed exterior walls should be assigned to a different perimeter thermal zone for each major orientation. Orientations within 45 degrees of each other may be combined.

• Separate top, bottom, and middle floors: Spaces exposed to ambient conditions, such as the top floor or an overhanging floor, and spaces in contact with the ground, such as the ground floor, must be zoned separately from zones that are not exposed to ambient conditions, such as an intermediate (typical) floor in a multi-story building.

## Computing energy required for heating and cooling needs through open source modelling

As the name implies, heating load calculations are carried out to estimate the heat loss from the building in winter so as to arrive at required heating capacities. Normally during winter months the peak heating load occurs before sunrise and the outdoor conditions do not vary significantly throughout the winter season. In addition, internal heat sources such as occupants or appliances are beneficial as they compensate some of the heat losses. As a result, normally, the heat load calculations are carried out assuming steady state conditions (no solar radiation and steady outdoor conditions) and neglecting internal heat sources. This is a simple but conservative approach that leads to slight overestimation of the heating capacity. For more accurate estimation of heating loads, one has to take into the thermal capacity of the walls and internal heat sources, which makes the problem more complicated.

For estimating cooling loads, one has to consider the unsteady state processes, as the peak cooling load occurs during the day time and the outside conditions also vary significantly throughout the day due to solar radiation. In addition, all internal sources add on to the cooling loads and neglecting them would lead to underestimation of the required cooling capacity and the possibility of not being able to maintain the required indoor conditions. Thus cooling load calculations are inherently more complicated as it involves solving unsteady equations with unsteady boundary conditions and internal heat sources.

For any building there exists a balance point at which the solar radiation (Qsolar) and internal heat generation rate (Qint) exactly balance the heat losses from the building. Thus from sensible heat balance equation, at balanced condition:

$$(Q_{solar} + Q_{int})_{sensible} = UA(T_{in} - T_{out})$$

where UA is the product of overall heat transfer coefficient and heat transfer area of the building, Tin is the required indoor temperature and Tout is the outdoor temperature. From the above equation, the outside temperature at balanced condition (Tout,bal) is given by:

$$T_{out,bal} = T_{in} - \frac{(Q_{solar} + Q_{int})_{sensible}}{UA}$$

If the outdoor temperature is greater than the balanced outdoor temperature given by the above equation, i.e., when Tout > Tout,bal, then there is a need for cooling the building. On the other hand, when the outdoor temperature is less than the balanced outdoor temperature, i.e., when Tout < Tout,bal, then there is a need for heating the building. When the outdoor temperature exactly equals the balanced outdoor temperature, i.e., when Tout = Tout,bal, then there is no need for either cooling or heating the building.

For residential buildings (with fewer internal heat sources), the balanced outdoor temperature may vary from 10 to 18o C. As discussed before, this means that if the balanced outdoor temperature is 18o C, then a cooling system is required when the outdoor temperature exceeds 18o C. This implies that buildings need cooling not only during summer but also during spring and fall as well. If the building is well insulated (small UA) and/or internal loads are high, then from the energy balance equation (35.2), the balanced outdoor temperature will reduce leading to extended cooling season and shortened heating season. Thus a smaller balanced outdoor temperature implies higher cooling requirements and smaller heating requirements, and vice versa. For commercial buildings with large internal loads and relatively smaller heat transfer areas, the balanced outdoor temperature can be as low as 2o C, implying a lengthy cooling season and a small heating season. If there are no internal heat sources and if the solar radiation is negligible, then from the heat balance equation, Tout,bal = Tin, this implies that if the outside temperature exceeds the required inside temperature (say, 25o C for comfort) then there is a need for cooling otherwise there is a need for heating. Thus depending upon the specific conditions of the building, the need for either cooling system or a heating system depends. This also implies a need for optimizing the building insulation depending upon outdoor conditions and building heat generation so that one can use during certain periods free cooling provided by the environment without using any external cooling system

**Methods of estimating cooling and heating loads**

Generally, heating and cooling load calculations involve a systematic, stepwise procedure, using which one can arrive at the required system capacity by taking into account all the building energy flows. In practice, a variety of methods ranging from simple rules-of-thumb to complex Transfer Function Methods are used in practice to arrive at the building loads. For example, typical rules-of-thumb methods for cooling loads specify the required cooling capacity based on the floor area or occupancy. Table below (Required cooling capacities for various applications based on rules-ofthumb (Croome and Roberts, 1981) shows typical data on required cooling capacities based on the floor area or application. Such rules-of-thumb are useful in preliminary estimation of the equipment size and cost. The main conceptual drawback of rules of-thumb methods is the presumption that the building design will not make any difference. Thus the rules for a badly designed building are typically the same as for a good design.

| Sl.no | Application | Required cooling capacity (TR) for 1000 $ft^2$ of floor area |
|---|---|---|
| 1. | Office buildings:<br>External zones<br><br>Internal zones | 25% glass: 3.5 TR<br>50% glass: 4.5 TR<br>75% glass: 5.0 TR<br>2.8 TR |
| 2. | Computer rooms | 6.0 – 12.0 TR |
| 3. | Hotels<br>Bedrooms<br><br>Restaurants | Single room: 0.6 TR per room<br>Double room: 1.0 TR per room<br>5.0 - 9.0 TR |
| 4. | Department stores<br>Basement & ground floors<br>Upper floors | 4.5 – 5.0 TR<br>3.5 – 4.5 TR |
| 5. | Shops | 5.0 TR |
| 6. | Banks | 4.5 – 5.5 TR |
| 7. | Theatres & Auditoriums | 0.07 TR per seat |

*Table 3 Building typology application and required cooling capacity summed up*

More accurate load estimation methods involve a combination of analytical methods and empirical results obtained from actual data, for example the use of Cooling Load Temperature Difference (CLTD) for estimating fabric heat gain and the use of Solar Heat Gain Factor (SHGF) for estimating heat transfer through fenestration. These methods are very widely used by air conditioning engineers as they yield reasonably accurate results and estimations can be carried out manually in a relatively short time. Over the years, more accurate methods that require the use of computers have been developed for estimating cooling loads, e.g. the Transfer Function Method (TFM). Since these methods are expensive and time consuming they are generally used for estimating cooling loads of large commercial or institutional buildings. ASHRAE suggests different methods for estimating cooling and heating loads based on applications, such as for residences, for commercial buildings etc.

## Cooling load calculations

As mentioned before, load calculations involve a systematic and stepwise procedure that takes into account all the relevant building energy flows. The cooling load experienced by a building varies in magnitude from zero (no cooling required) to a maximum value. The design cooling load is a load near the maximum magnitude, but is not normally the maximum. Design cooling load takes into account all the loads experienced by a building under a specific set of assumed conditions.

The assumptions behind design cooling load are as follows:

1. Design outside conditions are selected from a long-term statistical database. The conditions will not necessarily represent any actual year, but are representative of the location of the building. Design data for outside conditions for various locations of the world have been collected and are available in tabular form in various handbooks.

2. The load on the building due to solar radiation is estimated for clear sky conditions.

3. The building occupancy is assumed to be at full design capacity.

4. All building equipment and appliances are considered to be operating at a reasonably representative capacity.

The total building cooling load consists of heat transferred through the building envelope (walls, roof, floor, windows, doors etc.) and heat generated by occupants, equipment, and lights. The load due to heat transfer through the envelope is called as external load, while all other loads are called as internal loads. The percentage of external versus internal load varies with building type, site climate, and building design. The total cooling load on any building consists of both sensible as well as latent load components. The sensible load affects dry bulb temperature, while the latent load affects the moisture content of the conditioned space.

Buildings may be classified as externally loaded and internally loaded. In externally loaded buildings the cooling load on the building is mainly due to heat transfer between the surroundings and the internal conditioned space. Since the surrounding conditions are highly variable in any given day, the cooling load of an externally loaded building varies widely. In internally loaded buildings the cooling load is mainly due to internal heat generating sources such as occupants or appliances or processes. In general the heat generation due to internal heat sources may remain fairly constant, and since the heat transfer from the variable surroundings is much less compared to the internal heat sources, the cooling load of an internally loaded building remains fairly constant. Obviously from energy efficiency and economics points of view, the system design strategy for an externally loaded building should be different from an internally loaded building. Hence, prior knowledge of whether the building is externally loaded or internally loaded is essential for effective system design.

As mentioned before, the total cooling load on a building consists of external as well as internal loads. The external loads consist of heat transfer by conduction through the building walls, roof, floor, doors etc, heat transfer by radiation through fenestration such as windows and skylights. All these are sensible heat transfers. In addition to these the external load also consists of heat transfer due to infiltration, which consists of both sensible as well as latent components. The heat transfer due to ventilation is not a load on the building but a load on the system. The various internal loads consist of sensible and latent heat transfer due to occupants, products, processes and appliances, sensible heat transfer due to lighting and other equipment. Figure below shows various components that constitute the cooling load on a building.

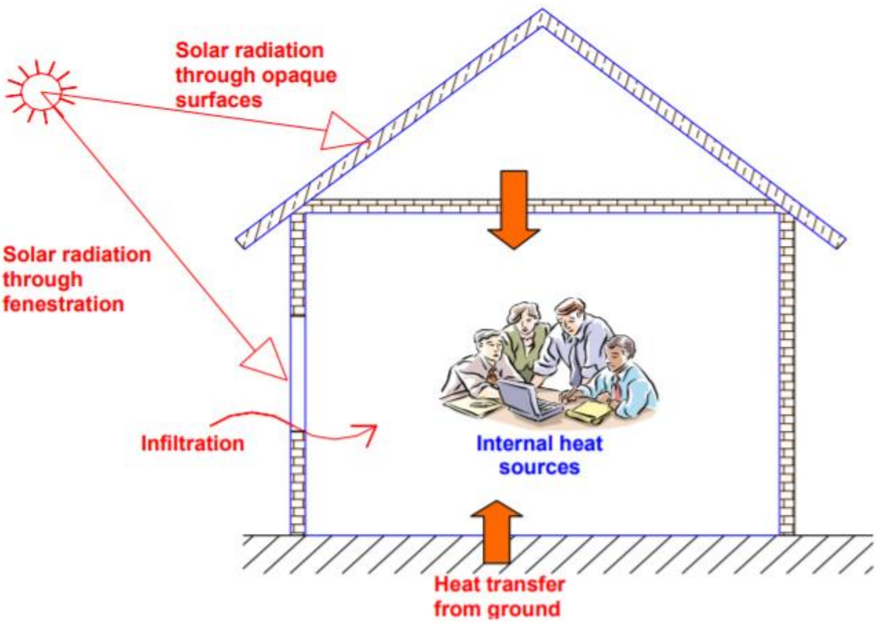



*Figure 23 various components that constitute the cooling load on a building.*

Estimation of cooling load involves estimation of each of the above components from the given data. In the present chapter, the cooling load calculations are carried out based on the CLTD/CLF method suggested by ASHRAE. For more advanced methods such as TFM, the reader should refer to ASHRAE and other handbooks.

**1. Estimation of external loads:**

a) **Heat transfer through opaque surfaces:** This is a sensible heat transfer process. The heat transfer rate through opaque surfaces such as walls, roof, floor, doors etc. is given by:

$$Q_{opaque} = U.A.CLTD$$

where U is the overall heat transfer coefficient and A is the heat transfer area of the surface on the side of the conditioned space. CLTD is the cooling load temperature difference.

**For sunlit surfaces,** CLTD has to be obtained from the CLTD tables as discussed in the previous chapter. Adjustment to the values obtained from the table is needed if actual conditions are different from those based on which the CLTD tables are prepared.

**For surfaces which are not sunlit** or which have negligible thermal mass (such as doors), the CLTD value is simply equal to the temperature difference across the wall or roof. For example, for external doors the CLTD value is simply equal to the difference between the design outdoor and indoor dry bulb temperatures, Tout-Tin.

**For interior air conditioned rooms** surrounded by non-air conditioned spaces, the CLTD of the interior walls is equal to the temperature difference between the surrounding non-air conditioned space and the conditioned space. Obviously, if an air conditioned room is surrounded by other air conditioned rooms, with all of them at the same temperature, the CLTD values of the walls of the interior room will be zero.

**Estimation of CLTD values of floor and roof** with false ceiling could be tricky. For floors standing on ground, one has to use the temperature of the ground for estimating CLTD. However, the ground temperature depends on the location and varies with time. ASHRAE suggests suitable temperature difference values for estimating heat transfer through ground. If the floor stands on a basement or on the roof of another room, then the CLTD values for the floor are the temperature difference across the floor (i.e., difference between the temperature of the basement or room below and the conditioned space). This discussion also holds good for roofs which have non-air conditioned rooms above them. For sunlit roofs with false ceiling, the U value may be obtained by assuming the false ceiling to be an air space. However, the CLTD values obtained from the tables may not exactly fit the specific roof. Then one has to use his judgement and select suitable CLTD values.

a. **Heat transfer through fenestration:**

Heat transfer through transparent surface such as a window, includes heat transfer by conduction due to temperature difference across the window and heat transfer due to solar radiation through the window. The heat transfer through the window by convection is calculated using Eq.(35.3), with CLTD being equal to the temperature difference across the window and A equal to the total area of the window. The heat transfer due to solar radiation through the window is given by:

$$Q_{trans} = A_{unshaded}.SHGF_{max}.SC.CLF$$

where Aunshaded is the area exposed to solar radiation, SHGFmax and SC are the maximum Solar Heat Gain Factor and Shading Coefficient, respectively, and CLF is the Cooling Load Factor. As discussed in a previous chapter, the unshaded area has to be obtained from the dimensions of the external shade and solar geometry. SHGFmax and SC are obtained from ASHRAE tables based on the orientation of the window, location, month of the year and the type of glass and internal shading device.

The Cooling Load Factor (CLF) accounts for the fact that all the radiant energy that enters the conditioned space at a particular time does not become a part of the cooling load instantly. As solar radiation enters the conditioned space, only a negligible portion of it is absorbed by the air particles in t he conditioned space instantaneously leading to a minute change in its temperature. Most of the radiation is first absorbed by the internal surfaces, which include ceiling, floor, internal walls, furniture etc. Due to the large but finite thermal capacity of the roof, floor, walls etc., their temperature increases slowly due to absorption of solar radiation.

As the surface temperature increases, heat transfer takes place between these surfaces and the air in the conditioned space. Depending upon the thermal capacity of the wall and the outside temperature, some of the absorbed energy due to solar radiation may be conducted to the outer surface and may be lost to the outdoors. Only that fraction of the solar radiation that is transferred to the air in the conditioned space becomes a load on the building, the heat transferred to the outside is not a part of the cooling load. Thus it can be seen that the radiation heat transfer introduces a time lag and also a decrement factor depending upon the dynamic characteristics of the surfaces. Due to the time lag, the effect of radiation will be felt even when the source of radiation, in this case the sun is removed. The CLF values for various surfaces have been calculated as functions of solar time and orientation and are available in the form of tables in ASHRAE Handbooks. Table below gives typical CLF values for glass with interior shading.

| Solar Time, h | Direction the sunlit window is facing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | NE | E | SE | S | SW | W | NW | Horiz. |
| 6 | 0.73 | 0.56 | 0.47 | 0.30 | 0.09 | 0.07 | 0.06 | 0.07 | 0.12 |
| 7 | 0.66 | 0.76 | 0.72 | 0.57 | 0.16 | 0.11 | 0.09 | 0.11 | 0.27 |
| 8 | 0.65 | 0.74 | 0.80 | 0.74 | 0.23 | 0.14 | 0.11 | 0.14 | 0.44 |
| 9 | 0.73 | 0.58 | 0.76 | 0.81 | 0.38 | 0.16 | 0.13 | 0.17 | 0.59 |
| 10 | 0.80 | 0.37 | 0.62 | 0.79 | 0.58 | 0.19 | 0.15 | 0.19 | 0.72 |
| 11 | 0.86 | 0.29 | 0.41 | 0.68 | 0.75 | 0.22 | 0.16 | 0.20 | 0.81 |
| 12 | 0.89 | 0.27 | 0.27 | 0.49 | 0.83 | 0.38 | 0.17 | 0.21 | 0.85 |
| 13 | 0.89 | 0.26 | 0.26 | 0.33 | 0.80 | 0.59 | 0.31 | 0.22 | 0.85 |
| 14 | 0.86 | 0.24 | 0.24 | 0.28 | 0.68 | 0.75 | 0.53 | 0.30 | 0.81 |
| 15 | 0.82 | 0.22 | 0.22 | 0.25 | 0.50 | 0.83 | 0.72 | 0.52 | 0.71 |
| 16 | 0.75 | 0.20 | 0.20 | 0.22 | 0.35 | 0.81 | 0.82 | 0.73 | 0.58 |
| 17 | 0.78 | 0.16 | 0.16 | 0.18 | 0.27 | 0.69 | 0.81 | 0.82 | 0.42 |
| 18 | 0.91 | 0.12 | 0.12 | 0.13 | 0.19 | 0.45 | 0.61 | 0.69 | 0.25 |

*Table 4 Typical CLF values for glass with interior shading*

b. **Heat transfer due to infiltration:**

Heat transfer due to infiltration consists of both sensible as well as latent components. The sensible heat transfer rate due to infiltration is given by:

$$Q_{s,inf} = \dot{m}_o \, c_{p,m}(T_o - T_i) = \dot{V}_o \, \rho_o c_{p,m}(T_o - T_i)$$

where o is the infiltration rate ( in m . V 3 /s), ρo and cp,m are the density and specific heat of the moist, infiltrated air, respectively. To and Ti are the outdoor and indoor dry bulb temperatures. The latent heat transfer rate due to infiltration is given by:

$$Q_{l,inf} = \dot{m}_o \, h_{fg}(W_o - W_i) = \dot{V}_o \, \rho_o h_{fg}(W_o - W_i)$$

where hfg is the latent heat of vaporization of water, Wo and Wi are the outdoor and indoor humidity ratio, respectively.

