Ceiling Fan Design Guide

Paul Raftery and David Douglass-Jaimes

First Edition Released March, 2020

Created with funding from the California Energy Commission's
Electric Program Investment Charge Program (EPC-16-013)

CBE
CENTER FOR THE BUILT ENVIRONMENT

Table of Contents

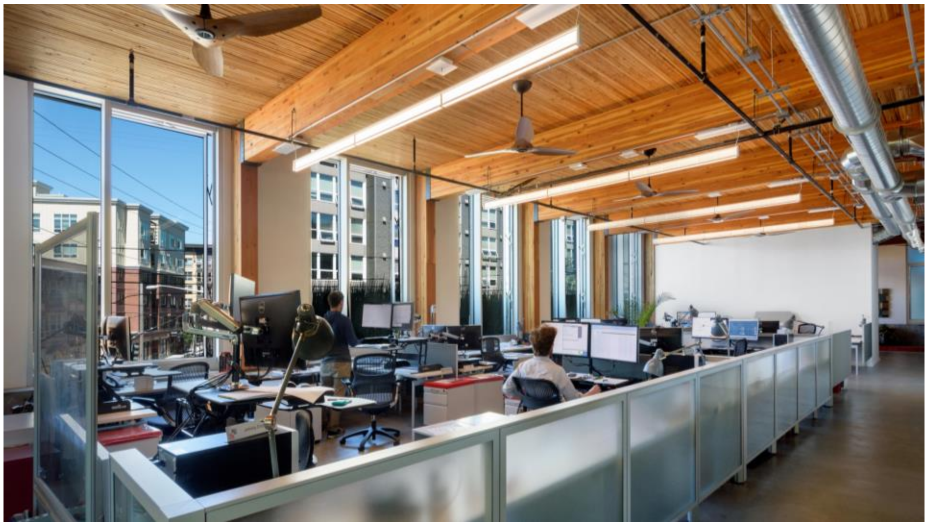


Figure 1: Bullitt Center, Seattle, WA, 2013. (Architecture:: Miller Hull, MEP: PAE Engineers, Photo: copyright Tim Griffith)

ABOUT THIS DESIGN GUIDE

This guide enables architects, designers, and engineers to maximize the many benefits of integrating ceiling fans into building systems. It introduces the advantages of using ceiling fans, describes how ceiling fans work, provides guidance and resources for designing spaces with ceiling fans and specifying ceiling fan products.

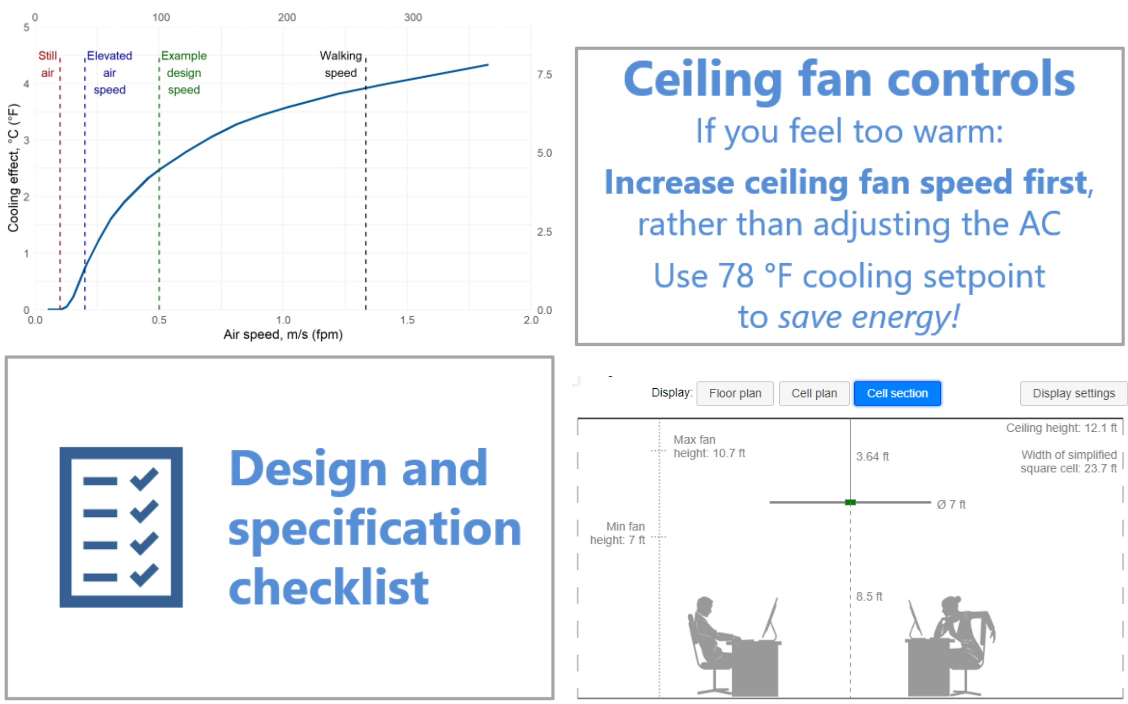


Figure 2: Highlights of the design guide include thermal comfort benefits of ceiling fans, guidance for control and user interface strategies, a ceiling fan design and specification checklist, and an introduction to the CBE Ceiling Fan Design Tool

Benefits Of Ceiling Fans

Ceiling fans are more than just a basic amenity for residential applications. Increasingly, ceiling fans are found in applications varying from industrial and warehouse applications to offices and high-end hospitality settings, and everything in between.

The extensive use of ceiling fans in residential applications (over 80% of single family homes in the United States have at least one ceiling fan), as demonstrated in Figure 3 below, indicates their effectiveness in supporting thermal comfort, and occupant demand for controllable air movement.

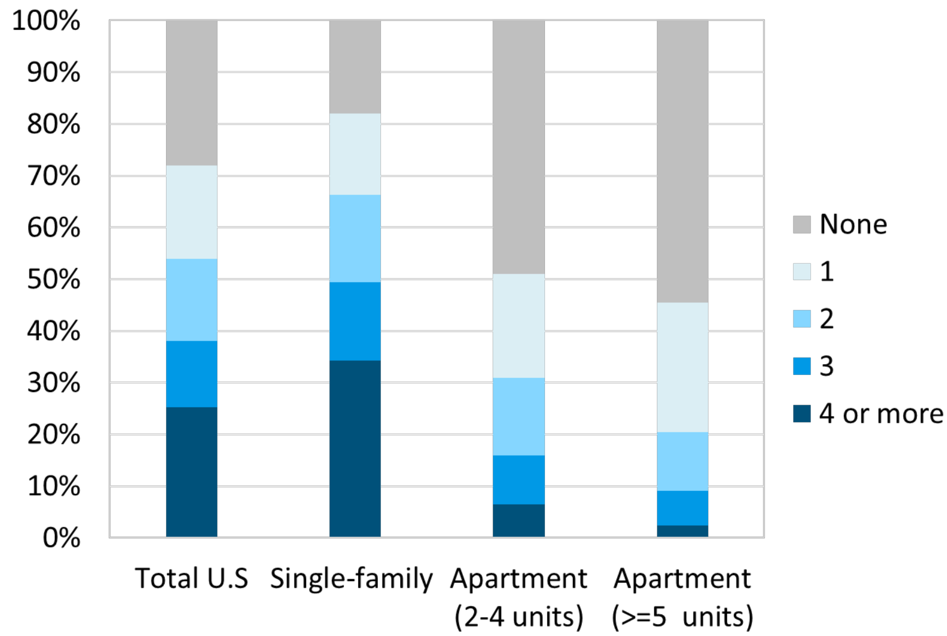


Figure 3: Number of fans per household by housing unit type, data source: U.S. Energy Information Administration 2015 Residential Energy Consumption Survey

This widespread applicability stems from the many benefits that ceiling fans can provide in interior environments.