As discussed in an earlier chapter, the infiltration rate depends upon several factors such as the tightness of the building that includes the walls, windows, doors etc and the prevailing wind speed and direction. As mentioned before, the infiltration rate is obtained by using either the air change method or the crack method. The infiltration rate by air change method is given by:

$$\dot{V}_o = (ACH).V / 3600 \quad m^3/s$$

where ACH is the number of air changes per hour and V is the gross volume of the conditioned space in m3 . Normally the ACH value varies from 0.5 ACH for tight and well-sealed buildings to about 2.0 for loose and poorly sealed buildings. For modern buildings the ACH value may be as low as 0.2 ACH. Thus depending upon the age and condition of the building an appropriate ACH value has to be chose, using which the infiltration rate can be calculated. The infiltration rate by the crack method is given by:

$$\dot{V}_o = A.C.\Delta P^n \quad m^3/s$$

where A is the effective leakage area of the cracks, C is a flow coefficient which depends on the type of the crack and the nature of the flow in the crack, ΔP is the difference between outside and inside pressure (Po-Pi) and n is an exponent whose value depends on the nature of the flow in the crack. The value of n varies between 0.4 to 1.0, i.e., 0.4 ≤ n ≤ 1.0. The pressure difference ΔP arises due to pressure difference due to the wind (ΔPwind), pressure difference due to the stack effect (ΔPstack) and pressure difference due to building pressurization (ΔPbld), i.e.,

$$\Delta P = \Delta P_{wind} + \Delta P_{stack} + \Delta P_{bld}$$

Semi-empirical expressions have been obtained for evaluating pressure difference due to wind and stack effects as functions of prevailing wind velocity and direction, inside and outside temperatures, building dimensions and geometry etc. Representative values of infiltration rate for different types of windows, doors walls etc. have been measured and are available in tabular form in air conditioning design handbooks.

c. **Miscellaneous external loads**

In addition to the above loads, if the cooling coil has a positive by-pass factor (BPF > 0), then some amount of ventilation air directly enters the conditioned space, in which case it becomes a part of the building cooling load. The sensible and latent heat transfer rates due to the by-passed ventilation air can be calculated using equations

$$Q_{s,inf} = \dot{m}_o\, c_{p,m}(T_o - T_i) = \dot{V}_o\, \rho_o c_{p,m}(T_o - T_i)$$

And

$$Q_{l,inf} = \dot{m}_o\, h_{fg}(W_o - W_i) = \dot{V}_o\, \rho_o h_{fg}(W_o - W_i)$$

by replacing Vo with V vent. BPF , where Vvent is the ventilation rate and BPF is the by-pass factor of the cooling coil. o . V vent BPF.V. vent . V In addition to this, sensible and latent heat transfer to the building also occurs due to heat transfer and air leakage in the supply ducts. A safety factor is usually provided to account for this depending upon the specific details of the supply air ducts. If the supply duct consists of supply air fan with motor, then power input to the fan becomes a part of the external sensible load on the building. If the duct consists of the electric motor, which drives the fan, then the efficiency of the fan motor also must be taken into account while calculating the cooling load. Most of the times, the power input to the fan is not known a priori as the amount of supply air required is not known at this stage. To take this factor into account, initially it is assumed that the supply fan adds about 5% of the room sensible cooling load and cooling loads are then estimated. Then this value is corrected in the end when the actual fan selection is done.

**2.Estimation of internal loads:**

The internal loads consist of load due to occupants, due to lighting, due to equipment and appliances and due to products stored or processes being performed in the conditioned space.

**a) Load due to occupants:** The internal cooling load due to occupants consists of both sensible and latent heat components. The rate at which the sensible and latent heat transfer take place depends mainly on the population and activity level of the occupants. Since a portion of the heat transferred by the occupants is in the form of radiation, a Cooling Load Factor (CLF) should be used similar to that used for radiation heat transfer through fenestration. Thus the sensible heat transfer to the conditioned space due to the occupants is given by the equation:

$$Q_{s,\,occupants} = (\text{No. of people}).(\text{Sensible heat gain / person}).CLF$$

Table below shows typical values of total heat gain from the occupants and also the sensible heat gain fraction as a function of activity in an air conditioned space. However, it should be noted that the fraction of the total heat gain that is sensible depends on the conditions of the indoor environment. If the conditioned space temperature is higher, then the fraction of total heat gain that is sensible decreases and the latent heat gain increases, and vice versa.

| Activity | Total heat gain, W | Sensible heat gain fraction |
|---|---|---|
| Sleeping | 70 | 0.75 |
| Seated, quiet | 100 | 0.60 |
| Standing | 150 | 0.50 |
| Walking @ 3.5 kmph | 305 | 0.35 |
| Office work | 150 | 0.55 |
| Teaching | 175 | 0.50 |
| Industrial work | 300 to 600 | 0.35 |

*Table 5 Heat gain due to various metabolic activites*

The value of Cooling Load Factor (CLF) for occupants depends on the hours after the entry of the occupants into the conditioned space, the total hours spent in the conditioned space and type of the building. Values of CLF have been obtained for different types of buildings and have been tabulated in ASHRAE handbooks. Since the latent heat gain from the occupants is instantaneous the CLF for latent heat gain is 1.0, thus the latent heat gain due to occupants is given by:

$$Q_{l,occupants} = (\text{No. of people}).(\text{Latent heat gain / person})$$

b) **Load due to lighting:** Lighting adds sensible heat to the conditioned space. Since the heat transferred from the lighting system consists of both radiation and convection, a Cooling Load Factor is used to account for the time lag. Thus the cooling load due to lighting system is given by:

$$Q_{s,lighting} = (\text{Installed wattage})(\text{Usage Factor})(\text{Ballast factor})CLF$$

The usage factor accounts for any lamps that are installed but are not switched on at the time at which load calculations are performed. The ballast factor takes into account the load imposed by ballasts used in fluorescent lights. A typical ballast factor value of 1.25 is taken for fluorescent lights, while it is equal to 1.0 for incandescent lamps. The values of CLF as a function of the number of hours after the lights are turned on, type of lighting fixtures and the hours of operation of the lights are available in the form of tables in ASHRAE handbooks.

c) **Internal loads due to equipment and appliances:** The equipment and appliances used in the conditioned space may add both sensible as well as latent loads to the conditioned space. Again, the sensible load may be in the form of radiation and/or convection. Thus the internal sensible load due to equipment and appliances is given by:

$$Q_{s,appliances} = (\text{Installed wattage}).(\text{Usage Factor}).CLF$$

The installed wattage and usage factor depend on the type of the appliance or equipment. The CLF values are available in the form of tables in ASHARE handbooks. The latent load due to appliances is given by:

$$Q_{l,appliance} = (\text{Installed wattage}).(\text{Latent heat fraction})$$

Table below shows typical load of various types of appliances.

| Appliance | Sensible load, W | Latent load, W | Total load, W |
|---|---|---|---|
| Coffee brewer, 0.5 gallons | 265 | 65 | 330 |
| Coffee warmer, 0.5 gallons | 71 | 27 | 98 |
| Toaster, 360 slices/h | 1500 | 382 | 1882 |
| Food warmer/$m^2$ plate area | 1150 | 1150 | 2300 |

*Table 6 Loads due to various electrical appliances*

For other equipment such as computers, printers etc, the load is in the form of sensible heat transfer and is estimated based on the rated power consumption. The CLF value for these equipment may be taken as 1.0 as the radiative heat transfer from these equipment is generally negligible due to smaller operating temperatures. When the equipment are run by electric motors which are also kept inside the conditioned space, then the efficiency of the electric motor must be taken into account. Though the estimation of cooling load due to appliance and equipment appears to be simple as given by the equations, a large amount of uncertainty is introduced on account of the usage factor and the difference between rated (nameplate) power consumption at full loads and actual power consumption at part loads. Estimation using nameplate power input may lead to overestimation of the loads, if the equipment operates at part load conditions most of the time.

If the conditioned space is used for storing products (e.g. cold storage) or for carrying out certain processes, then the sensible and latent heat released by these specific products and or the processes must be added to the internal cooling loads. The sensible and latent heat release rate of a wide variety of live and dead products commonly stored in cold storages are available in air conditioning and refrigeration handbooks. Using these tables, one can estimate the required cooling capacity of cold storages. Thus using the above equations one can estimate the sensible (Qs,r), latent (Ql,r) and total cooling load (Qt,r) on the buildings. Since the load due to sunlit surfaces varies as a function of solar time, it is preferable to calculate the cooling loads at different solar times and choose the maximum load for estimating the system capacity. From the sensible and total cooling loads one can calculate the Room Sensible Heat Factor (RSHF) for the building. As discussed in an earlier chapter, from the RSHF value and the required indoor conditions one can draw the RSHF line on the psychrometric chart and fix the condition of the supply air.

**Solved example of a calculation**

**10.** An air conditioned room that stands on a well ventilated basement measures 3 m wide, 3 m high and 6 m deep. One of the two 3 m walls faces west and contains a double glazed glass window of size 1.5 m by 1.5 m, mounted flush with the wall with no external shading. There are no heat gains through the walls other than the one facing west. Calculate the sensible, latent and total heat gains on the room, room sensible heat factor from the following information. What is the required cooling capacity?

| | | |
|---|---|---|
| Inside conditions | : | 25°C dry bulb, 50 percent RH |
| Outside conditions | : | 43°C dry bulb, 24°C wet bulb |
| U-value for wall | : | 1.78 W/m$^2$.K |
| U-value for roof | : | 1.316 W/m$^2$.K |
| U-value for floor | : | 1.2 W/m$^2$.K |
| Effective Temp. Difference (ETD) for wall: | | 25°C |
| Effective Temp. Difference (ETD) for roof: | | 30°C |
| U-value for glass | ; | 3.12 W/m$^2$.K |
| Solar Heat Gain (SHG) of glass | ; | 300 W/m$^2$ |
| Internal Shading Coefficient (SC) of glass: | | 0.86 |
| Occupancy | : | 4 (90 W sensible heat/person) (40 W latent heat/person) |
| Lighting load | : | 33 W/m$^2$ of floor area |

| | | |
|---|---|---|
| Appliance load | : | 600 W (Sensible) + 300 W(latent) |
| Infiltration | : | 0.5 Air Changes per Hour |
| Barometric pressure | : | 101 kPa |

**Ans.:** From psychrometric chart,

For the inside conditions of 25ºC dry bulb, 50 percent RH:

$$\mathbf{W_i = 9{,}9167 \times 10^{-3}\ kgw/kgda}$$

For the outside conditions of 43ºC dry bulb, 24ºC wet bulb:

$$\mathbf{W_o = 0.0107\ kgw/kgda,\ density\ of\ dry\ air = 1.095\ kg/m^3}$$

**External loads:**

a) Heat transfer rate through the walls: Since only west wall measuring 3m x 3m with a glass windows of 1.5m x 1.5m is exposed; the heat transfer rate through this wall is given by:

$$\mathbf{Q_{wall} = U_{wall}A_{wall}ETD_{wall} = 1.78 \times (9\text{-}2.25) \times 25 = 300.38\ W\ (Sensible)}$$

b) Heat transfer rate through roof:

$$\mathbf{Q_{roof} = U_{roof}A_{roof}ETD_{roof} = 1.316 \times 18 \times 30 = 710.6\ W\ (Sensible)}$$

c) Heat transfer rate through floor: Since the room stands on a well-ventilated basement, we can assume the conditions in the basement to be same as that of the outside (i.e., 43°C dry bulb and 24°C wet bulb), since the floor is not exposed to solar radiation, the driving temperature difference for the roof is the temperature difference between the outdoor and indoor, hence:

$$\mathbf{Q_{floor} = U_{floor}A_{floor}ETD_{floor} = 1.2 \times 18 \times 18 = 388.8\ W\ (Sensible)}$$

d) Heat transfer rate through glass: This consists of the radiative as well as conductive components. Since no information is available on the value of CLF, it is taken as 1.0. Hence the total heat transfer rate through the glass window is given by:

$$\mathbf{Q_{glass} = A_{glass}\,[U_{glass}(T_o - T_i) + SHGF_{max}SC] = 2.25[3.12 \times 18 + 300 \times 0.86] = 706.9\ W\ (Sensible)}$$

e) Heat transfer due to infiltration: The infiltration rate is 0.5 ACH, converting this into mass flow rate, the infiltration rate in kg/s is given by:

$m_{inf}$ = density of air x (ACH x volume of the room)/3600 = 1.095 x (0.5 x 3x3x6)/3600

$$\mathbf{m_{inf} = 8.2125 \times 10^{-3}\ kg/s}$$

Sensible heat transfer rate due to infiltration,$Q_{s,inf;}$

$$\mathbf{Q_{s,inf} = m_{inf}c_{pm}(T_o – T_i) = 8.2125 \times 10^{-3} \times 1021.6 \times (43 – 25) = 151\ W\ (Sensible)}$$

Latent heat transfer rate due to infiltration, $Q_{l,inf}$:

$$\mathbf{Q_{l,inf} = m_{inf}h_{fg}(W_o – W_i) = 8.8125 \times 10^{-3} \times 2501 \times 10^{3}(0.0107 – 0.0099) = 16.4\ W\ (sensible)}$$

**Internal loads:**

a) Load due to occupants: The sensible and latent load due to occupants are:

$$\mathbf{Q_{s,occ} = no.of\ occupants \times SHG = 4 \times 90 = 360\ W}$$

$$\mathbf{Q_{l,occ} = no.of\ occupants \times LHG = 4 \times 40 = 160\ W}$$

b) Load due to lighting: Assuming a CLF value of 1.0, the load due to lighting is:

$$\mathbf{Q_{lights} = 33 \times floor\ area = 33 \times 18 = 594\ W\ (Sensible)}$$

c) Load due to appliance:

$$\mathbf{Q_{s,app} = 600\ W\ (Sensible)}$$

$$\mathbf{Q_{l,app} = 300\ W\ (Latent)}$$

Total sensible and latent loads are obtained by summing-up all the sensible and latent load components (both external as well as internal) as:

$$\mathbf{Q_{s,total} = 300.38+710.6+388.8+706.9+151+360+594+600 = 3811.68\ W} \qquad \textbf{(Ans.)}$$

$$\mathbf{Q_{l,total} = 16.4+160+300 = 476.4\ W} \qquad \textbf{(Ans.)}$$

Total load on the building is:

$$\mathbf{Q_{total} = Q_{s,total} + Q_{l,total} = 3811.68 + 476.4 = 4288.08\ W} \qquad \textbf{(Ans.)}$$

Room Sensible Heat Factor (RSHF) is given by:

$$\mathbf{RSHF = Q_{s,total}/Q_{total} = 3811.68/4288.08 = 0.889} \qquad \textbf{(Ans.)}$$

To calculate the required cooling capacity, one has to know the losses in return air ducts. Ventilation may be neglected as the infiltration can take care of the small ventilation requirement. Hence using a safety factor of 1.25, the required cooling capacity is:

**Required cooling capacity = 4288.08 x 1.25 = 5360.1 W ≈ 1.5 TR** **(Ans.)**

**REFERENCES**


1. https://old.amu.ac.in/emp/studym/6310.pdf
2. https://www.cedengineering.com/userfiles/Cooling%20Load%20Calculations%20and%20Principles%20R1.pdf
3. https://www.slideshare.net/spsu/12-cooling-load-calculations

# UNIT – III – Daylighting and shading simulations

# Introduction

The use of sun control and shading devices is an important aspect of many energy-efficient building design strategies. In particular, buildings that employ passive solar heating or daylighting often depend on well-designed sun control and shading devices.

During cooling seasons, external window shading is an excellent way to prevent unwanted solar heat gain from entering a conditioned space. Shading can be provided by natural landscaping or by building elements such as awnings, overhangs, and trellises. Some shading devices can also function as reflectors, called light shelves, which bounce natural light for daylighting deep into building interiors.

The design of effective shading devices will depend on the solar orientation of a particular building facade. For example, simple fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high. However, the same horizontal device is ineffective at blocking low afternoon sun from entering west-facing windows during peak heat gain periods in the summer.

Exterior shading devices are particularly effective in conjunction with clear glass facades. However, high-performance glazings are now available that have very low shading coefficients (SC). When specified, these new glass products reduce the need for exterior shading devices.

Thus, solar control and shading can be provided by a wide range of building components including:

- Landscape features such as mature trees or hedge rows;
- Exterior elements such as overhangs or vertical fins;
- Horizontal reflecting surfaces called light shelves;
- Low shading coefficient (SC) glass; and,
- Interior glare control devices such as Venetian blinds or adjustable louvers.

*Figure 24 Aluminium architectural sun shade, horizontal sun control device, vertical fins*

Fixed exterior shading devices such as overhangs are generally most practical for small commercial buildings. The optimal length of an overhang depends on the size of the window and the relative importance of heating and cooling in the building.

In the summer, peak sun angles occur at the solstice on June 21, but peak temperature and humidity are more likely to occur in August. Remember that an overhang sized to fully shade a south-facing window in August will also shade the window in April when some solar heat may be desirable.

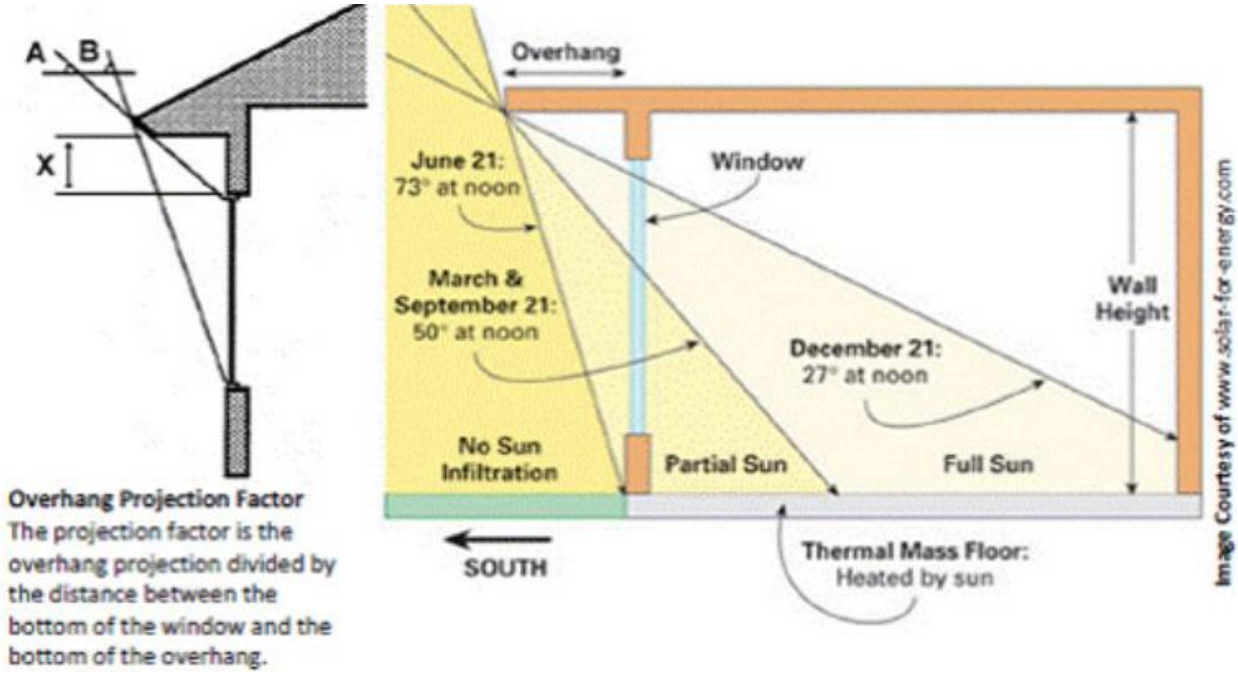



*Figure 25 Image depicting direct radiation penetration due to shading device and various solar angles*

To properly design shading devices it is necessary to understand the position of the sun in the sky during the cooling season. The position of the sun is expressed in terms of altitude and azimuth angles.

- The altitude angle is the angle of the sun above the horizon, achieving its maximum on a given day at solar noon.
- The azimuth angle, also known as the bearing angle, is the angle of the sun's projection onto the ground plane relative to south.

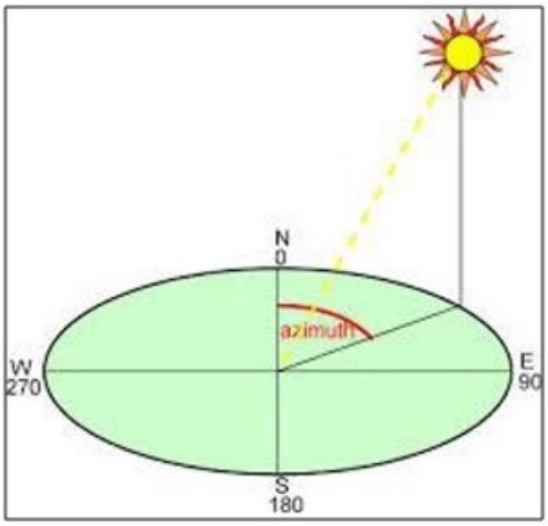



*Figure 26 Azimuth angle depiction*

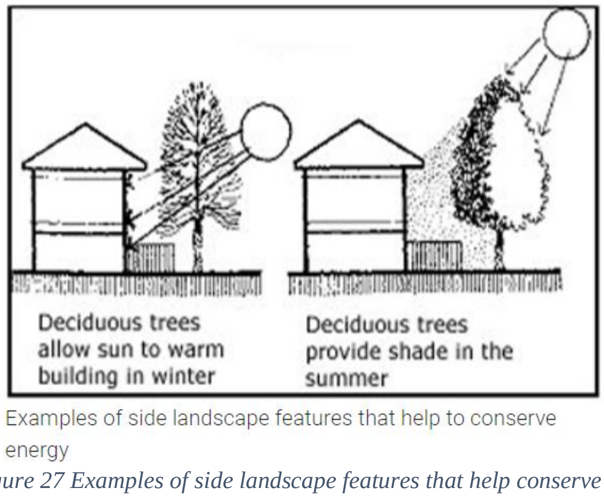
Shading devices can have a dramatic impact on building appearance. This impact can be for the better or for the worse. The earlier in the design process that shading devices are considered they more likely they are to be attractive and well-integrated in the overall architecture of a project.

## Principles of shading design

Given the wide variety of buildings and the range of climates in which they can be found, it is difficult to make sweeping generalizations about the design of shading devices. However, the following design recommendations generally hold true:

- Use fixed overhangs on south-facing glass to control direct beam solar radiation. Indirect (diffuse) radiation should be controlled by other measures, such as low-e glazing.
- To the greatest extent possible, limit the amount of east and west glass since it is harder to shade than south glass. Consider the use of landscaping to shade east and west exposures.
- Do not worry about shading north-facing glass in the continental United States latitudes since it receives very little direct solar gain. In the tropics, disregard this rule-of-thumb since the north side of a building will receive more direct solar gain. Also, in the tropics consider shading the roof even if there are no skylights since the roof is a major source of transmitted solar gain into the building.
- Remember that shading effects daylighting; consider both simultaneously. For example, a light shelf bounces natural light deeply into a room through high windows while shading lower windows.
- Do not expect interior shading devices such as Venetian blinds or vertical louvers to reduce cooling loads since the solar gain has already been admitted into the work space. However, these interior devices do offer glare control and can contribute to visual acuity and visual comfort in the work place.
- Study sun angles. An understanding of sun angles is critical to various aspects of design including determining basic building orientation, selecting shading devices, and placing Building Integrated Photovoltaic (BIPV) panels or solar collectors.
- Carefully consider the durability of shading devices. Over time, operable shading devices can require a considerable amount of maintenance and repair.
- When relying on landscape elements for shading, be sure to consider the cost of landscape maintenance and upkeep on life-cycle cost.

Shading strategies that work well at one latitude, may be completely inappropriate for other sites at different latitudes. Be careful when applying shading ideas from one project to another.




Examples of side landscape features that help to conserve energy

Curtain wall and a light shelf in a second-floor library space

*Figure 27 Examples of side landscape features that help conserve energy (left); Curtain wall and a light shelf in a second floor library space (right)*

## Tools for shading design and analysis

### Tools for Shading Analysis

Solar Pathfinder - The Solar Pathfinder has been the standard in the solar industry for solar site analysis for decades. Its panoramic reflection of the site instantly provides a full year of accurate solar/shade data, making it the instrument of choice.

**SunEye™ -** The Solmetric SunEye™ (discontinued) is a hand held electronic device that allows users to instantly assess total potential solar energy given the shading of a particular site. Identifying the shading pattern early in the process reduces the expense of system and home design and improves the efficiency of the final system or house.

**Steprobotics** - accurate solar shade analysis tool. The user attaches a special fish eye lens to the front camera of the phone and converts it into a solmetric sun eye.

**HORIcatcher -** HORIcatcher is an easy and fast tool to take outdoor pictures of the horizon. The pictures can be used to determine the solar energy input, sunshine duration and sun exposure reduced by obstacles like trees, houses or mountains. HORIcatcher is supplied with a digital camera.

**Pilkington Sun Angle Calculator -** This handy tool provides a relatively simple method of determining solar geometry variables for architectural design, such as designing shading devices or locating the position of the sun relative to a particular latitude and time.

**Sonnenbahn Indikator Pro -** is a simple tool for site evaluation

**Some shading software are as follows:**

**Autodesk ECOTECT Analysis** - is an industry leading building analysis program that allows designers to work easily in 3D and apply all the tools neccesary for an energy efficient and sustainable future.

**METEONORM -** Global Meteorological Database for Solar Energy and Applied Meteorology. METEONORM is a comprehensive climatological database for solar energy applications: a meteorological database containing comprehensive climatological data for solar engineering applications at all points of the globe between the polar circles; a computer program for climatological calculations; a data source for engineering design programs in the passive, active and photovoltaic application of solar energy with comprehensive data interfaces; a standardization tool permitting developers and users of engineering design programs access to a comprehensive, uniform data basis.

**Shadow Analyser -** Shadow Analyzer is an advanced parametric CAD tool for professionals in the area of Solar Energy Engineering and Architecture.

**Shadows -** Shadows is a program used to design sundials and astrolabes and it is very useful also in solar energy engineering. Supports plane sundials with polar style of any orientation and reclination, analemmatic sundials, cylindrical and bifilar sundials. Simulates, displays and animates the shadow of the style and offers complete ephemeris of the Sun and draws the Solar Diagram.

**pvPlanner -** Simulation tool for planning and optimisation of photovoltaic systems using climate and geographic data at high temporal and spatial resolution and new generation high performance algorithms.

**Amethyst ShadowFX** - Amethyst ShadowFX is a sun and shadow modeling program for architects and town planners. Amethyst ShadowFX enables you to easily generate shadow profiles cast by buildings and other objects for any latitude, longitude and time of year.

**Sombrero -** A PC-tool to calculate shadows on arbitrarily oriented surfaces. For both, active use of solar energy (domestic hot water, photovoitaics) as well as for passive solar architecture, shading or lighting of planes plays an important role Sombrero provides quantitative results for the shading of collectors or windows by buildings, trees, overhangs or he horizon.

**Panorama master -** with "Panorama master" you can make exact matched set of photos - base for panorama picture.

**Horizon -** software simulates sun path diagrams for arbitrary latitude.

**SAM (System Advisor Model).** This software is totally free and is one of the most powerful tools for any type of PV analysis. It includes a "shading losses" option that allows you to design a 3D layout in order to simulate shading. Having said this, the 3D design tool inside SAM is nowhere comparable to Sketchup and it can be really hard to model the obstacles. Ideally to want to obtain the shading losses by using other methods and input them into SAM for analysis.

**Scanifly.** Online tool based on drone images. If you have a drone that take geolocated images you can upload them to this platform and get a 3D model not only of the building, but also the obstacles around it, like trees, etc... After that you can automatically place your solar array and obtain a shade analysis that can be exported to other platforms. If you don't have a drone you could outsource it to them.

**Aurora Solar**. In the high-end of the online tools you will find Aurora Solar. This tool has everything you would need and more. When it comes to shadow analysis it provides LIDAR data that allows you to remotely get the dimension of objects like trees without on-site survey. For more precise calculations you can manually input the dimensions of obstacles. It will output a visually attractive energy report to share with your clients. If you can afford it, this would be the best tool you could get.

**Solar Pathfinder.** For more detailed calculations you would need an on-site shading measurement. Solar pathfinder is the traditional way to get a real and accurate report of the shading profile of the building. It includes the pathfinder itself, which is a semi-transparent dome that shows you the shading profile in that particular place. You could also use the software that let you process all that data called SP Assistant or extract the information yourself into an excel spreadsheet.

## Daylight simulation modelling

- **The Classic Design Process**
  First, the designer proposes an initial design which is evaluated in some manner to deter-mine it it meets the design requirements. Based on the results of the initial design evaluation,the designer either, accepts the design and the design process ends, or the initial design isupdated and re-evaluated iteratively until it is accepted. While the term “evaluation” isused, this is actually the same process ofmodeling/simulationpresented in chapter1.Inthe daylighting industry modeling/simulation techniques can be broadly grouped into three classes: physical-models, mathematical-models,and the previously undiscussed simplified techniques.

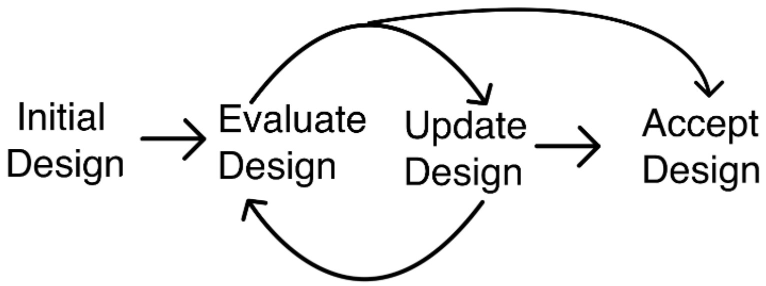



*Figure 28 Classic design cycle: A design is proposed, it is evaluated, the design is updated based on evaluation, then re-evaluated and re-updated until the design is deemed adequate and finally accepted*

- **Simplified Techniques** Simplified Techniques make various assumptions about the daylighting analysis both on the model and simulation side. These assumptions reduce accuracy, but make the analysis much more tractable. For example, a simplified method may assume uniform sky conditions (very rarely, if ever, realized in nature) or a fixed position for illumination analysis within a space. Based on so called, “rules-of-thumb” heuristics, these techniques don’t rely on first principles of daylight, but rather on experience gathered within the industry to predict the adequacy of a design. A limited number of examples are presented in the sections below. Window-Head-Height-Rule A classic example of a simplified daylighting analysis technique is the Window-Head-Height-Rule. This rule simply states the depth of daylight penetrating a side lit oce space with venetian blinds is approximately one to two times the window head height. Meaning, activities located within this region of the floor plan can effectively be regarded as occurring in a “day lit” space.

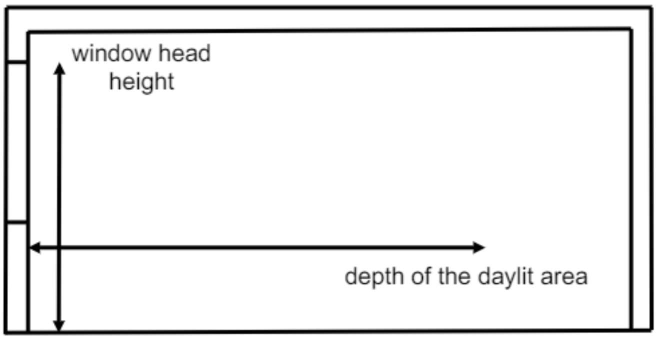



*Figure 29 Side lit office demonstrating the simplified daylight analysis technique, window-head-height rule*

**View of the Outdoor Percentage** This metric is defined as the percentage of an occupant’s view which is made up of glazing versus other building constructions (e.g. opaque envelope, partition walls) and contents (e.g.desks, people, equipment). That is, the number of steradians which can be defined as glazing divided by the total steradians of the human visual system, approximately. This gives an indication of the magnitude of impact daylight will have on an occupant with respect to views of the outside, a meaningful metric for today’s buildings. Further, it helps quantify the increasingly important consideration of circadian rhythm preservation which is dependent on exposure to sunlight. This metric has an optimal location, with no view and total view each being negative for occupants. The “best” value is often context dependent.

**Advantages and Disadvantages** Advantages of Simplified Techniques include simple and easy to apply calculations or heuristic evaluations which give a base insight into a proposed design’s behavior. Disadvantages include the major assumptions involved in these loose calculations and the associated inferences from reality in the results. Referring to Figure1.1, clearly Simplified

Techniques are in the lower left section of the plot, offering a very low cost investigation technique and a corresponding low realism return with respect to the actual system.

**Mathematical-Modeling/ Simulation**

Mathematical-models representing light are studied by the branch of physics known as optics. Optics has been the pursuit of some of the most famous scientific inquires of all time. Names including Newton, Maxwell, Plank, and Einstein are among the scientists who have explored this space and derived beautifully elegant models describing light's behavior in a myriad of different scenarios. Depending on the scope of explanation, mathematical-models for light can be broken down into three, successively more approximate classes: quantum optics, physical optics, and geometric optics.

Quantum optics uses mathematical principles including waves and particles from quantum mechanics to faithfully describe complicated light behaviors such as the photoelectric effect. It is a very faithful representation of light, however, comes at a high cost in terms of complexity and abstraction. This complexity is severely limiting for engineering applications, thus quantum optics mathematical-models are rarely used in engineering applications.

Physical optics, or wave optics, involves approximations in its mathematical models when compared to quantum optics. Still it captures interesting phenomena such as interference and diffraction by modeling light as waves. While an approximation itself, physical optics is still quite complicated in its application to real systems of engineering interest, thus too sees limited applications. Finally, geometric optics, or ray optics, makes the most approximations of all the mathematical models associated with light. Using rays,vectors representing EMR movement, and bidirectional reflection (mapping between incoming ray direction and outgo-ing ray reflection) and transmission properties (mapping between incoming ray direction and outgoing ray transmission) at a material surface, it captures the vast majority of observable phenomena in building lighting applications. This usage of far simpler mathematical mod-els, including the Law of Reflection and Law of Refraction, still, however, create non-trivial computational loads for building lighting applications. Yet these costs are at a reasonable level for engineering analysis and hence see usage.