The key benefits of ceiling fans are as follows:

- Thermal Comfort
- Improved Air Distribution
- Improved Perceived Air Quality
- HVAC First Cost Savings
- Energy Savings

The following subsections describe each of these benefits in more detail.

Thermal Comfort

Simply stated, thermal comfort is an occupant's satisfaction ("comfort") with the perceived temperature ("thermal sensation") of their environment. For centuries, humans have been using fans to help regulate thermal comfort. The reason for this is simple: in warm conditions there is generally less heat lost from the skin than in cooler conditions, and so people are at risk of warming up (the science of thermal comfort is described in more detail below). Increased air movement across the skin carries away more heat from the body (via convection and evaporation), and thereby restores comfort. Since the advent of mechanical HVAC systems, building designers have largely focused on a single factor of thermal comfort: air temperature. However, modifying other factors of thermal comfort, such as air speed, changes how a particular air temperature is perceived. Occupants near a ceiling fan will feel cooler than they would at the same temperature in still air, similar to the phenomenon of "wind chill", though the wind chill index is typically used for higher air speeds and colder temperatures than occur indoors. Similarly, when the air temperature is warmer, occupants near a fan will feel more comfortable than they would in still air conditions.

Improved Air Distribution

In addition to the thermal comfort benefits of increased air speeds, ceiling fans can also improve air distribution, working in concert with the HVAC system to provide the desired thermal conditions more consistently throughout a space. When correctly designed and operated, ceiling fans support the HVAC system to minimize temperature gradients within a space, providing more consistent temperature and air quality conditions throughout a space. This improved air distribution can be effective for both heating and cooling scenarios. For example, ASHRAE Standard 62.1 – Ventilation for Acceptable Indoor Air Quality lists a ventilation effectiveness of 0.8 for ceiling-supplied warm air systems (due to stratification of the warm air near the ceiling), but adding ceiling fans in this scenario brings the ventilation effectiveness back to 1.0, or fully mixed condition, reducing the amount of outside air required.

Improved Air Quality

By increasing air movement and improving air distribution in a space, ceiling fans also improve air quality. The increased air movement prevents the sensation of stale or stuffy air, and can help dissipate odors. One recent study has also documented a measurable air quality improvement from ceiling fans by dissipating CO_2 and other exhaled pollutants that would otherwise gather near occupants in still air conditions. Large-scale studies of occupant survey data indicate that occupants would prefer more air movement than they have, especially in conditions where occupants report feeling warm, as illustrated in Figure 4.

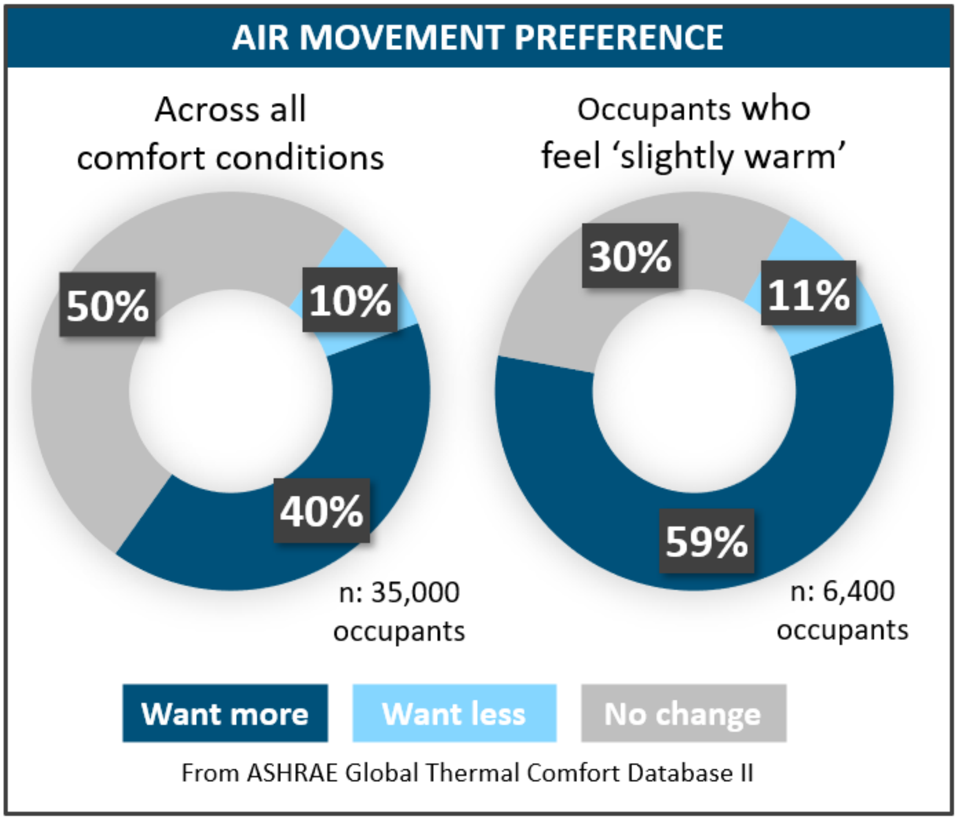


Figure 4: Occupant preference for more air movement (Data source: ASHRAE Global Thermal Comfort Database II)

First Cost Savings

The benefits described above—thermal comfort, improved air distribution, and improved air quality—achieve more than just increased occupant satisfaction, they can also help reduce first costs for HVAC systems. Using ceiling fans to more effectively distribute air throughout a space can reduce the extent of distribution ductwork and diffusers required to serve a zone. Additionally, if the same zone is designed to a slightly higher cooling setpoint due to the comfort cooling effect provided by the fans, this can also reduce the required latent and sensible cooling capacity of the HVAC system, providing first cost savings to equipment and ductwork.

Energy Savings

Perhaps most importantly, when implemented effectively as an integral component of a building's thermal comfort strategy, ceiling fans can also result in significant energy savings by reducing the demand on the HVAC system. Although ceiling fans consume energy, the potential HVAC savings outweighs fan energy use, typically by a factor ranging between 10 and 100 times. The primary energy saving derives from thermal comfort benefits of ceiling fans, keeping occupants comfortable at higher temperatures and allowing for increased cooling setpoints. Effectively, a room with ceiling fans is thermally comfortable over a wider range of temperatures than a room without ceiling fans. This wider range of temperatures reduces the cooling and fan energy consumption of the HVAC system. Counterintuitively, this wider range of temperatures also reduces *heating* energy consumption because when a space is warmer, it will take longer to cool down to the heating setpoint. Lastly, when ceiling fans are used to provide air distribution, reducing the extent of distribution ductwork and diffusers, they also help reduce HVAC fan energy by reducing the pressure drop in the air system. The section on Modelling, Simulation and Estimating Energy Savings discusses these effects in more.

History

Methods of increasing air speeds to produce a cooling effect have been in use for centuries, from the most rudimentary handheld fans to more elaborate systems of sail-like fabric sheets or wooden panels mounted to ceilings. Ceiling-mounted "punkah" fans, like those shown in Figure 5, were common in places like colonial India and the Antebellum South in the US, and were manually operated with ropes pulled by servants or enslaved people. For a more localized cooling effect, there were also fan chairs like the one used by George Washington, as shown in Figure 5.

Figure 5: Historical fan technologies: fabric punkah fans at the Church of St. Francis in Kochi, India, circa 1795 ([photo by Adam Jones]() via Wikimedia Commons, [creative commons license CC BY-SA 3.0]()), and a carved wood punkah fan at Melrose Plantation in Natchez, Mississippi, circa 1847 (photo courtesy [The Punka Project]()); George Washington's fan chair, circa 1790 (photo courtesy [The Punka Project]()); ceiling fans on a New York City subway car, circa 1910, at the New York Transit Museum ([photo by Eric Fisher]() via Wikimedia Commons, [creative commons license CC BY 2.0]()).

The first electric ceiling fan was invented by Philip Diehl in 1882, and the new technology quickly gained in popularity. In the 1910s ceiling fans were even installed on New York City subway trains. However, with the advent of mechanical cooling, and a concerted marketing effort to present air conditioners as the sole modern, healthy means of providing comfort cooling, ceiling fans waned in popularity and largely disappeared from many types of indoor spaces.

However, the inherent effectiveness of ceiling fans at cooling with air movement did not change, and today designers and engineers are increasingly recognizing the synergy of *combining* modern ceiling fans with mechanical HVAC systems to improve comfort and energy efficiency in a broad range of applications. Ceiling fans should no longer be seen simply as a decorative element or residential amenity, but rather as an integral part of an effective thermal comfort system.

CEILING FANS AND THERMAL COMFORT

In this section we discuss the thermal comfort related effects of increased air movement using ceiling fans for cooling applications. We also discuss tools such as the CBE Thermal Comfort Tool to help determine the right air speed and other factors for optimal thermal comfort. Figure 6 shows the cooling effect–or how many degrees warmer the air temperature can be to provide the same level of thermal comfort–associated with increased air speeds. This figure also highlights that the design air speeds under discussion in this guide are well below the air speeds that a person experiences every day. An example design speed of 0.5 m/s or 100 fpm, equal to approximately 2 °C or 4 °F cooling effect, is approximately half the air speed that a person experiences just from the relative motion of walking slowly through still-air conditions.

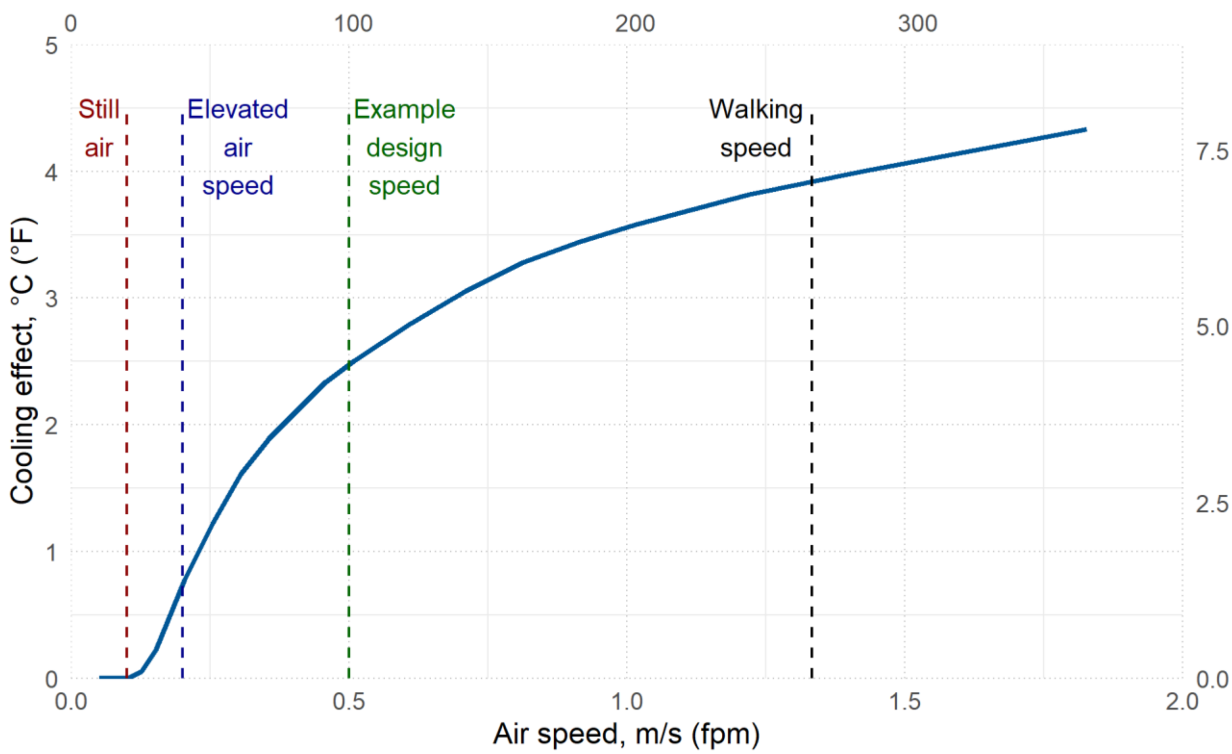


Figure 6: Cooling effect of increased air speed[1]

Human Body Thermoregulation

As discussed above, thermal comfort is an occupant's satisfaction ("comfort") with the perceived temperature ("thermal") of their environment. This satisfaction depends on how much heat is released or retained by the occupant's body. Heat transfer to and from the body occurs in four ways. These are listed in order of decreasing amount of heat transfer under standard conditions:

- Radiation - heat transfer via electromagnetic waves between objects that are not touching. The most familiar form of radiant heat transfer is the radiant energy from the sun. However,

[1] for a 'typical' office worker in cooling conditions, according to ASHRAE 55:2017 at an operative temperature of 76F, 50% relative humidity, 0.6 clo, 1.13 met.

longwave radiation to surrounding surfaces is also a primary mechanism of heat loss from the human body.

- Convection – heat transfer between a solid source and a fluid, in this case between skin and air, is of similar magnitude to heat transfer by radiation under standard conditions (still air). The amount of heat loss from the body through convection depends on the air speed, as that directly affects the convective heat transfer rate from the skin. Still air acts like an insulator, with convection only occurring due to the buoyancy driven effect driven by the temperature difference between skin (or clothes) and the surrounding air. As air speed increases, this gives rise to forced convection, allowing for more heat to be released.
- Evaporation - heat loss through the phase change of sweat from liquid to vapor. The phase change requires energy in the form of heat extracted from the skin, cooling the body when sweat evaporates. The rate of evaporation depends on the humidity of the surrounding air, with drier air able to absorb more moisture through evaporation.
- Conduction - heat transfer between objects in contact. The cooling sensation of holding a cold drink or the warming sensation of touching a hot surface are both examples of heat transfer through conduction. Conduction is typically responsible for the smallest share of heat loss from the body.

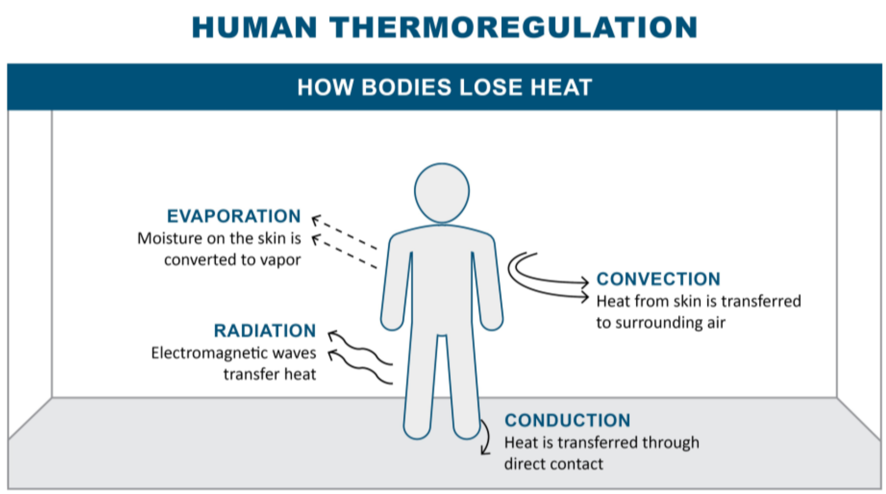


Figure 7: Human body heat rejection

Factors of Thermal Comfort

ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy identifies six factors that affect thermal comfort:

- Metabolic Rate - the rate of transformation of chemical energy into heat and mechanical work, based on the level of activity. For example, the body generates more heat while walking than while sitting still.
- Clothing Insulation - the insulating effect of clothing preventing heat loss from the body. For example, shorts and a short-sleeve shirt will allow more heat loss from the body than pants and a heavy sweater.