While some simplified building daylighting scenarios (e.g. overcast sky illumination of a horizontal plane) can be evaluated using geometric optics via analytical solutions, these are exceedingly rare. The vast majority of daylighting designs must be modeled and simulated using numerical techniques as employed by digital computers. The actual implementation of these techniques in analysis tools is complex and has seen a long history of development, well characterized and recently reviewed. Currently, the computer program Radiance is by far the industry leading implementation of a geometric optics tool for daylighting analysis. Radiance uses a simple work flow illustrated in Figure below.

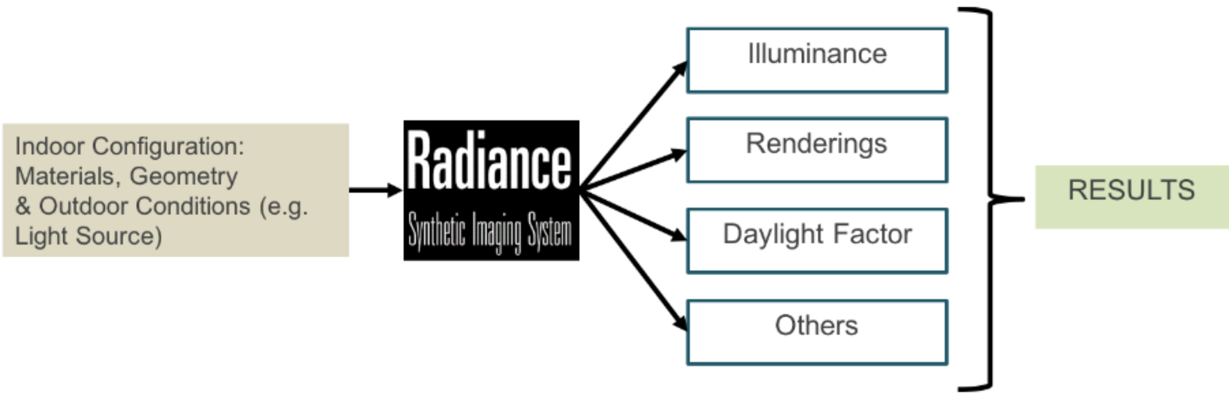



*Figure 30 Radiance work flow: Construct model including space geometry, material properties, and light sources; specify and execute analysis, evaluate resulats*

First, a model of a proposed lighting design is constructed comprising the space geometry, material properties, and light sources (i.e. daylighting and electric luminaires). Next, a specification and execution of the type of desired analysis is completed. For example, one may desire to calculate horizontal illuminance at the workplane height of80 cm at a vertically oriented grid of points, for a given sky condition. Finally, the results are interpreted to determine if the design is adequate for the purposes of the space. Note, the Illuminating Engineering Society of North America's (IESNA) Lighting Handbook has numerous metrics to evaluate lighting, many of which Radiance can calculate, as well as specifications of acceptable values regarding those metrics for various building types. Radiance uses the Central Radiance Equation (CRE) to model light's behaviour and a large collection of over 25 material properties models to capture light's interaction with surfaces. The CRE is solved recursively using a combined deterministic-stochastic algorithm with adjustable parameters based on the particular needs of an analysis. Radiance is an open source modelling/simulation framework originally developed at Lawrence Berkeley National Laboratory (LBNL) by Greg Ward in the late 1980's. While it sees continuous development, the core of the framework is relatively static. The book, "Rendering with Radiance", therefore is still a relavent reference for both learning how to use Radiance as well learning the details of the algorithmic solution it implements for the CRE. There also exist other ray based modeling /simulation tools available. Given the dynamic nature of this field, however, there has been some turnover with respect to which programs have seen continued support and development. As such, the United States chapter of the International Building Performance Simulation Association (IBPSA-USA) keeps a rolling registry of tools which can be explored [26]. It was formally maintained by the United States Department of Energy (US DOE) and as of this writing contained several hundred tools for building performance simulation of many different systems, with lighting a key contingent.

**Physical-Modeling/ Simulation**

As stated above, developing mathematical-models/simulation techniques that accurately describe light's behavior is a well established and challenging problem. As such, building physical models of proposed daylighting systems is still common practice. Daylight models are constructed at either full scale or reduced scale, and depending on the purpose of the model, will exhibit different properties.

**Full Scale**

Full scale daylighting tests are quite rare, even with the overall size of the daylighting community being quite large. This is a direct result of the extensive investments required to make such models, instrument them, and finally perform simulations to examine their response. An example of a facility capable of such full scale daylight testing is the FLEX LABat Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. This laboratory offers many cutting edge facilities such as side-by-side test bays, a rotating test bay capable of "following" the sun, as well as extensive collections of sensors and instruments to monitor experiments. Many experiments have been conducted in the laboratory, however, true to form, they are quite expensive and took a large effort to implement.

**Reduced Scale: Model Types**

Scale models for daylighting analysis come in many forms, with variations tailored to different types of analysis. In general, these analysis can be grouped into the classes of qualitative (i.e. understanding general behavior, yet not concerned with specific values) or quantitative (i.e. concerned with accurate phenomena valuations). Regardless of model type and analysis, a large body of best practices has been developed offering both practical and theoretical advice. A selected list of reduced scale daylighting models are presented below.

**Massing Model:** These models are simply shaped, opaque masses which are used to qualitatively study how light falls within a space. Generally, constructed of foam, cardboard,or even 3D printed, they are done on the building scale, when considering multiple buildings in close proximity where their shadows will interact. These models can be used on heliodons, outdoors, as well as in sky domes.

**Daylight Penetration:** Arguably the most complicated, these models aim to determine how much, and where, daylighting will fall within a floor plan or on the walls and ceiling of a proposed building. Both qualitative and quantitate variations exist, with the material properties and geometry of the model replicating that of the real system critical for the later. Even small deviations in reflective properties of the model versus system can have significant affects as multiple bounces of light compound the effect. Illuminance meters can be used with these models to predict actual indoor illuminance, however, errors must be accounted for in the results analysis.

**Shadow Analysis:** These are simple geometrically precise models which are put on heliodons in order to study how the direct beam radiation from the sun will interact with the building geometry. For these studies, the most important factor is to ensure no parasitic lightenters the model through transparent walls or other light leaks. One of the main advantages of this analysis is actually seeing unique light patterns present in the space. Erradicts, or random beams of light within a building only visible for certains periods of the year, are one daylighting feature which can be effectively studied with these models.

**Combinations:** Different model types can be used in conjunction. Take for example, using amassing model next to a daylight penetration model in order to represent an opaque building adjacent to a proposed building under analysis. The massing model will influence the daylighting penetration model significantly, however, doesn't need to have the corresponding level of detail. This model combination may be used in an overcast sky simulator or on a heliodon.

**Reduced Scale: Excitation Generators**

While various reduced scale model types exist for the study of daylighting, they typically need to be subjected to some lighting excitation in order to learn about their behavior. Several specialized instruments exist for scaled model daylighting simulations, a selection of which are listed below.

**Overcast Sky Simulator:** These instruments, also known as mirror boxes, have mirrored walls and an overhead source of light. The overhead light source is turned on, causing light to be reflected of the mirror walls, creating a "uniform" source of luminous excitation. The goal is to reproduce the CIE Uniform Sky [39] which is used to excite a scale model. An example of an Overcast Sky Simulator can be found at the University of California, Berkeley at the Center for the Built Environment (CBE) in the College of Environmental Design. Another exists at the University of Idaho. These tools typically are used with illuminance meters within the model and on top of the model to calculate the metric Daylight Factor(DF).

- **Sky Dome:** Also known as artificial skies, these instruments attempt to reproduce the entire non-uniform sky vault as closely as possible with respect to realistic luminous excitation sources. This is accomplished through the use of thousands of individually controlled lamps oriented in a hemisphere. Often realizing one of the 15 standard CIE Sky Models, these instruments too excite scale models, however, are significantly more expensive and specialized than Overcast Sky Simulators. Important considerations for sky domes are parallax error.. A well known example is the Sky Dome at Bartenbach LichtLabor, Innsbruck, Austria with adjustable brightness, color temperature, and light distribution.

- **Heliodon:** These instruments consists of an adjustable table surface, called the "table,"to which models are attached, and a collimated light beam produced to represent the Sun. The table can then be adjusted such that the collimated beam is in the same position as the Sun would be for any given day of the year and time of that day. This allows for mostly qualitative analysis of the direct beam component of the Sun and how it interacts with the building. Cameras can be used to capture the light distribution within a space, helping designers and owners visualize what the final building will look like at different times of the year. It should be noted, however, traditional heliodons only study direct beam radiation, as their light is simply a collimated beam. Another type of heliodon, the scanning heliodon is changing this, and making a heliodon capable of measuring phenomena well beyond that the direct beam

- **Scanning Heliodon:** Very new on the daylighting scene, and relatively very expensive, scanning heliodons combine a section of a Sky Dome, called a Sky Patch, and a compute r controlled traditional heliodon table. By continuously moving the table and adjusting the Sky Patch lighting distribution, a simulation of the entire sky can be produced during ascan. These tools are newer on the market, however, and the daylighting community is stilladjusting to their use.

- **Outdoor Sunlight:** Often simply taking a model of any type outside and allowing realdaylight to excite it can o↲er "insight" and "inspiration." Further, devices exist for heliodonlike studies under real sun, sometimes called "pocket heliodons." Aligning the "pocketheliodon" in the proper orientation then take the currently available direct sunlight anduses it as a heliodon. Even bringing a material sample under real daylight can change adesigner's perspective with respect to how it will behave in real conditions. Finally, designsessions outdoors often are communal type events, where brainstorming occurs, producinginnovations in the design

## Daylight simulation criteria

The last decade has seen multiple advances of how to numerically analyze the overall performance of daylit spaces. These advances include a trend away from static and towards dynamic, climate-based daylight simulations (Reinhart, Mardaljevic and Rogers 2006; Mardaljevic, Heschong and Lee 2009), more refined glare prediction and simulation methods (Wienold and Christoffersen 2006) and occupancy behavior models that mimic occupant use of shading and lighting controls (Reinhart 2004). These innovations stand in harsh contrast to current daylighting design practice that still favors the use of rules of thumb during schematic design and largely relies on the daylight factor and illuminance distributions under clear sky conditions during solstice and equinox days (Galasiu and Reinhart 2007). One is left wondering why the design community at large is not picking up the above mentioned advanced design analysis schemes? Several barriers towards the adoption of these technologies come to mind:

**1. No single simulation environment:** Part of the problem may be that different technical advances have been realized in different simulation environments and without appropriate graphical user interfaces which makes them difficult and time-consuming to learn and whose use is therefore hard to justify for design teams.

**2. Simulation time:** Another practical concern is that some of the advanced daylight simulation techniques – especially those that rely on raytracing – tend to require prohibitively long computation times.

**3.Too complicated simulation process**: A recent study on modeling errors made by simulation novices of sixty-nine models of the same sidelit space found that the beginners' models had so many shortcomings that their relevance for the design process was questionable altogether (Ibarra and Reinhart 2009). If non-experts cannot even model the mean daylight factor in a standard sidelit space, what are the odds that they are going to get a fully integrated daylight/glare/thermal simulation right?

**4. Outdated rating schemes:** A missing driver for change is that building standards and rating schemes have generally remained rather static as far as daylight metrics are concerned, i.e. there is no immediate pressure for practitioners to move towards more advanced daylighting analysis.

**5. No clear understanding of simulation outcomes:** An additional barrier is that casual software users - even if they happen to get the simulations right – oftentimes lack the expertise to interpret the simulation results as well as the know-how to fix the design problems raised by the simulation. Barriers 1 to 3 are important but mainly technical in nature. The authors believe that if senior design decision makers and code authorities can be convinced that computer-based daylighting analysis can facilitate the design of better daylit buildings (barriers 4 and 5), then the financial incentives will be made available for software developers, educators and others to overcome these technical barriers. At the time of writing, barrier 4 was actually not fully valid any more as several rating systems either had already or were in the process of introducing daylighting compliance paths that are derived from climate-based illuminance metrics. Examples are the Collaborative for High Performance Schools (CHPS 2010), the International Green Construction Code (ICC 2010) and LEED for Schools (USGBC 2009).

# Factors affecting accuracy of daylight models

## Daylight metrics

**Daylight Autonomy (DA)** was the first of a string of annual daylight metrics, now commonly referred to as ‘dynamic daylight metrics’. It is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. It was originally proposed by the Association Suisse des Electriciens in 1989 and was improved by Christoph Reinhart between 2001-2004. It is a major innovation since it considers a geographic location’s specific weather information on an annual basis. It also has power to relate to electric lighting energy savings if the user-defined threshold is set based upon electric lighting criteria. The user is free to set the threshold above which Daylight Autonomy is calculated. For the graphs to the right, we selected a Daylight Autonomy threshold of 300 lux (DA300). The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50% of the time

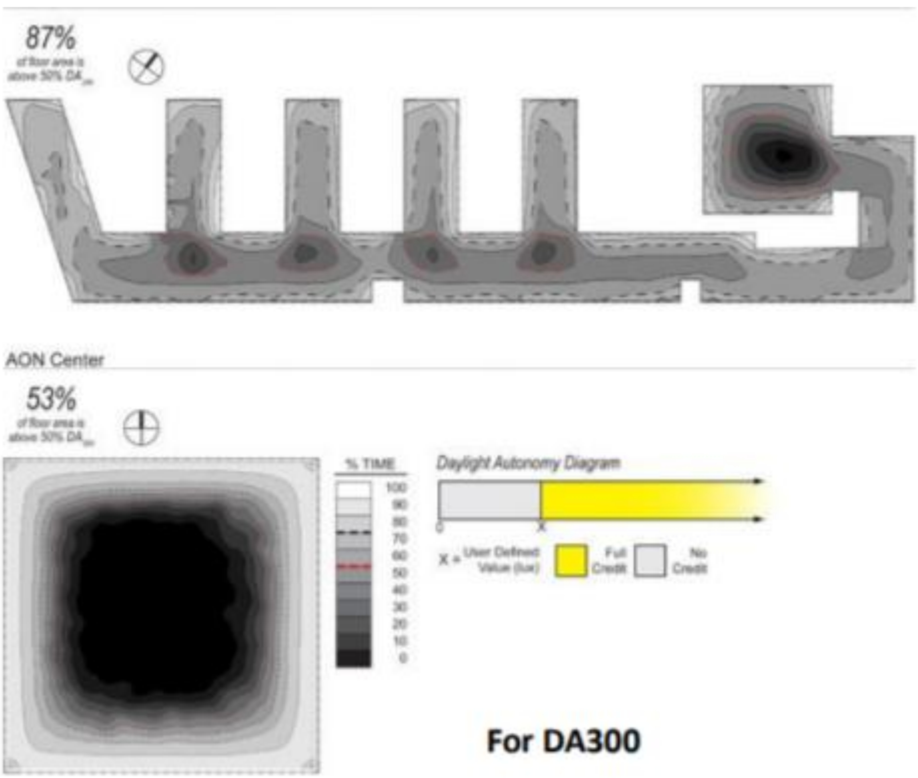



*Figure 31 Daylight Autonomy*

**Spatial Daylight Autonomy (sDA)** Compares % time above threshold illumination to % floor area above threshold e.g., sDA300/50% = analysis point exceeds 300 lux for 50% of the time (or more)

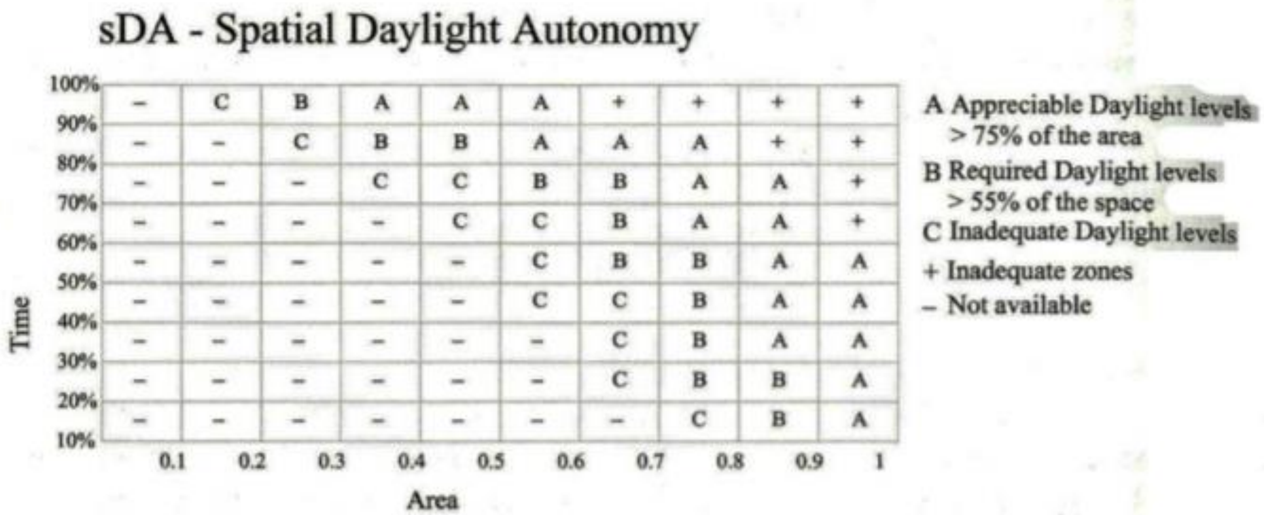



*Figure 32 Spatial Daylight Autonomy*

**Useful daylight Illuminance (UDI) [110–2,500 lux**] Based on climate data analysis • UDI fell short [0–100 lux] insufficient illumination • UDI supplementary [100–300 (500) lux] integrate with electric light • UDI autonomous [300 (500)–2,500 lux] no electric light required • UDI exceeded [>2,500 lux] bad situation: glare, overheating, etc