- Air Temperature - the temperature of air at a certain point.
- Mean Radiant Temperature - the average temperature of the surfaces surrounding a certain point, weighted by how large an angle that surface makes when viewed from that point.
- Air velocity or speed - the velocity or speed of air at a certain point.
- Humidity - how much moisture the air contains.

How Ceiling Fans Help Meet Thermal Comfort Goals

Ceiling fans increase air speed, and increased air speed accelerates two of the heat transfer mechanisms described above: convection and evaporation. Thus, ceiling fans accelerate heat loss from the body, providing a cooling sensation. The cooling sensation from increased air speed allows the body to maintain thermal comfort at higher air temperatures than what would be comfortable in still air.

In addition to providing comfort at increased temperatures, ceiling fans are capable of providing instantaneous comfort effects that thermostat adjustments cannot. A thermostat and HVAC system that conditions the whole room generally takes 15 minutes or longer before the occupant will perceive a change in their thermal environment. However, a ceiling fan has an almost instantaneous effect. If an occupant feels too warm, turning on or increasing the speed of a ceiling fan instantly provides a cooling sensation. Similarly, if an occupant is too cool and the fan is operating, reducing the ceiling fan speed or turning it off instantly provides a warmer sensation. Ceiling fans are also ideally suited to providing adaptive or transitional comfort for changing human comfort conditions. Adjusting ceiling fan speeds can help accommodate the natural fluctuations in body temperature and comfort preferences throughout the day. Similarly, the adjustable nature of ceiling fans can provide enhanced thermal comfort during transitional moments, such as the changing comfort needs when transitioning from an active metabolic rate event (for example, after walking from a meeting in a different part of the building, or arriving in to work from a morning commute) to a resting metabolic rate (such as sitting at a desk in an office), or simply due to different personal thermal comfort requirements of occupants in the same physical space.

In order to determine how much air movement is needed for thermal comfort and occupant satisfaction, we can look at ASHRAE Standard 55 and the CBE Thermal Comfort Tool.

ASHRAE Standard 55 Thermal Environmental Conditions For Human Occupancy

ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy identifies factors (discussed above) that may affect thermal comfort in an indoor environment and how occupant satisfaction is affected when these factors are changed. The standard also provides methods to determine optimal values for each of the factors to create a comfortable environment.

Standard 55 outlines both a graphical and analytical method to determine acceptable thermal comfort zones. In the graphical comfort zone method (Section 5.3.1 of the standard), comfort zones are shown on a graph based on occupant metabolic rates and clothing insulation levels. By using space conditions, such as temperature and humidity, it can be determined whether the space falls within the occupants' comfort zone. This method can only be used however when the occupants' metabolic rates and clothing insulation levels are within a certain range and does not account for changes in comfort zone due to elevated air speed.

The analytical comfort zone method (Normative Appendix B) can be used for a wider range of occupant characteristics. The analytical comfort method calculates a predicted mean vote (PMV) based on a combination of thermal comfort factors. PMV is an index that predicts the average vote of thermal sensation in a large group of people on scale from –3 (cold) to 3 (hot), where a score of 0 would be considered perfectly comfortable. Using this method, a PMV between –0.5 and 0.5 must be obtained to be ASHRAE 55 compliant.

ASHRAE 55-2017 Addendum C introduces comfort control classification levels (CCCLs) into the standard, where a lower CCCL number indicates an improved level of occupant comfort. This captures the beneficial effects of increased opportunities for local and group level control of thermal comfort.

Table 1: ASHRAE 55-2017 Addendum C comfort control classification levels (CCCLs)

CCCL	Required Control Measure(s)	Informative Examples Meeting CCCL
1	Personal control of **two** or more	• Private office with a ceiling fan and an occupant adjustable thermostat • Shared office with desktop fans and seat warmers for each occupant
2	Personal control of **one**	• Private office with an occupant adjustable thermostat • Shared office with a desktop fan for each occupant
3	Multi occupant control of **two** or more	• Shared office with an occupant adjustable thermostat and ceiling fan control
4	Multi occupant control of **one**	• Shared office with an occupant adjustable thermostat
5	**No** occupant control	• Shared or private office with an un-adjustable thermostat or no thermostat

Thermal Comfort Calculations With Elevated Air Speed

Standard 55 also provides a method called The Elevated Air Speed Comfort (Section 5.3.3. of standard) to calculate thermal comfort in situations of elevated airspeed. This method uses a combination of the Analytical Comfort Zone Method combined with the Standard Effective Temperature (SET) method (Normative Appendix D of standard). Since increasing air speeds has a cooling effect, the method calculates adjusted air and radiant temperatures according to how occupants are expected to feel under increased air speed conditions to calculate a new PMV value. The "Standard Effective Temperature" (SET) output translates the 6 thermal comfort factors (from above) into a single temperature equivalent. The SET provides a single metric that can be compared across a variety of comfort conditions.

Cooling effect is also used to calculate the Cooling Fan Efficiency (CFE). CFE is defined in ASHRAE Standard 216, currently under development, as the ratio of the cooling effect to the input power of the fan. CFE gives people a standardized way to compare how much cooling a fan provides when consuming the same amount of energy.

CBE Thermal Comfort Tool

A helpful tool to find comfort zones at elevated air speeds according to ASHRAE 55 methodology is the CBE Thermal Comfort Tool, an online tool developed by The Center for the Built Environment at the University of California at Berkeley.

The user enters temperature, air speed, humidity, metabolic rate and clothing level into the tool to calculate results including PMV, SET, and ASHRAE 55 compliance as well as generating the graph below in Figure 8. The blue shaded area represents the ASHRAE 55 compliant comfort zone while the red mark shows where the user inputs are relative to the comfort zone. The tool also supports the international comfort standard ISO EN 16798.

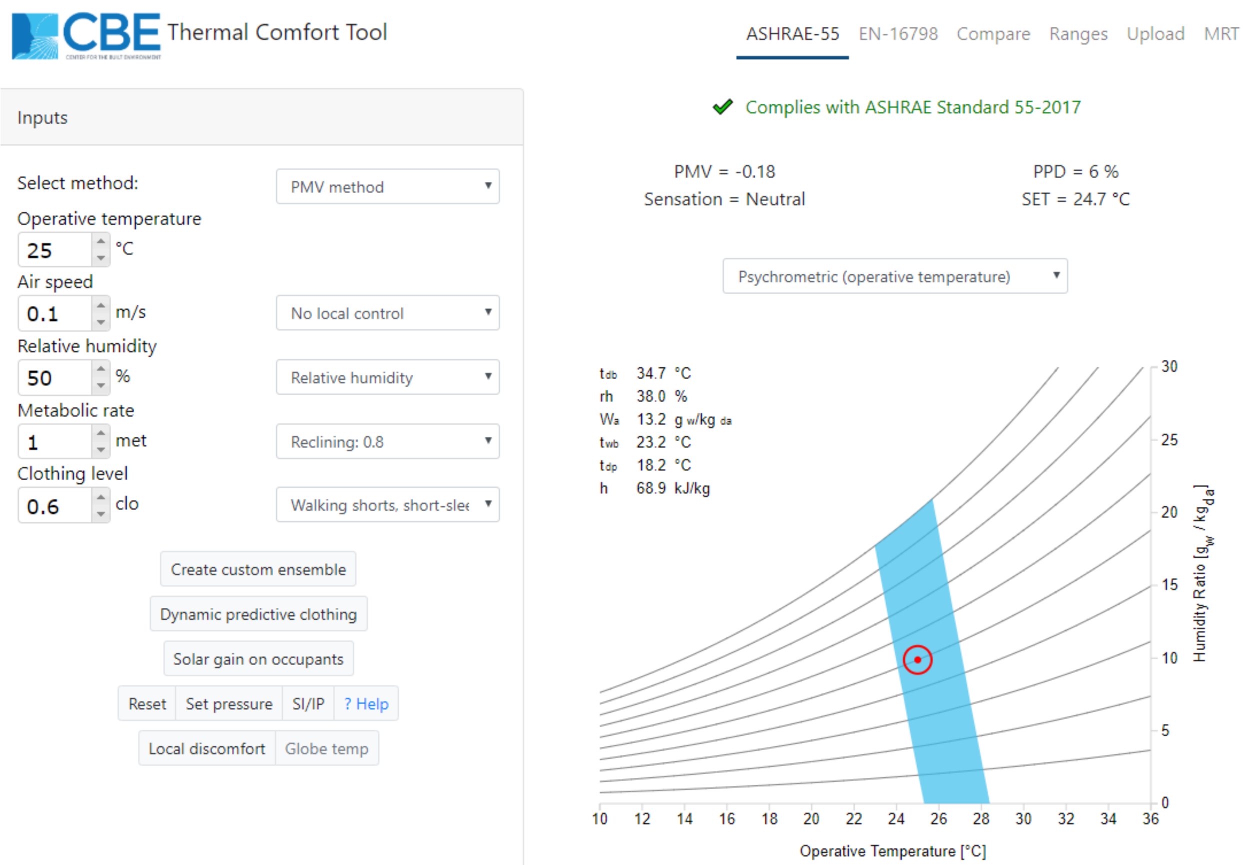


Figure 8: Example screenshot of the CBE Thermal Comfort Tool, showing user inputs, psychometric chart, and results

The CBE Thermal Comfort Tool also takes into account elevated air speeds. As the air speeds increase, the range of acceptable temperatures increases, and the blue shaded area shifts to the right. Using higher air speeds allows the user to be ASHRAE 55 compliant at higher cooling temperature setpoints. Note that Standard 55 has a maximum average air speed permitted in the case that occupants do not have control over the system (0.8 m/s or 160 fpm). This can be specified as an input in the Thermal Comfort Tool as well. To support this functionality, users can also select the "air speed vs. operative air temperature" mode from the drop down menu above the chart to view the comfort range and results in terms of air speed and temperature, as shown in Figure 9, below.

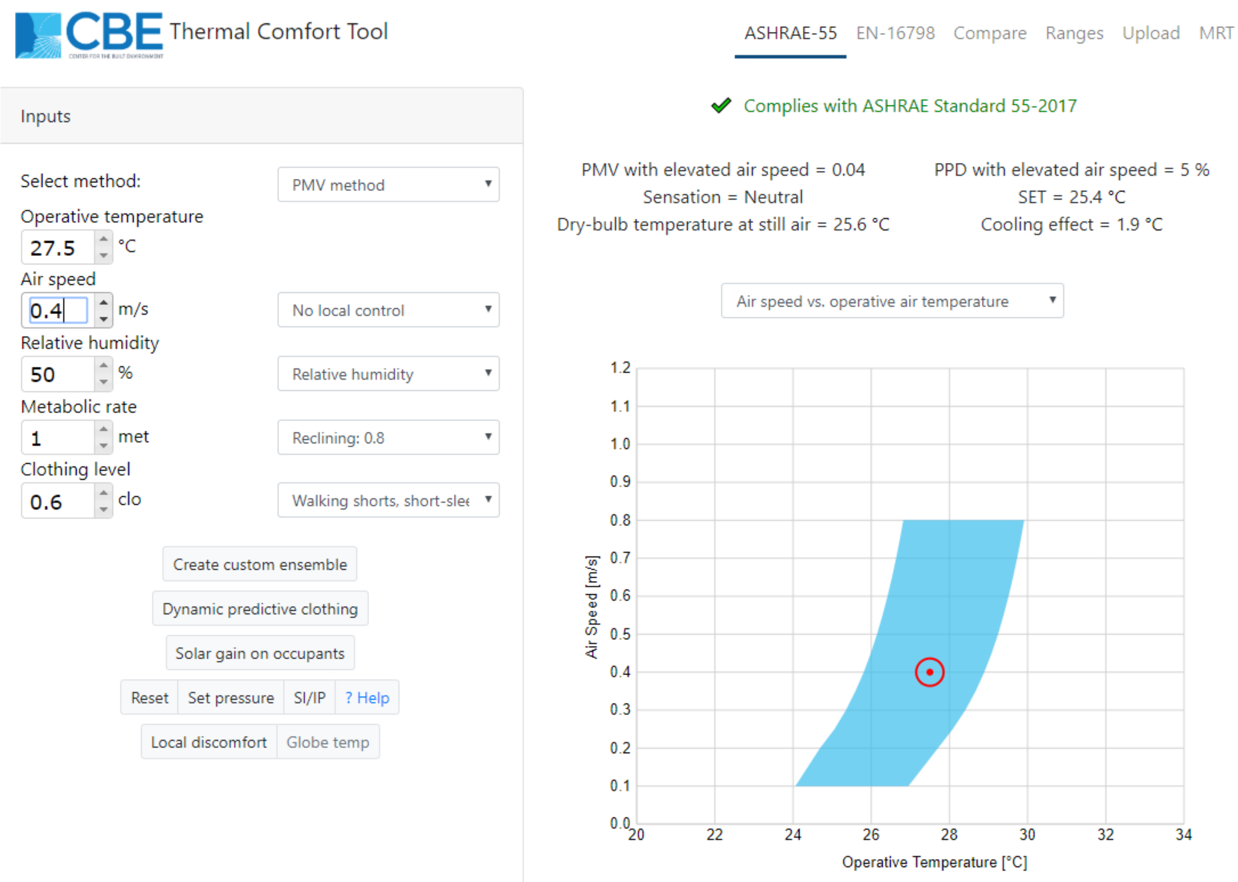


Figure 9: Example screenshot of the CBE Thermal Comfort Tool showing air speed vs. operative air temperature mode

Ceiling Fans For Destratification In Heating Mode

In addition to directly cooling occupants, ceiling fans also effectively mix the air in a space, which has several applications. The most common of these applications is where the temperatures in a space are stratified, with much warmer air close to the ceiling and cooler air near the floor. This typically occurs in spaces with high ceilings or where the heating equipment has a relatively high discharge temperature. In these conditions, ceiling fans can mix the air in the space such that the temperature at the floor (and close where the thermostat is located) is close to the average temperature in the space. This can save energy and also improve occupant comfort. Ceiling fans can run in either direction to achieve this mixing, though they will use more power to achieve the same mixing effect when operating in reverse (moving air upward) than forwards (moving air downward). Note that when destratifying, the space is typically operating in heating mode and operating at the lower end of the range of temperatures that define the thermal comfort zone. As such it is very important to maintain very low air speeds in the occupied zone in order to avoid the sensation of draft. Depending on the specific conditions, the occupant locations, and the minimum speed capabilities of the fan, running the fan in forward or reverse may be better able to achieve this goal.