**Continuous Daylight Autonomy** Zach Rogers proposed Continuous Daylight Autonomy (cDA) in 2006 as a basic modification of Daylight Autonomy. Continuous Daylight Autonomy awards partial credit in a linear fashion to values below the user defined threshold. If 300 lux were specified as the

DA threshold (DA300) and a specific point exceeded 300 lux 50% of the time on an annual basis, then the cDA300 might result in a value of approximately 55-60% or more. For example, say a certain interior grid point has 150 lux due to daylight at a given time step, DA300 would give it 0 credit for that time step whereas cDA300 would give it 150/300=0.5 credit for that time step. For the graphs to the right, we selected a Continuous Daylight Autonomy threshold of 300 lux (cDA300). The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50% of the time giving partial credit for time steps below 300 lux

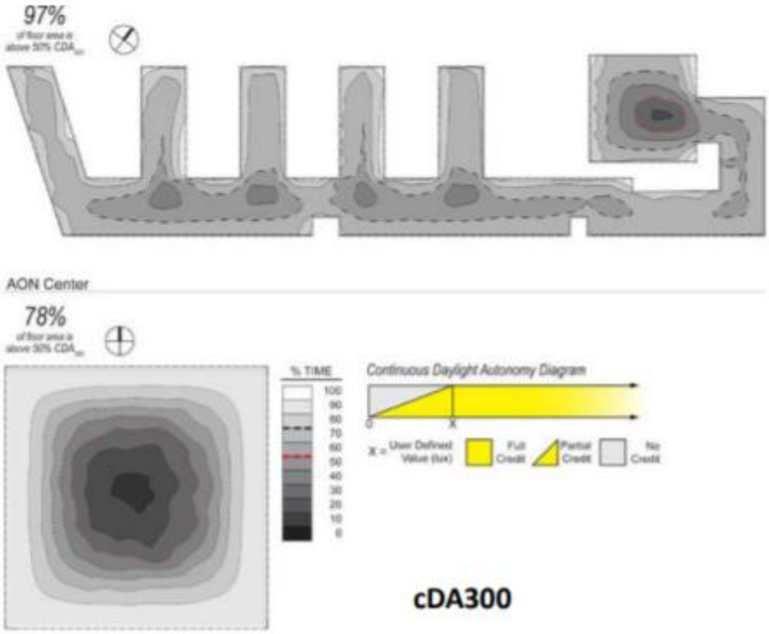



*Figure 33 Continuous Daylight Autonomy*

**Daylight Factor:** The concept of Daylight Factor (DF) was developed in the United Kingdom in the early 20th century. Daylight Factor is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies. Daylight Factor is typically calculated by dividing the horizontal work plane illumination indoors by the horizontal illumination on the roof of the building being tested and then multiplying by 100. For example, if there were 20,000 lux available outdoors and 400 lux available at a given point indoors, then the DF for that point would be calculated as follows DF = 400/20,000 *100 or DF=2

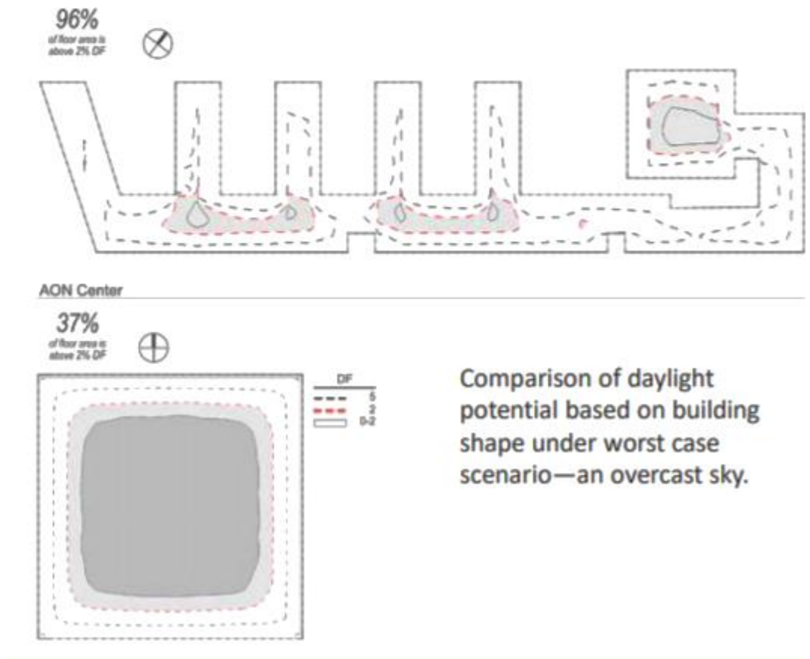



*Figure 34 Continuous Daylight Autonomy*

**Daylight autonomy (DA) and Continuous daylight autonomy (cDA**) • DA = percentage of annual daylight hours 500–2,500 lux • cDA = DA + the sum of (x/500) when illumination x is below 500 lux

**Daylight Saturation Percentage (DSP**) • Full credit for hours between 430 and 4,300 lux • Penalty >4,300 lux

Below is an image comparing DA300 and cDA300.

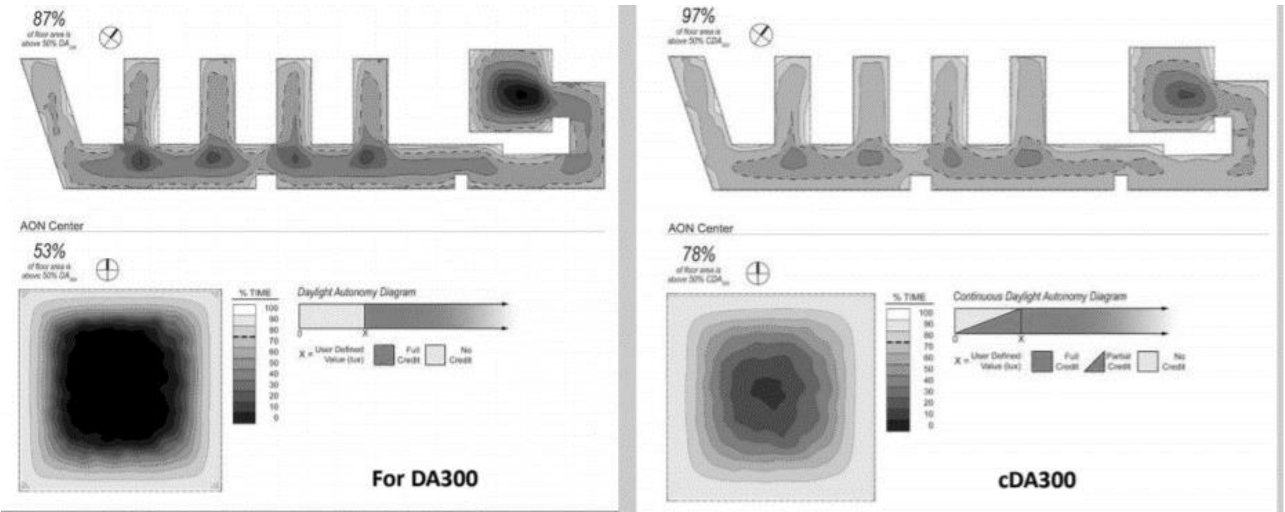



*Figure 35 Comparative DA-300 and cDA-300 ratings*

**Useful Daylight Illuminance Useful Daylight Illuminance (UDI)** is a modification of Daylight Autonomy conceived by Mardaljevic and Nabil in 2005. This metric bins hourly time values based upon three illumination ranges, 0-100 lux, 100-2000 lux, and over 2000 lux. It provides full credit only to values between 100 lux and 2,000 lux suggesting that horizontal illumination values outside of this range are not useful. There is significant debate regarding the selection of 2,000 lux as an ‘upper threshold’ above which daylight is not wanted due to potential glare or overheating. There is little research to support the selection of 2,000 lux as an absolute upper threshold. The graphical percent values represent the percentage of the floor area that that meets the UDI criteria at least 50% of the time.

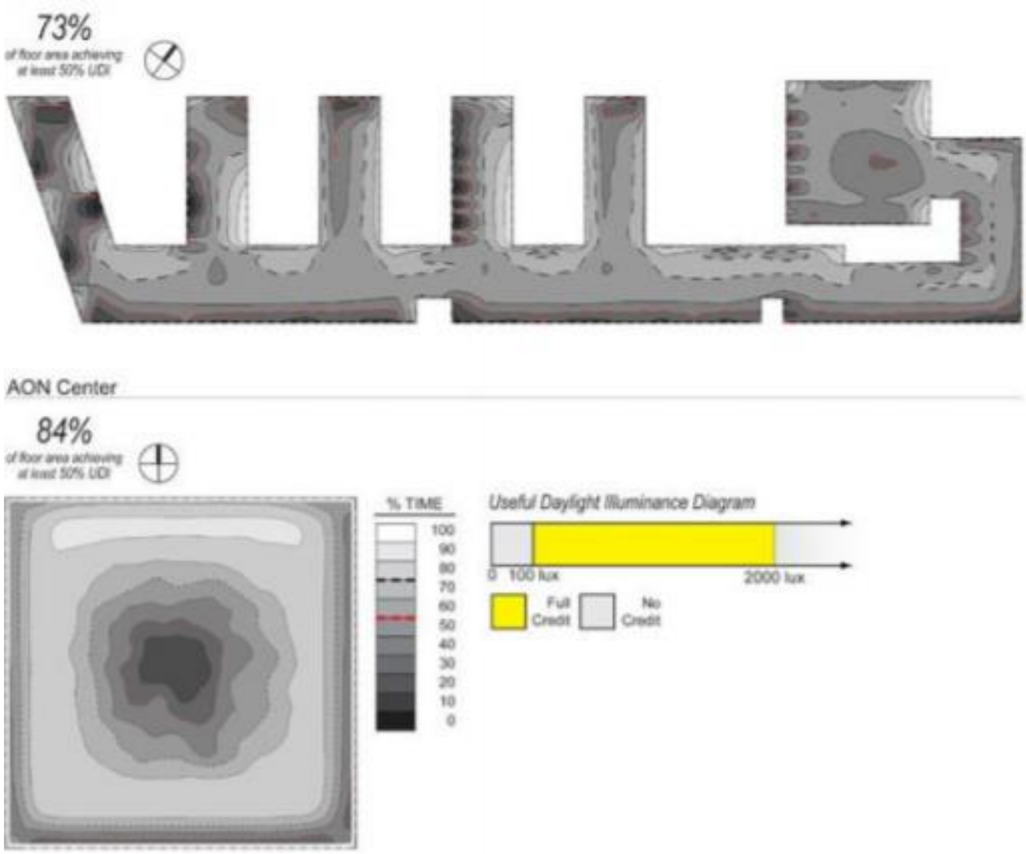



*Figure 36 Useful Daylight Illuminance*

**Daylight Saturation Percentage** Daylight Saturation Percentage (DSP) is a modification of Useful Daylight Illuminance that increases the lower limit to 40 footcandles (precisely 430 lux) and increases the upper limit to 400 footcandles (precisely 4,300 lux). It goes further to penalize grid point annual hour values above 400 footcandles by forcing them to be subtracted from the grid point annual hour values within the range of 40-400 footcandles. The Lighting and Daylighting Committee for the Collaborative for High Performance Schools program developed it in 2006. The graphical percent values represent the percentage of the floor area that meets the DSP criteria at least 50% of the time while also accounting for the penalty for hours above the 400 footcandle upper threshold.

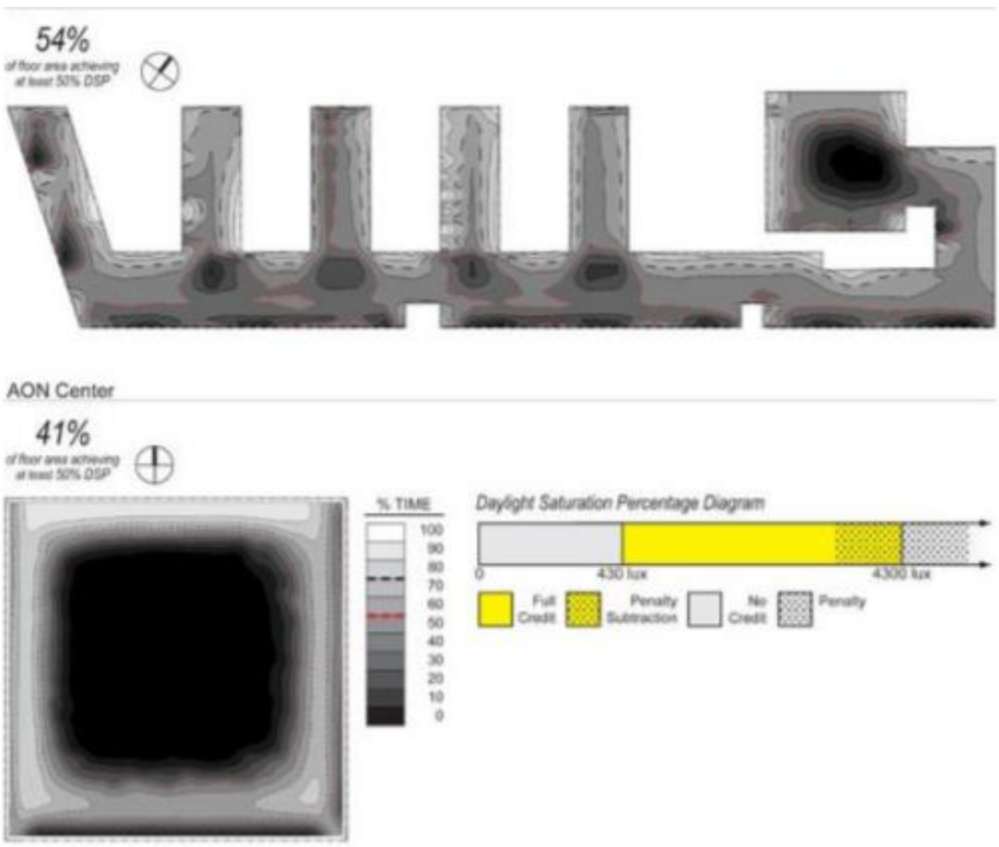



*Figure 37 Daylight Saturation Percentage*

Below is a comparison between Useful daylight illuminance and Daylight saturation percentage

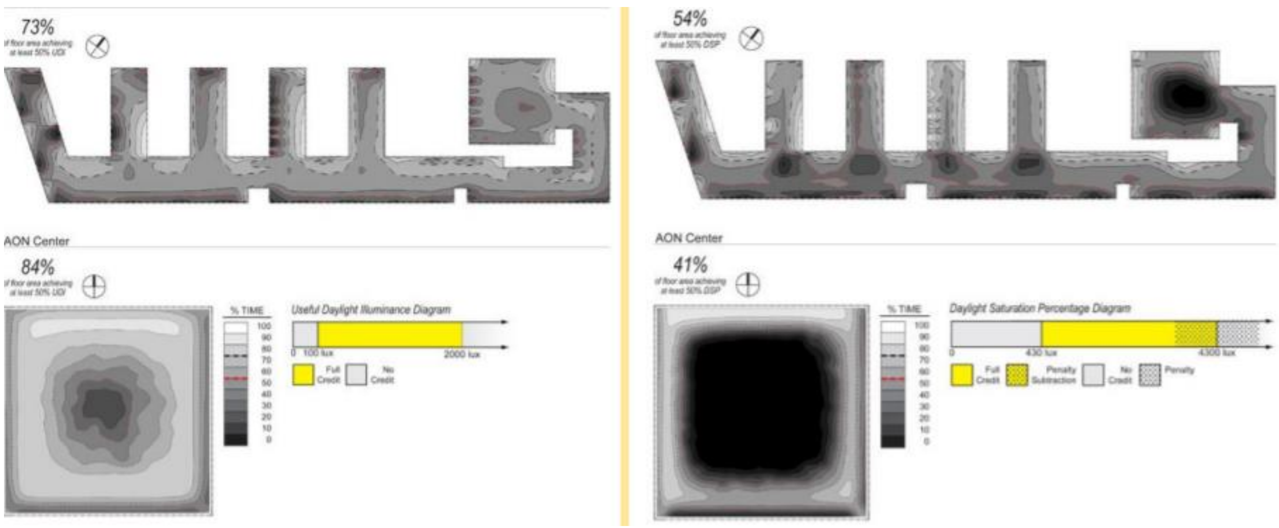



*Figure 38 Useful Daylight Illuminance vs Daylight Saturation Percentage*

## Glare

Luminance based analysis methods have been historically difficult to conduct in scenes with daylight due to expensive equipment and the variable nature of scenes with daylight. Hand held luminance meters are not only expensive but it is difficult to record data in a space with daylight in a comprehensive manner before the daylight conditions change. High Dynamic Range (HDR) photography techniques have made access to luminance data from real daylighted spaces far more feasible to generate and computational methods are facilitating rapid development of new luminance-based analysis metrics. These techniques have been available in digital daylight simulations for many years but the development of these techniques for real spaces is more recent.

The images below reveal the potential of luminance based analysis methods with calibrated fisheye lens cameras and HDR photography. In these images simple luminance ratios are shown for a space that a user rated as 'preferable' (above) and for a space the same user rated as 'just disturbing glare' (below). Advanced computational methods allow designers to examine real spaces and digitally simulated spaces with emerging luminance based metrics to assess visual comfort and aspects of quality. However, there is currently very little guidance for designers seeking to refine design solutions based upon these metrics because it is still an emerging research area

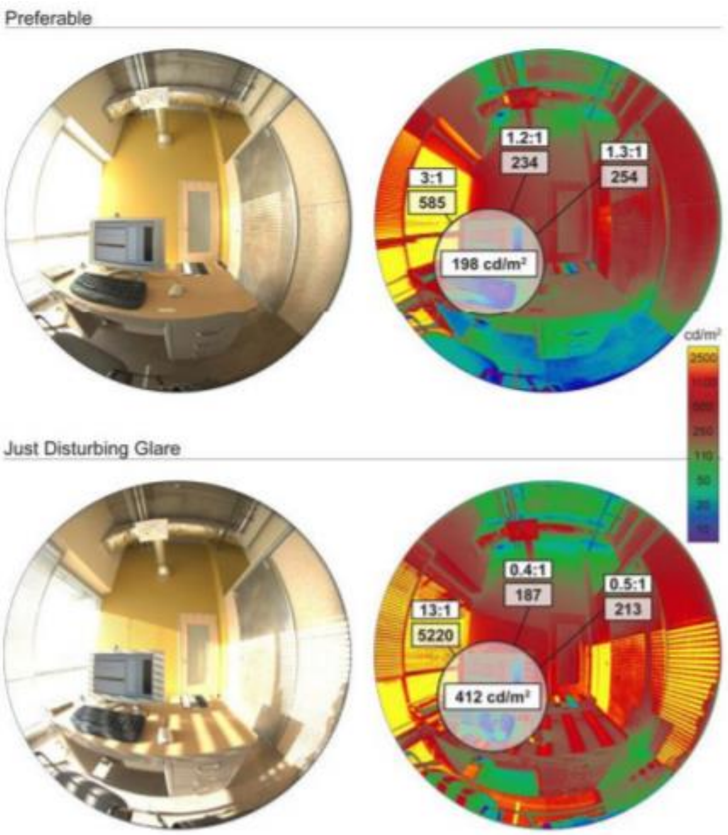



*Figure 39 Glare*

## Daylighting simulation exercises using daylight models (AND)

## Shading design exercises using open source simulation software

The software LIGHTSTANZA will be taught to students briefly for this section.

**About Lightstanza:** LightStanza is simple to use, but does not oversimplify daylight solutions . Working in your internet browser, LightStanza runs on the validated Radiance engine and handles complicated calculations with ease. LightStanza was founded in 2015 by a leading expert in the field who participates in technical standards committees.

## BIM integration

BIM is the process of generating and managing building data and its various components throughout the building's life cycle by using three dimensional, real-time, dynamic building modeling software to increase productivity in building design and construction.

Unlike past 3D innovations in the building industry, BIM is more than a conceptual modeling tool. BIM encompasses building geometry, spatial relationships, geographic information, quantities and properties of building components. BIM has been one of the most important developments to hit the construction industry in decades and is essentially digitization of the construction process. No industry, including hand cartoon animation or film photography, has ever been the same after being digitized.

During the pre-construction phase BIM allows for a quick way to determine cost and schedule feasibility with various configurations to find the best value. The quality of the design is greatly improved and the visualization aspect allows key decisions to be made earlier in the process.

Incorporating daylight in a building is a key strategy for passive design that impacts visual and thermal comfort. Architects and engineers use Building Information Modeling (BIM) software to produce design and documentation drawings. New daylighting analysis tools allow designers to leverage this technology to optimize natural lighting and create healthier and more productive environments.

Daylighting strategies offset electric light usage, which can account for 50 percent of a building's total electrical consumption. Daylight enhances environmental comfort by providing access to increased natural light. Using analysis tools helps designers harness daylight while minimizing the negative impacts of excessive direct sunlight.

Designers can help promote occupant health, wellness, and productivity by embracing natural light as an integral part of building design.

Many architecture firms utilize computer-rendering software to simulate fenestration and performance of shading systems. Shading studies and photorealistic renderings are common in-house exercises, as are design strategies that incorporate shading devices, light shelves, solar tubes, glazing types, and reflective surfaces.

Many firms already use BIM software, a 3D modeling tool, for design and documentation. Designers have begun to use this software to conduct daylighting analysis and learn how to optimize natural light. The tools are intuitive, accurate, and produce fast results.

While visual renderings are used to study the *quality* of lighting in a space, they do not measure light *quantity*. Daylighting analysis can help solve important building design dilemmas: how daylight relates to solar heat gain, how much light is available for specific tasks, and how to avoid glare.

Though the latest BIM technology allows architects to conduct their own daylighting analysis, enlisting daylighting specialists early in the design process introduces a fresh perspective and challenges architects to optimize their daylighting design and find creative solutions. Knowledgeable consultants with hands-on experience can help avoid missed opportunities.

As the model incorporates all of the trades, it compels early coordination that detects clashes of the various systems that can save up to 10% of the construction cost due to reduced changes in the field. It is estimated more than two thirds of the construction industry is using BIM, but daylighting takes sustainability one step further.

**BIM future prospects**

Building owners' manuals of the future will go digital with BIM as the most important component. One of the most valuable benefits of BIM technology is the ability to provide a digital owner's manual rather than thousands of pages of blue prints. The building owner gets a digital copy of the completed project model that can be used for decades of operation and maintenance.

Considering that 85 percent of the cost of a building over 30 years is in maintenance and operation, having a digital copy of the completed project that includes all information related to the building eases the task of ongoing maintenance.

Daylighting goes beyond cutting a hole in a roof, but requires an integrated approach to be successful. Effective daylighting requires decisions about the building form, location, climate, building components and lighting controls. In return, properly daylit buildings can repay installation costs quickly-often in less than two years.

Daylighting can be installed in buildings to replace electric lighting for 1/20 of the cost of enough solar PV panels to generate an equivalent amount of electricity using the same sun at the same high-energy-demand times of the day.

BIM and daylighting are the ultimate team in planning and sustainability. Working together, BIM and daylighting reduce total energy cost and enhance the building's life cycle for years to come.

**REFERENCES**


1. https://www.wbdg.org/resources/sun-control-and-shading-devices#:~:text=Designing%20Shading%20Systems&text=Use%20fixed%20overhangs%20on%20south,to%20shade%20than%20south%20glass.
2. https://www.linkedin.com/pulse/shadow-analysis-tools-software-eduardo-rodriguez-e-i-t-/
3. https://www.webpages.uidaho.edu/arch570/DaylightMetrics.pdf
4. https://www.ibpsa.us/sites/default/files/publications/SB10-DOC-TS08A-02-Reinhart.pdf
5. https://escholarship.org/uc/item/8516z0hv#page=35
6. https://www.pupnmag.com/article/bim-and-daylighting-the-ultimate-planning-and-sustainability-duo/

# UNIT – IV – Analysis of building performance

**Metering systems**

**Energy metering in residential buildings**

In Multi-family apartment buildings and Housing associations owned Single-family houses, heat - and where relevant cooling - meters are used to identify how much energy has been consumed by each occupant. Registering the energy consumption allows fair and more accurate energy cost allocation. It also raises the awareness among the occupants to lower their consumption and by that increase the buildings' energy efficiency and save on their energy costs.

Therefore every apartment can be equipped with an energy meter. These are so called 'secondary side meters'. Danfoss offers high quality ultrasonic meters that can be mounted in the flow or return pipe. The meters offer a new level of installation and commissioning simplicity by using a special App. The meters can be readout fast and easy by combing the App with a hand-held wireless radio receiver. Occupants don't need to be at home in order to register their energy consumption, a simple 'walk by' the meters is sufficient to register the data.

Sometimes also primary side meters are used. They register the total amount of heating or cooling energy provided to, or generated in, the apartment building.

**Energy metering in commercial buildings**

In commercial buildings with multiple occupants the use of heat and cool meters is increasingly popular. They are used for sub-metering to determine the amount of energy (heating / cooling or domestic hot water) is consumed by each occupant. Registering the energy consumption allows fair and more accurate energy cost allocation. It also raises the awareness among the occupants to lower their consumption and by that increase the buildings' energy efficiency and save on their energy costs.

Primary side meters register the total amount of heating or cooling energy provided to, or generated in, the building. Secondary side meters register the amount of energy consumed per occupant, floor or room in the building. The exact possibilities depend on the design of the HVAC system.

**Metering and Submetering**

- In commercial real estate, metering is the best way of getting more information about what's going on in your building. Every optimization project, from simple changes in the building's heating schedule to major renovations, is more likely to succeed if the team behind it has access to detailed information about building utility flows from meters and submeters.
- This guide is intended to tell you everything you need to know about what is possible with modern metering and submetering. With actions informed by a detailed look at the way utilities move through your building, it is possible to significantly reduce their consumption in some cases and shift necessary use to cut operational costs in others. Other types of meters give building engineers information about the quality of air in a tenant space to assist in efforts to make the space more comfortable and safe. Since the advent of "internet of things" technology, advanced metering has become more affordable, opening up new business applications in commercial real estate.

## The Case for Submeters

Before we get into how different meters can be installed, we should discuss why a building team would want meters that are more advanced than the ones that come standard with a utility connection. Every operational commercial building or complex must have building-level meters installed in order to access public water, gas, and electricity. These meters give a measure of utility consumption for the entire structure and are often read once per month or less.

Installing meters at one or more levels below the building-level meter (a.k.a. submeters) gives you a more granular look at what's going on in your building. A submeter installed for each tenant space lets you bill tenants for the resources that they actually consume, instead of dividing total consumption by floor space, giving them an incentive to conserve. This also provides the building team with backup when a tenant complains about a bill, and makes it simple to track unusual consumption spikes down to their sources

Similar to this last point, submeters installed to monitor large building equipment, like HVAC systems or cooling towers, ensure that your team will know early on if there's a problem. This last point is especially important; millions of dollars are frequently saved in a day because a serious leak or fire hazard is detected.

## Meter Types and Scoping

The first step to installing advanced meters throughout a building is scoping. This involves taking stock of the level of detail that the building team wants and assessing the existing infrastructure in the building. If the team is happy with the current level of resolution that is being tracked in the building – whether that resolution is at the building level or deeper – then the only thing that has to be done may be to connect the existing meters to a wireless gateway. A building team looking for more detail might want meters installed to measure tenant consumption, to track energy and water used by large equipment, or even to individual spaces within a larger unit.

When new meters have to be installed, the scoping process involves choosing the correct meters to use based on the utility being measured, cost, and the specifics of the building's layout. Below is a brief overview of the options for each utility.

**Electric**

The most common way to measure electric current is by using a current transformer, usually called a CT. CTs consist of a loop of wire that is wound around the device a variable number of times. When connected to and placed around a wire carrying an alternating current (the primary), this produces a smaller, proportional current in the loop of wire (the secondary) that is easier to measure with an electric meter like an Emon or Rail 350.

CTs are used for measuring current at every level, from the power grid to relatively small loads in buildings. Because the current in the secondary is proportional to the current in the primary and the number of "turns" wound around the device, CTs can be very large or very small, depending on what they're designed to measure. In some industrial settings, individual components of a machine might be metered using their own CT. In a commercial building, individual floors, tenant spaces, and important pieces of building equipment are often metered.

**Water, Gas, and Steam**

There are three primary options for measuring flow: in-line meters, insertion meters, and ultrasonic meters. Within the first two categories, there are several options for each type of utility. For example, the most common in-line gas meter is a diaphragm meter, which directs the flow of gas with internal valves and chambers, but there are also rotary meters and orifice meters for other situations. Steam has the most options because it can be measured directly or the condensate produced by steam cooling can be measured.

In-line meters are the most affordable type of meter to purchase for small pipes, but they are generally the most difficult to install. As the name suggests, this type of meter is installed in-line with the water pipe, meaning that the flow of the utility has to be shut off during installation. A section of the pipe then has to be removed and replaced with the meter. When the water, gas, or steam is turned back on, it passes through the meter and is measured. In-line meters are also fairly expensive for pipes that are greater than 3” in diameter.

Insertion meters are small rods that are inserted into a pipe through a hole and held in place by a saddle. Because they only need a small hole, the flow can be left on and the rod can be inserted (quickly) in a process called a “hot tap.” Compared to an ultrasonic meter, insertion meters only require a small section of pipe (though they do need more than in-line meters). Inside, the rod may hold a small turbine that measures flow or it may rely on a more complicated technique.

Ultrasonic meters are usually more expensive to purchase than other types of flow meters, but they are considerably easier to install. Where they are an option, this usually makes them the most cost-effective option overall. They consist of two bands that are a pre-set distance apart from each other and a central display. The bands send ultrasonic pulses between each other and calculate flow through the pipe by measuring the speed of each pulse. The downside to ultrasonic meters is that they generally require a straight run in the pipe that is 20x diameter before the first band and 10x to 20x diameter after the second band, which is not always available.

## HVAC

Measuring the amount of HVAC energy going to multiple locations in a building from a single unit generally requires a BTU meter, which consists of a flow meter and two temperature sensors. The flow meter measures the rate of flow of the working substance – often water – and the temperature sensors measure the heat in the working substance as it enters the tenant space and as it leaves it.

Armed with knowledge of the working substance’s density, specific heat, and the data collected from the sensors above, the amount of energy consumed in the heat exchange process can be calculated with the following formula:

Measuring HVAC requires multiple meters.

Armed with knowledge of the working substance’s density, specific heat, and the data collected from the sensors above, the amount of energy consumed in the heat exchange process can be calculated with the following formula:

$$Q=V^*C_p{}^*\varrho\ ^*(T_{supply}-T_{Return})$$

## Collecting Data From Meters

Having that data isn’t much good if you don’t have an effective way of accessing it. In many buildings, engineers still have to perform the familiar monthly rite of walking to each meter in the building, clipboard in hand, recording the numbers on the outside of each box. This process is time-consuming and extremely error-prone. In particular, the clipboard approach is vulnerable to systematic errors that can cause significant losses, especially when multipliers are involved.

Fortunately, there are modern solutions to this problem that circumvent the long-walk-with-clipboard entirely.

Many meters are pulse enabled, which means that they convert their data into digital pulses for output. For example, a pulse-enabled electric meter might be configured to send a pulse for every kilowatt-hour that passes through the wire it’s measuring. The computer reading the pulses knows that, if 20 pulses are read in an hour, the building used 20 kWh in that time. These pulses can then be routed to a digital gateway that sends them over the internet to a computer waiting to interpret them.

More modern meters may use a communications protocol like Modbus to transfer information instead of pulses. This approach is more reliable and allows for more detailed information to be transferred than just consumption data.

Utility companies will sometimes give customers access to “interval” data online. This is utility consumption data that is provided at a regular delay – often about a day. This is pretty basic, especially because the utility usually only considers building-level data, but it can be useful for tracking consumption against targets throughout the month.

Real-time data is even more useful. Most modern energy management systems pull data from meters and transmit it over the internet to the cloud. There, it can be presented in up-to-the-minute detail. This makes it possible to do things like sending alerts when something is behaving abnormally, investigating usage spikes while they’re happening, or making adjustments to operations in real time.

### Viewing and Analyzing Meter Data

Getting data out of meters is only half the battle. Presenting that data in a way that is intuitive and that leads to actionable insights is at least as difficult of a technical challenge.

Modern energy management systems generally use a digital platform to present the data they collect from meters and submeters. The most basic visualization is an energy curve, which is the shape made by a building’s energy consumption over the course of a single day. The ideal energy curve for a standard office should rise quickly in the morning from a low baseload, stay relatively flat throughout the working day, and fall back to the baseload after hours. In practice, there are some common deviations from this curve that are good targets for efficiency projects. The use of other utilities often will follow a similar pattern.

Another basic tool is budget tracking, which plots your consumption against your budget on a monthly, quarterly, or yearly basis.

The next step is decoding your building data to find valuable insights that you can act on. This is where data analytics come in, and it’s here that higher-end energy management systems set themselves apart from the competition.

Applying data analytics to utility consumption data creates powerful tools like weather normalization, which combines weather forecasts with historical data about how your building performs in different conditions to predict a range in which it will perform today. This sets your building’s utility consumption in context; an average energy curve on a perfect day might mean that HVAC units are working harder than they should, for example, but slightly higher than average curve on an especially hot day could still represent an efficient use of energy. Analysis of the same data can also help an energy management system to recommend startup and shutdown times that match the specific needs of your building given the day’s weather, helping your team to shave off energy costs every day.

## The Future of Metering

As time goes on, new and better metering technology will be introduced. We’re already seeing meters that measure new variables, like CO2 and other air quality indicators, making their way into buildings as costs come down. While environmental sensors won’t help building teams to reduce utility costs, some tenants find them valuable for the productivity gains that they facilitate. Low air quality is associated with lower employee productivity and a higher number of sick days taken.