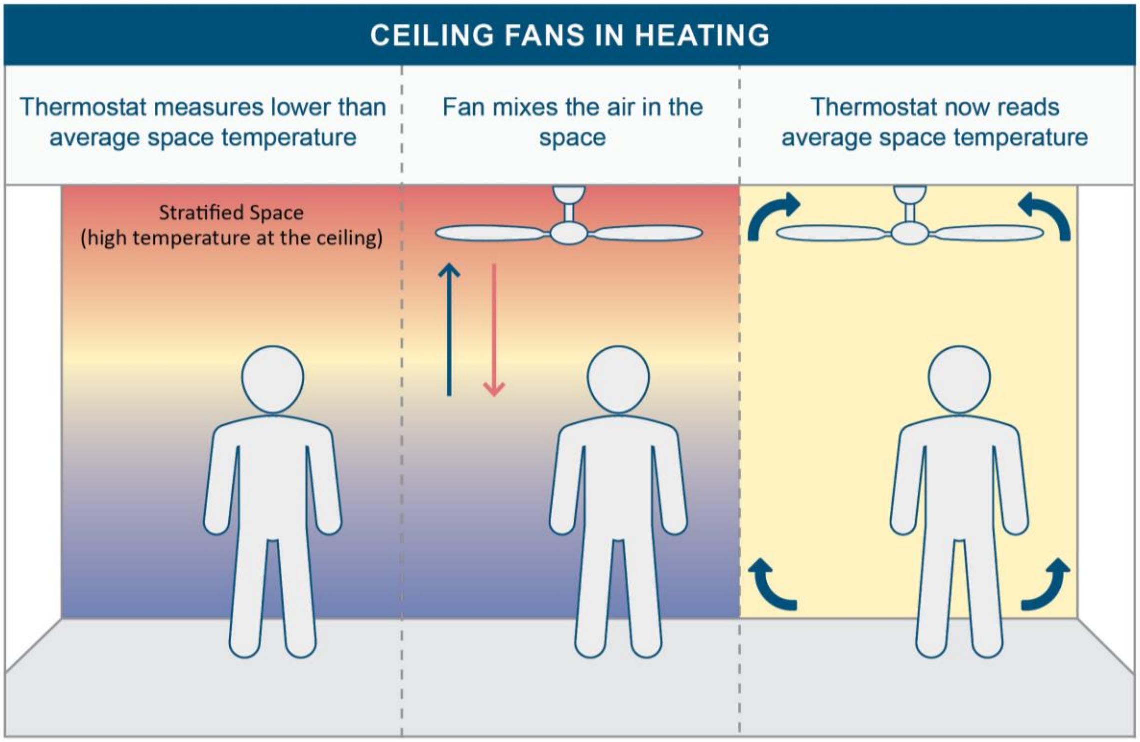


Figure 10: Ceiling fans for destratification

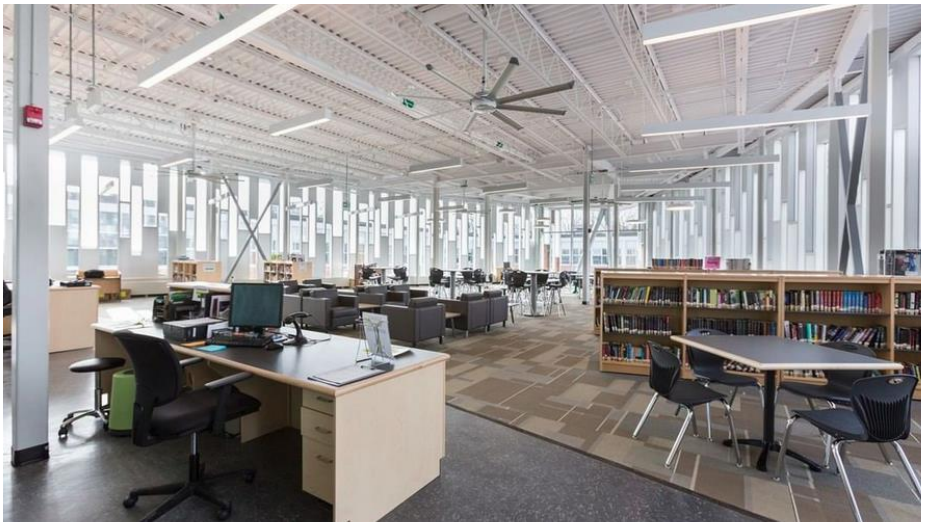


Figure 11: Large-diameter ceiling fans at Barrie North School library. (Photo copyright Big Ass Fans)

ABOUT CEILING FANS

The following sections describe the different types of ceiling fans, and the features that differentiate ceiling fan models.

Fan Types

As part of the "Uniform Test Method for Measuring the Energy Consumption of Ceiling Fans"[2] the US Department of Energy (DOE) defines a variety of ceiling fans types. For the purpose of this guide, discussions focus on two main ceiling fan types:

- **Standard ceiling fan –** any ceiling fan with a diameter greater than 18 inches but no more than 7 feet, and with the lowest point of the fan blades more than 10 inches below the ceiling. A standard ceiling fan not exceed the limits outlined in Table 2 below.
- **Large-diameter ceiling fan** – any ceiling fan that is greater than seven feet in diameter. These are often also known as High Volume Low Speed (HVLS) fans.

In addition to these two primary types of ceiling fans, the DOE defines several other fan types that are commonly used, many of which fall under the category of small-diameter ceiling fan.

- **Small-diameter ceiling fan** – any ceiling fan that is more than 18 inches in diameter but less than or equal to seven feet in diameter, and with an airflow of at least 1,840 CFM and a rotational speed of more than 90 RPM at its highest speed.
    - **High-speed small-diameter ceiling fan** – any small-diameter ceiling fan that has a blade thickness of less than 3.2 mm at the edge or a maximum tip speed greater than the applicable limit specified in Table 2 below.

---

[2]Appendix U to Subpart B of Part 430 – Uniform Test Method for Measuring the Energy Consumption of Ceiling Fans, Code of Federal Regulations, Title 10, Chapter II, Subchapter D. https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=723eddbb09c4b806e38bab695a9f2dbd&mc=true&n=pt10.3.430&r=PART&ty=HTML#ap10.3.430_127.u

- **Low-speed small-diameter ceiling fan** – any small-diameter ceiling fan that has a blade thickness greater than or equal to 3.2 mm at the edge and a maximum tip speed less than or equal to the applicable limit specified in Table 2 below. ("Standard ceiling fans", defined above, are a type of low-speed small-diameter ceiling fan.)
    - **Hugger ceiling fan** – any low-speed small-diameter ceiling fan for which the lowest point on the fan blades is less than or equal to 10 inches from the ceiling.

- **Very-small-diameter ceiling fan** – any ceiling fan with one or more fan heads, each of which has a blade span of 18 inches or less, and with an airflow of at least 1,840 CFM and a rotational speed of more than 90 RPM at its highest speed.
- **Highly-decorative ceiling fan** – any ceiling fan with a maximum rotational speed of 90 RPM and less than 1,840 CFM airflow at high speed.

Note that while these DOE definitions include a variety of subcategories for small-diameter fans, any fan larger than seven feet in diameter is simply a "large-diameter" fan, with no further differentiation.