Traditional meters are also improving and becoming more affordable, meaning more profitable use cases will become available. For example, submetering is mostly limited to important pieces of building equipment and large (usually commercial) tenant spaces at present. This isn’t a technical problem – submetering is just generally too expensive to be worth it for smaller spaces. As meters become more affordable, the resolution with which teams can manage their properties will increase.

A little bit further away, but potentially more useful in the long run are advances in analytics that could allow algorithms to make operational changes to buildings automatically based on meter data. As algorithms improve, more and more steps will be trusted to the computer. Eventually, buildings could become a closed loop, allowing their human teams to focus on repairs, maintenance, and relationships with tenants while utility use is optimized by a computer.

**Analysis of collecting data from existing buildings**

**Performance metrics**

To be able to compare energy consumption, the first step is to group together hotels of the same category. For this case study, we will focus on mid-range hotels belonging to a single hotel chain. In this type of hotel, the main sources of energy consumption are heating, cooling, domestic hot water, catering, and lighting. The main factors that impact consumption are the number of rooms, the weather, and occupancy rates (or number of overnight stays). Therefore, these factors should be used to normalise the data to ensure that comparisons between hotels are consistent. The following performance metrics must be determined to meet the objectives stated above:

1. Whole building energy use intensity (EUI) kWh/m² and kWh/occupancy level

2. Whole building electricity EUI kWh/m² and kWh/occupancy level

3. Whole building gas EUI m3/m²/HDD and CDD (heating degree days and cooling degree days); mainly used for heating and domestic hot water

4. Whole building water use m3/occupancy level

5. Whole building electrical consumption breakdown by time of use (TOU)

6. Whole building electrical power demand kWh with identification of over demand periods

7. Whole building reactive energy consumption

8. Whole building space heating EUI kWh/m²/HDD and CDD

9. Whole building domestic hot water EUI (production) kWh/m² and kWh/occupancy rate

10. Whole building domestic hot water volume m3/m² and m3/occupancy level

11. Total cooling consumption EUI kWh/m²/HDD and CDD

12. Total ventilation EUI kWh/m²

13. Kitchen electrical consumption kWh

14. Kitchen cold water consumption m3/m²

15. Lighting consumption for common areas kWh/m²

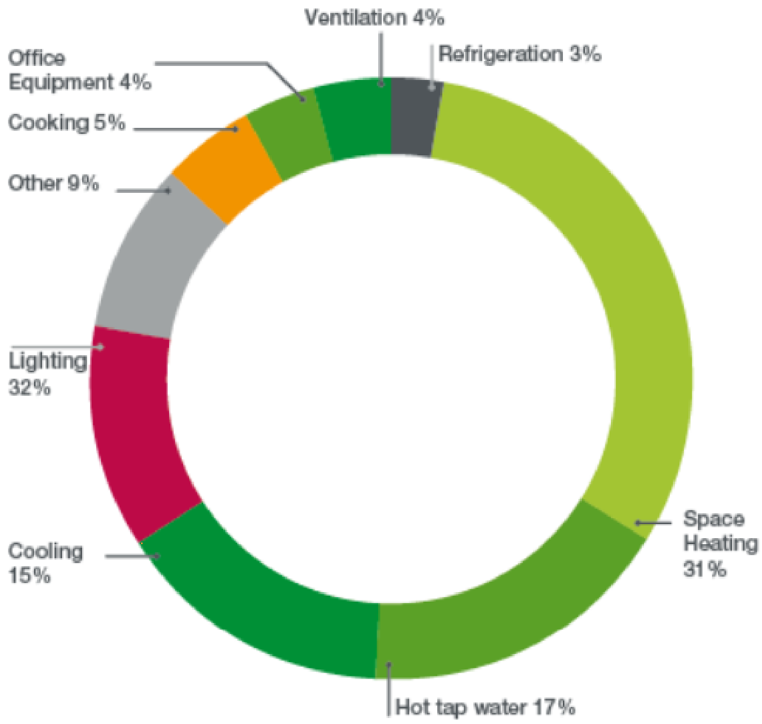



*Figure 40 Potential end uses*

**Metering points**

We must first identify which data are required to build the performance metrics.

| | Performance metric | Static data | Dynamic data |
|---|---|---|---|
| 1 | Whole building EUI (kWh/m² and kWh/occupancy level) | Gross floor area (m²)<br>kWh/m³ ratio for gas | Building electrical consumption (kWh)<br>Building gas consumption (m³)<br>Occupancy level |
| 2 | Whole building electricity EUI kWh/m² and kWh/occupancy level | Gross floor area (m²) | Building electrical consumption (kWh)<br>Occupancy level |
| 3 | Whole building gas EUI m³/m²/HDD | Gross floor area (m²) | Building gas consumption (m³)<br>Outdoor temperature (for HDD) |
| 4 | Whole building water use intensity m³/occupancy level | | Water consumption (m³)<br>Occupancy level |
| 5 | Whole building electrical consumption breakdown per TOU | | Building electrical consumption (kWh)<br>TOU signals |
| 6 | Whole building electrical power demand | Gross floor area (m²) | Main electric power (kW) |
| 7 | Whole building space heating EUI kWh/m²/HDD | Gross floor area (m²) | Gas consumption for space heating boiler<br>Outdoor temperature (for HDD) |
| 8 | Whole building DHW EUI kWh/m² and kWh/occupancy level | Gross floor area (m²)<br>kWh/m³ ratio for gas | Gas consumption for DHW boiler<br>Water pump consumption (kWh) |
| 9 | Whole building DHW volume intensity m³/m² and m³/occupancy level | Gross floor area (m²) | Cold water volume entering the DHW system (m³)<br>Occupancy level |
| 10 | Total cooling EUI kWh/m²/HDD | Gross floor area (m²) | Chiller consumption (kWh),<br>water pump consumption (kWh)<br>Outddor temperature (for HDD) |
| 11 | Total ventilation EUI kWh/m² | Gross floor area (m²) | Kitchen electrical consumption |
| 12 | Kitchen electrical consumption (kWh) | | Kitchen electrical consumption |
| 13 | Kitchen water consumption (m³) | | Kitchen water consumption (m³) |
| 14 | Lighting common areas EUI | Gross floor area (m²) | Lighting consumption of common areas (kWh) |

At this stage, we need to consider building characteristics like locations of main incoming meters, electrical and mechanical rooms, and network distributions. This will help determine the necessary metering points. Most of the performance metrics can be built using direct metering. However, other methods are recommended for two metrics in particular:

- Metering common lighting consumption with direct metering would be too costly, as it would require adding four meters to each floor panelboard to be able to separate lighting from other end-use consumption. Therefore, each panelboard's consumption is measured and common area lighting consumption determined at night.

• Gas consumption for DHW boiler: as there is no gas for cooking, the difference between whole-building gas consumption and the gas consumption of the space heating boiler can be used to calculate this metric.

Below is Floor plan to help identify necessary metering points:

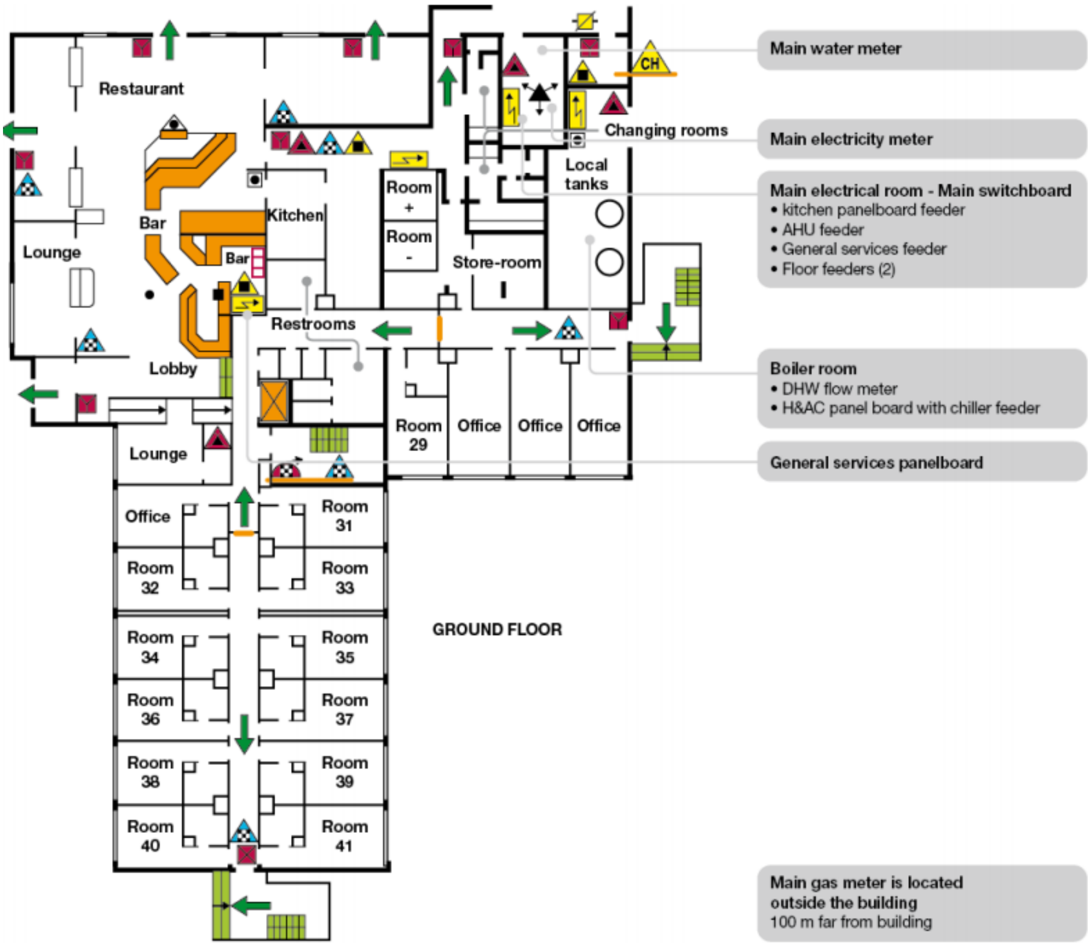



*Figure 41 Example floor plan with the different metering points*

Metering diagrams with the different metering points as below

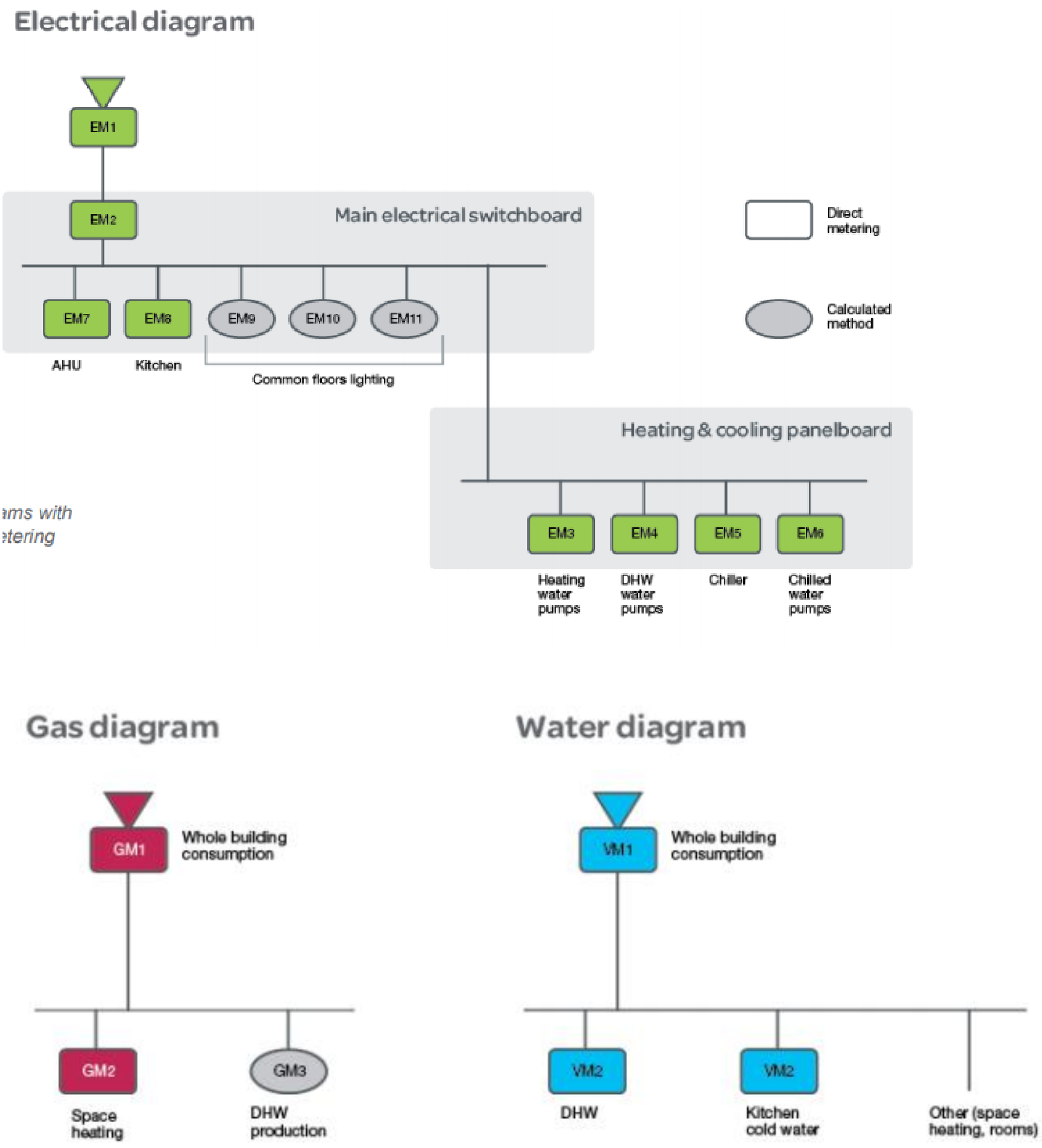



*Figure 42 Metering diagrams with the different metering points*

Examples of meters and their characteristics are as shown below:

| Selected meter | | | EM | Rating | Main characteristics |
|---|---|---|---|---|---|
|  |  | PM5110 with clamp-on CT (only 2 hours shutdown was acceptable) or NSX circuit-breaker with Micrologic 5.2E trip-unit | EM2 | < 630 amps | Active, reactive, apparent power and energies<br>U, I, Power factor and frequency<br>Minimum & Maximum, Alarming<br>THD |
|  |  | PM3250 or NSX circuit-breaker with Micrologic 5.2E trip-unit | EM5, EM7, EM8 | < 250 amps | Active, reactive, apparent power and energies<br>U, I, Power factor and frequency |
|  | | iEM3110 with solid core | EM3, EM4, EM6 | < 63 amps | Only kWh consumptions |

*Table 7 Some meters and their characteristics*

Metering best practices summary table as below:

| Performance metric | Static data | Dynamic data | Recording frequency | Measurement method | Meter | Location |
|---|---|---|---|---|---|---|
| Whole building EUI (kWh/m² and kWh/occupancy level) | Gross floor area (m²) kWh/m³ ratio for gas | Building electrical consumption (kWh) | yearly, monthly | Direct metering | Electrical meter - main switchboard incoming (EM2) | Main electrical room |
| | | Building gas consumption (m³) | yearly, monthly | Direct metering | Main gas meter (GM1) | Outside building |
| | | Occupancy level | yearly, monthly | N/A | Manual reading from Hotel management system | |
| Whole building electricity EUI kWh/m² and kWh/occupancy level | Gross floor area (m²) | Building electrical consumption (kWh) | yearly, monthly, weekly, daily | Direct metering | Electrical meter - main switchboard incoming (EM2) | Main electrical room |
| | | Occupancy level | yearly, monthly | N/A | Manual reading from Hotel management system | |
| Whole building gas EUI m³/m²/HDD | Gross floor area (m²) | Building gas consumption (m³) | yearly, monthly, weekly, daily | Direct metering | Main gas meter (GM1) | Outside building |
| | | Outdoor temperature (for HDD) | daily | Direct metering | Temperature sensor PT100 (TM1) | Outside building |

| | | | | | | |
|---|---|---|---|---|---|---|
| Whole building electrical consumption breakdown per TOU | | Building electrical consumption (kWh) | yearly, monthly, weekly, daily | N/A | Electrical meter - main switchboard incoming (EM2) | Main electrical room |
| | | TOU signals | weekly, daily | Direct metering | Main electricity meter (EM1) | Main electrical room meter |

| | | | | | | |
|---|---|---|---|---|---|---|
| Whole building electrical power demand | Gross floor area ($m^2$) | Main electric power (kW) | yearly, monthly, weekly, daily | Direct metering | Electrical meter - main switchboard incoming (EM2) | Main electrical room |
| Whole building reactive energy consumption (kvarh) | | Electrical reactive energy (kvarh) | yearly, monthly, weekly, daily | Direct metering | Electrical meter - main switchboard incoming (EM2) | Main electrical room |
| Whole building space heating EUI kWh/m²/HDD | Gross floor area ($m^2$) | Gas consumption for space heating boiler | yearly, monthly, weekly, daily | Direct metering | Gas sub-meter (GM2) | Boiler room |
| | | Water pump consumption (kWh) | weekly, daily | Direct metering | Electrical meter (EM3)-heating water pumps feeder | Boiler room |
| | | Outdoor temperature (for HDD) | weekly, daily | Direct metering | Temperature sensor PT100 (TM1) | Outside building |
| Whole building DHW EUI kWh/m² and kWh/occupancy level | Gross floor area ($m^2$) kWh/$m^3$ ratio for gas | Gas consumption for DHW boiler | yearly, monthly, weekly, daily | By difference GM1-GM2 | N/A | N/A |
| | | DHW pump consumption (kWh) | weekly, daily | Direct metering | Electrical meter (EM4) - DHW pumps feeder | Boiler room |
| Whole building DHW volume intensity $m^3/m^2$ and $m^3$/occupancy level | Gross floor area ($m^2$) | Cold water volume entering the DHW system ($m^3$) | yearly, monthly, weekly, daily | Direct metering | Flow meter (WM2) at entrance of the hot water tank | Boiler room |
| | | Occupancy level | yearly, monthly, weekly, daily | N/A | Manual reading from Hotel management system | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Total cooling EUI kWh/m²/HDD | Gross floor area (m²) | Chiller consumption (kWh) | yearly, monthly, weekly, daily | Direct metering | Electrical meter (EM5) - Chiller feeder | Boiler room |
| | | Water pump consumption (kWh) | yearly, monthly, weekly, daily | Direct metering | Electrical meter (EM6) - Chilled water pumps feeder | Boiler room |
| | | Outddor temperature (for HDD) | yearly, monthly, weekly, daily | Direct metering | Temperature sensor PT100 (TM1) | Outside building |
| Total ventilation EUI kWh/m² | Gross floor area (m²) | AHU electrical consumption | yearly, monthly, weekly, daily | Direct metering | Electrical meter (EM7) - AHU feeder | Main electrical room |
| Kitchen electrical consumption (kWh) | | Kitchen electrical consumption | yearly, monthly, weekly, daily | Direct metering | Manual reading from hotel management system | |
| Kitchen water consumption (m³) | | Kitchen water consumption (m³) | yearly, monthly, weekly, daily | Direct metering | Water sub-meter (WM3) | |
| Lighting common areas EUI | Gross floor area (m²) | Lighting consumption of common areas(kWh) | yearly, monthly, weekly, daily | By data analysis - from general service consumption | Electrical meter (EM8) - General services panelboard feeder | Main electrical room |

*Table 8 Metering best practices*

### Designing metering systems in brief

• Set objectives to identify user needs and determine the scope of future energy monitoring systems. Users of the system should provide input on the main features that should be included.

• Determine performance metrics and the data to be measured that will link building activity and energy consumption.

• Determine the metering points that will allow operators to monitor and control the building according to their objectives, and to ensure gathered data enables the desired analysis.

• Select meters based on your objectives. If main meters are able to read energy data, reuse may be possible, otherwise new incoming meters should be installed. Select additional meters as per metering points requirements and building operation requirements and objectives.

## Economic aspects of energy simulation results: LCA , payback analysis, break-even analysis, cost-benefit analysis, present worth analysis

### Building Life Cycle Assessment

There are many factors that must be considered before evaluating claims that one or another building type or product offers a better environmental return. To understand the **full environmental impact** of a structure over decades of use, all phases, starting before construction and continuing through demolition, must be considered. **Life cycle assessment (LCA)** seeks to quantify the environmental impacts over the infrastructure life cycle by identifying the costs during each phase.

LCA can be used to obtain credits in certification systems like LEED, but traditional LCA methods can be time, resource, and data-intensive. For complex systems like residential buildings, these demands can lead to delayed assessments with evaluations carried out after important design decisions have already been made, reducing their effectiveness. CSHub researchers have developed a **streamlined approach** to LCA that requires significantly less time and data, which can reduce expense as well as uncertainty and allow assessments to be conducted earlier in the building design process when decisions can have the greatest impact.

There are many factors that must be considered before evaluating claims that one or another building type or product offers a better environmental return. To understand the **full environmental impact** of a structure over decades of use, all phases, starting before construction and continuing through demolition, must be considered. **Life cycle assessment (LCA)** seeks to quantify the environmental impacts over the infrastructure life cycle by identifying the costs during each phase.

LCA can be used to obtain credits in certification systems like LEED, but traditional LCA methods can be time, resource, and data-intensive. For complex systems like residential buildings, these demands can lead to delayed assessments with evaluations carried out after important design decisions have already been made, reducing their effectiveness.

Life cycle assessment of a building can be represented as below in the image:

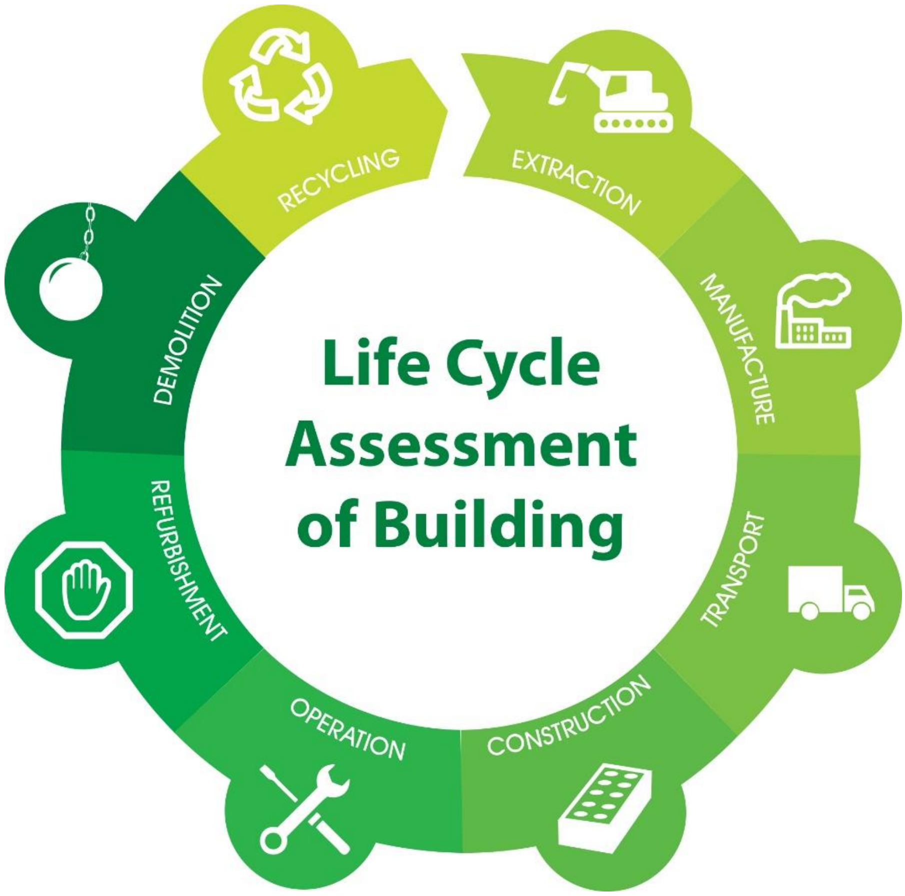



*Figure 43 Life cycle assessment of a building depiction*

**Some relevant definitions are as follows:**

• Environmental product declaration (EPD): a life cycle assessment of a building product that has been conducted by a manufacturer in accordance with a product category rule (PCR). The scope includes the materials used and the manufacturing of the product. Results are usually made publicly available.

• Whole building LCA: a life cycle assessment of the building products and the construction of the building. Also referred to as the embodied impact of the building. It does not include building operation.

• Whole building and whole life LCA: a complete life cycle assessment of the building, including building products, construction, operation, and end-of-life.

**Phases of the building life cycle and the scope of building product EPDs, whole building LCAs, and whole building and whole life LCAs.**


| | Products | Construction | Operation | End-of-Life |
|---|---|---|---|---|
| Building product EPD | ✓ | | | |
| Whole building LCA | ✓ | ✓ | | ✓ |
| Whole building & whole life LCA | ✓ | ✓ | ✓ | ✓ |

*Figure 44 Phases of the building life cycle and the scope of building product EPDs, whole building LCAs and whole building and whole life LCAs*

## COMPARISONS

It is tempting to compare the results of EPDs and LCAs conducted by different entities. However, there are several challenges associated with comparing results due to differences in approaches. Comparisons among EPDs and LCAs can only be made when they are conducted for products or buildings that serve the same function using the same approach. The current system for EPDs is geared towards compliance with the Leadership in Energy and Environmental Design (LEED) building rating system, which offers points for buildings that use products that have an EPD. The points are intended to encourage manufacturers to measure the environmental footprint of their products.

There is no requirement for manufacturers to lower their footprint, nor is there a requirement for a footprint threshold. This is because the current system does not require EPDs to be based on the same PCR or approach. If a system were in place to ensure that EPDs used the same approach (e.g., using a single software tool and data), EPDs could be used to make vendor decisions. That is, selection of vendors for products that have already been specified in the design. Similarly, if an LCA is conducted that includes multiple design alternatives using a single approach, the LCA can be used to make design decisions. That is, selection of different product types (e.g., materials or energy systems) for use in the design.

Acceptable uses for comparative EPDs and LCAs depending on the approach used. Red text indicates approach not currently in place.

| Approach for Analysis of Alternatives | Building Product EPD | Whole Building LCA | Whole Building & Whole Life LCA |
|---|---|---|---|
| **Different** | LEED points | None | None |
| **Same** | LEED points and *vendor* decisions | LEED points and *design* decisions* | LEED points and *design* decisions |

*Design decisions can only be made using whole building LCA if design alternatives have equivalent operational requirements (e.g., energy consumption)

*Table 9 Acceptable uses for comparative EPDs and LCAs*

**Key points to be noted are:**

- Existing literature on the life cycle analysis of buildings focuses primarily on the energy use and greenhouse gas emissions of small to mid-sized houses.
- Variations in building design (structure and materials), lifetime, and study scope limit the ability to compare study results.
- The use phase of buildings accounts for the majority of life cycle impacts, though there are indications that materials may play a large role, particularly in energy efficient homes.
- Uncertainty is typically not accounted for within data or shown in study results.
- There is a lack of a methodology that is scalable to various building designs and geographic locations that also considers uncertainty.
- Designers, policymakers, and the general public must be aware of materials impacts in order to meet long and short-term emissions reductions goals.

### Similarities and differences in LCA design

The design of a life cycle assessment for a building depends on the goal of the study. Most studies have an overarching goal of understanding the impact of a building, but take different angles towards reaching this number depending on the intended use of the study or the audience. For example, a researcher may be interested in understanding what building structure has the lowest GHG emissions in the construction phase. Alternately, a study might examine the effect of energy efficiency measures, like improved insulation, on the consumption of energy over the lifetime of the building. As such, variations in the study's objectives can lead to potentially significant differences in the final results making comparison between studies challenging or impossible. This section will provide an overview of different considerations used in the key assumptions within life cycle assessments.

### Functional unit

Defining the functional unit is a key step of an LCA. A functional unit is a quantitative measurement of the function that a product or service provides that serves as the basis of LCA calculations. For example, a functional unit might be a light bulb providing a specified brightness and used in Europe for one year, or a single apple grown and eaten in the US. In this report, only studies examining residential buildings were considered; however, the definition of a residential building varies widely.

Many studies rely on the building's footprint, or floor area, as the base of measurement for the functional unit, allowing different scenarios to be applied to a standard structure size in a hypothetical context.

### Lifetime

In studies considering the use phase, the lifetime of the home is a key consideration. The lifetime is generally determined by how long residents tend to stay in a home, the functional lifetime of the building itself, or the length of time for a generation to pass. Lifetimes varied from 25 – 100 years in the literature assessed, most falling between 30-50 years. Studies using 100 year time frames, such as Borjesson's, tend to include significant renovation activities as part of the longer term life cycle. We can also consider lifetimes in order to make results relevant in terms of meeting climate change mitigation goals set for the next few decades.

### System Boundaries

The life cycle of even the simplest products can become very complex. Where one "draws the line" is a key question in any life cycle assessment, creating a large potential difference in life cycle results. As such, it's necessary to clearly define the activities one is including and excluding in a study in order to understand the results in the proper context. This section will provide an overview of the boundaries typically considered within an LCA. Which life cycle phases are included in the study is one main element of boundary setting, an example of which is shown in Figure below.

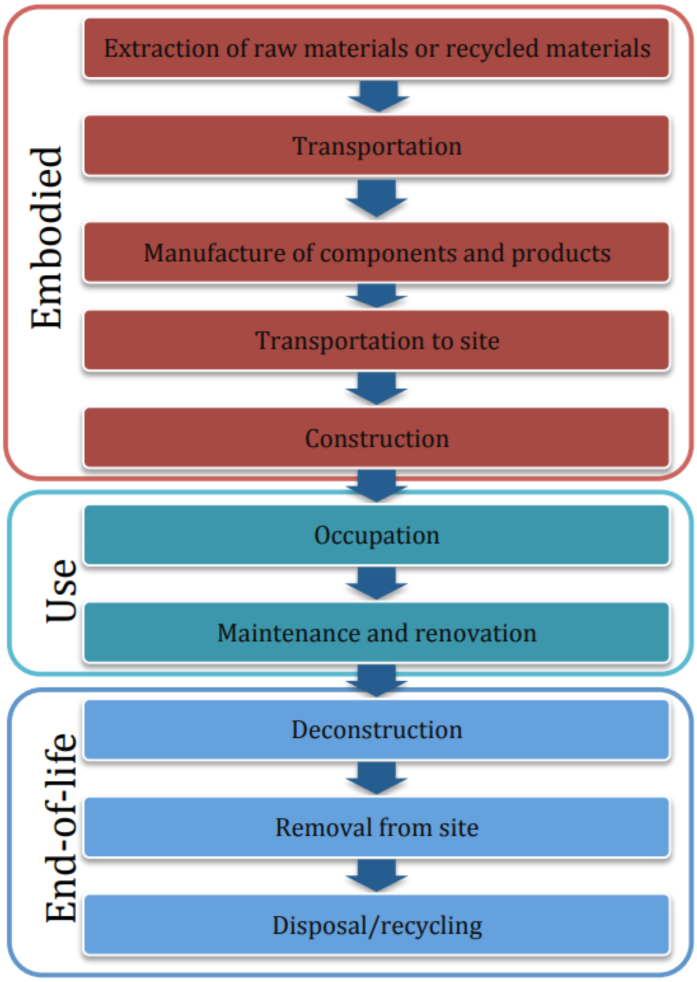



*Table 10 Life cycle phases*

The studies in this report considered life cycle phases in several ways:

1. **Cradle-to-site, or embodied phase:** The energy and GHG emissions from the materials extraction and manufacturing through a completion of building construction (excluding use and disposal).
2. **Use Phase:** The energy and GHG emissions consumed during the operation of the house.
3. **Cradle-to-grave:** The GHG or energy used from extraction and manufacturing of materials to the house's eventual disposal.

Geographic boundaries are a key differentiator between each study; each study considered in this review focused on a particular region, and oftentimes a specific location, like a city. The energy source for a region (i.e. coal vs. hydropower) can have a large impact on the use phase energy, making locality a critical factor. Different climactic zones may change the heating or cooling requirements, necessitating the use of different types of materials or appliances. Further, location is a factor for the transportation of materials to the construction site. This regional specificity should be a clear consideration of any building LCA, particularly those focused in the use phase.

**Summarizing conclusions**

An emerging trend in LCA literature shows that while energy consumption is decreased with improved energy efficiency, this can cause an increase in embodied energy due to the additional materials burden required for some energy efficiency measures. This point is significant for a number of reasons. Most energy efficiency standards focus on the use phase of a building, leaving the embodied phase out, This is due to the fact that operational energy will continue to account for 90% of the energy used in buildings. However, codes are becoming more stringent, environmental awareness is increasing, and demand for energy efficient buildings is increasing. As a result, it is becoming more relevant to consider the embodied phase as part of building codes and standards. Furthermore, if energy efficient construction inherently creates a spike in carbon emissions compared with traditional building construction, it may become an especially relevant consideration for regions adopting carbon mitigation plans. As such, it is important to fully understand both the embodied and use impacts of buildings constructed with energy efficiency measures in various combinations.

While the existing body of literature is robust and valuable, the lack of consistency within the methodologies makes it difficult to definitively reach such conclusions. Particularly, there is no common methodology to adequately address a wide range of building forms and lifetimes in various geographic regions. In addition, most studies relied on commercial databases as the main data source – there was an overall absence of local primary data. This lack of data illuminates the potential for considerable uncertainty within quantitative results, an aspect that was not adequately considered in most publications. It is vital that LCA studies report uncertainty, not only to understand the confidence of the results provided, but also to enable comparison and inform data collection efforts.

Furthermore, there is limited research on the renovation of existing housing with energy efficiency measures. Understanding the threshold where the impact of new construction or renovation exceeds the use phase benefits will shed light on what measures are most beneficial in which cases. As such, it is vital to develop a methodology that can accommodate variable building characteristics as well as provide insight into uncertainty in the results. Such a tool could add value to global initiatives that promote, or mandate, sustainable building.

## REFERENCES


1. Why modern buildings MUST have energy metering system (electrical-engineering-portal.com)
2. Energy Metering System for Commercial & Residential Buildings - Danfoss | Danfoss
3. Designing a metering system for small and medium-sized buildings (schneider-electric.com)
4. CSHub Building LCA & EPD Topic Summary (mit.edu)
5. Buildings Life Cycle Assessment (LCA) | Concrete Sustainability Hub (mit.edu)
6. Microsoft Word - BuildingLCAReview_v15.docx (mit.edu)