Table 2: Ceiling Fan Blade and Tip Speed Criteria (Adapted from DOE Definitions)

Airflow Direction	Thickness (t) of edges of blades		Tip speed threshold	
	mm	(inch)	m/s	(feet per minute)
Downward-Only	4.8 > t ≥ 3.2	(3/16 > t ≥ 1/8)	16.3	(3200)
Downward-Only	t ≥ 4.8	(t ≥ 3/16)	20.3	(4000)
Reversible	4.8 > t ≥ 3.2	(3/16 > t ≥ 1/8)	12.2	(2400)
Reversible	t ≥ 4.8	(t ≥ 3/16)	16.3	(3200)

As noted above, this guide is primarily focused on two main fan types, defined above as standard ceiling fans and large-diameter ceiling fans. However, much of the discussion in this guide will also be relevant to the other small-diameter ceiling fan types beyond the "standard" definition, and there is significant overlap between many of the small-diameter ceiling fan subcategories. Note, for example, that "standard ceiling fans" are a type of low-speed small-diameter ceiling fan, and "hugger ceiling fans" are essentially equivalent to standard ceiling fans but with fan blades mounted closer to the ceiling (despite the negative effect on efficiency) for suitability in spaces with lower ceiling heights.

In general, a larger diameter fan blade can move a larger volume of air than a smaller diameter fan blade. As fan diameter increases, rotational speed is typically limited to prevent excessive noise from the fan blades, especially near the blade tip. Additionally, where fans can be mounted at blade heights below 10 ft (i.e. almost all standard fans), rotational speed must be limited to meet safety criteria (see UL 507) for the maximum speed of the blade tips. Large-diameter ceiling fans are sometimes referred to as "high volume low speed" or HVLS fans. Because the design and shape of the fan blades can also have a significant impact on airflow, as described in more detail below, the HVLS terminology is typically used to describe large ceiling fans that are designed to prioritize performance in large commercial and industrial spaces. For example, some large-diameter ceiling fans include "winglets" or blade tip fences (see examples in Figure 11: Large-diameter ceiling fans at Barrie North School library. (Photo copyright Big Ass Fans), Figure 38: High School Gymnasium, San Marcos, CA (Architecture: LPA Architect, Photo: copyright

Cris Costea), and Figure 40: Bluescope Buildings, North Carolina, USA (Photo: copyright Big Ass Fans)) to maximize airflow and minimize noise, which is a less common problem in standard fans as the blade tip speed is already constrained for safety reasons.

Though standard ceiling fans are often thought of in their residential applications, they are equally effective for comfort cooling in most nonresidential applications (including offices, classrooms, gyms, hospitality, etc.) where they can be positioned near the occupants. Large-diameter ceiling fans require higher ceilings (typically at least 11 ft) and larger spaces free from obstructions to accommodate their increased diameter. As a result, large-diameter ceiling fans are most often found in nonresidential commercial and industrial applications.

Although the fan type definitions from the DOE are focused on fan diameter, in the case of specific fan products there is some overlap in terms of applications and fan styles. Some large-diameter fans are available in styles that are more frequently associated with standard fans, and some manufacturers have HVLS fan models in diameters less than seven feet. Additionally, there are some large-diameter fans that have a relatively low maximum rotational speed and thus, meet blade tip speed and thickness requirements for mounting below 10 ft, though these also have a relatively low maximum airflow.

The DOE also defines a variety of other specialty ceiling fan types (including belt-driven ceiling fans, centrifugal ceiling fans, multi-head ceiling fans, and oscillating ceiling fans), but those specialty types are not the subject of this guide.

Blade Types And Configuration

Blade shape, number of blades, and blade pitch are important factors in increasing energy efficiency while maximizing air flow through the fan blades.

There are two main types of blades shapes shown in Figure 12 below. Blade shapes have evolved over time from flat to airfoil-style blades to become more energy efficient and maximize air movement. As the name implies, flat ceiling fan blades are flat panels mounted at a fixed angle, whereas airfoil blades are similar to airplane wings in section. Similar to the cross-section of an aircraft wing, the curvature of the airfoil blades helps increase air flow through the ceiling fan, minimizing air turbulence at the trailing edge of the blade common to flat blades. Airfoil-style blades are thus typically more efficient and also quieter than flat blades. However, flat blades are cheaper to manufacture. Note that flat blades will perform equally whether the fan is operating in the forwards (blowing down) or reverse (blowing upwards) direction. In contrast, airfoil blades will not operate as efficiently in reverse, and will typically have a lower airflow when doing so. Some fan models have blades that can be manually attached in inverted position, or can mechanically invert the blade while it is attached to the fan, which allows for improved efficiency when operating in reverse.

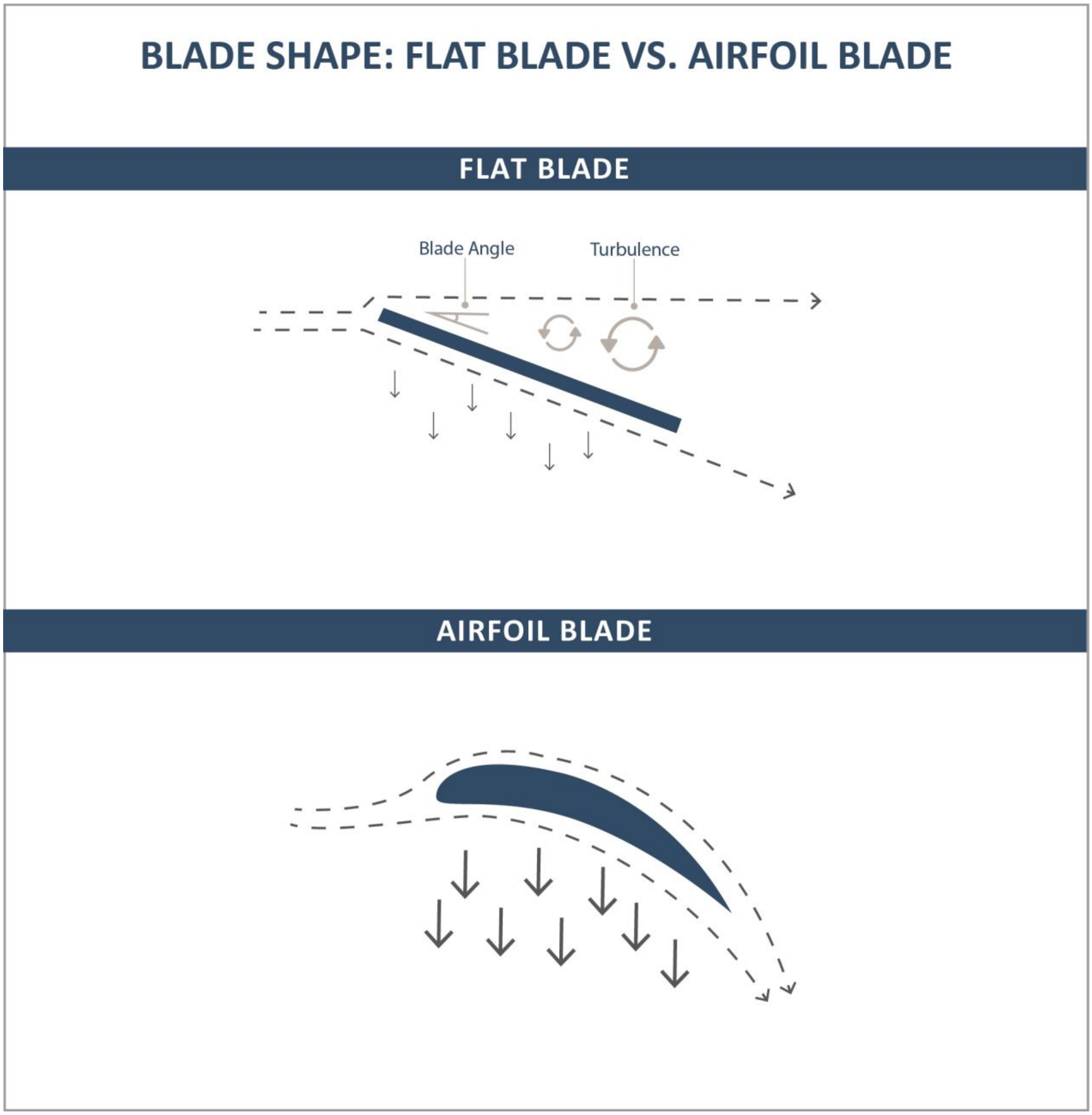


Figure 12: Ceiling Fan Blade Types

The number of blades is an important factor in increasing airflow of ceiling fans. Although increasing the number of blades will increase airflow, the increased weight and drag due to the blades can cause a loss in energy efficiency. Standard fans typically have between 3 and 5 blades, though some models have as few as 2 blades or up to 6 blades. Large-diameter fans typically have 6 or 8 blades, though some models have as few as 3 blades.

Similarly, increasing the blade's angle may also increase airflow at the cost of energy efficiency. Academic modeling studies have found the optimal blade angle to be 8-10° for residential fans. Manufacturers recommend 12-15°. Some airfoil-style blades also vary the blade angle over the length of the fan blade, with steeper angles toward the center of the fan to maximize air flow for the low blade speed in this region, and reducing to shallower angles toward the tips where the blade speed is high in order to limit drag and maximize energy efficiency.

Motor And Drive Types

There are three main types of motors used in ceiling fans: AC Induction, Permanent Magnet DC (PMDC), and Brushless Direct Current (DC) motors. Generally, there are very large percentage efficiency savings from moving from AC to DC motors for small fans, and far less of an effect for large diameter fans.

- AC Induction:
  - How it works: Electromagnets on outside of motors (stator) creates a rotating magnetic field causing motor rotation through induction.
  - Benefits: Provides constant, even airflow and are cheaper than DC motors.
- PMDC:
  - How it works: Permanent magnets are located on the motor stator creating a stationary magnetic field. A segmented commutator rotates within the magnetic field creating a mechanical switching of current direction.
  - Benefits: More energy efficient than AC motors and provides constant force over a wider range of speeds than AC motors.
- Brushless DC:
  - How it works: Permanent magnets are rotated in motor creating a rotating magnetic field. Current direction in the stator is switched in relation to the magnetic field to create rotation.
  - Benefits: Most energy efficient of the three motor types (for small motors on small diameter fans, a DC motor often will use 70% less energy than an AC motor), most quiet, and has a longer service life than PMDC motors.

Fans may also be either direct drive or gear-driven. Almost all small-diameter fans are direct drive, but large-diameter ceiling fans may either be direct-drive or gear-driven.

Direct-drive fans are quieter than gear-driven fans, have a more refined appearance and have reduced operating cost. However, direct-drive fans do provide less air flow and it may be harder to replace the motors. Due to this, direct-drive fans are typically used in situations where sound level and aesthetics are a concern and less airflow is needed.

On the other hand, gear-driven fans allow for higher motor power and are often used in situations where maximizing airflow is a priority over sound levels or aesthetics. This is well suited for industrial settings where ceilings are high and there is little or no air conditioning.

Figure 13: Coastal Biology Building, University of California Santa Cruz. (Architecture: EHDD, Photo: copyright Michael David Rose)

FAN SELECTION, SIZING, AND LAYOUT

The following sections provide guidance on how to understand fan performance metrics, and recommendations for fan size, spacing, and location.

Understanding Fan Metrics

A number of factors determine a fan's performance, as well as its suitability to a given application. Some of the most critical factors are described in the following sections.

Diameter and rotational speed

Ceiling fans are available in a wide range of diameters, from very small fans approximately 18 inches in diameter to very large fans up to 24 feet in diameter. Determining the appropriate fan diameter depends largely on the dimensions of the space and the application, as discussed in more detail later in this guide. The California Energy Commission maintains the Modernized Appliance Efficiency Database System (MAEDbS), which contains a large dataset of information on ceiling fans as well as many other types of appliances. For context, this dataset shows that the majority of fan models on the market today are between 4 and 5 ft in diameter, and presumably therefore aimed at the residential market, as illustrated in Figure 14, below.

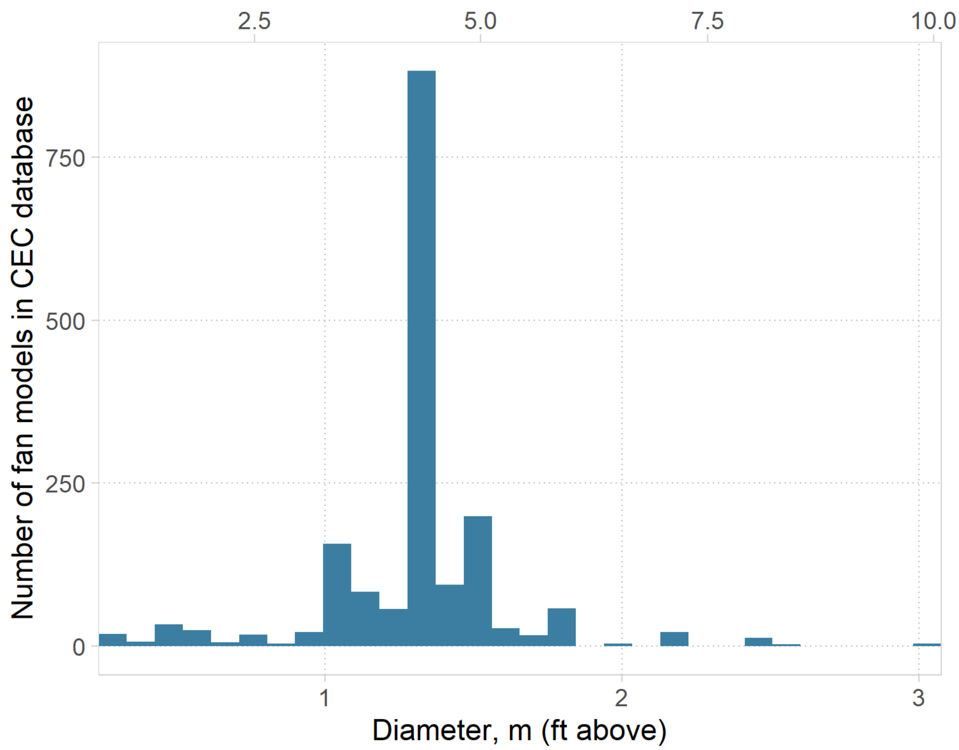


Figure 14: Distribution of fan diameters in a random sample of the fans in the CEC MAEDbS appliance database

All other factors being equal, a larger diameter fan will produce greater airflow through the fan than a smaller diameter fan at the same rotational speed. Figure 15 below shows a range of example fans of varying diameters and the range of possible airflows and rotational speeds at which those fans can operate. In general, higher airflow through the fan generally results in higher average air speeds in the space. Additionally, larger fan diameters increase the uniformity of air speeds throughout a space. Lastly, larger diameter fans increase the depth of the boundary layer of air moving along the floor in the spreading zone outside the fan blades. This figure also highlights the differences between fan models even if they have the same diameter. Comparing the TypeG and TypeF fans, of equal diameter (8 ft), it is clear that the range of performance varies by fan type. The TypeG fan has a higher maximum airflow, a lower minimum airflow, and a higher rotational speed for any particular airflow point.

For any particular fan, airflow is linear with rotational speed, as Figure 15 also shows. Additionally, the air speed at any point in the space is also directly linear with fan rotational speed. So, if a point in the room measures 100 fpm when the fan is rotating at 80 rpm, it will measure approximately 50 fpm at 40 rpm. This relationship begins to break down at very low air speed, very low rotational speeds, or where the fan blade height is unusually far from the floor (e.g. > 10 ft).

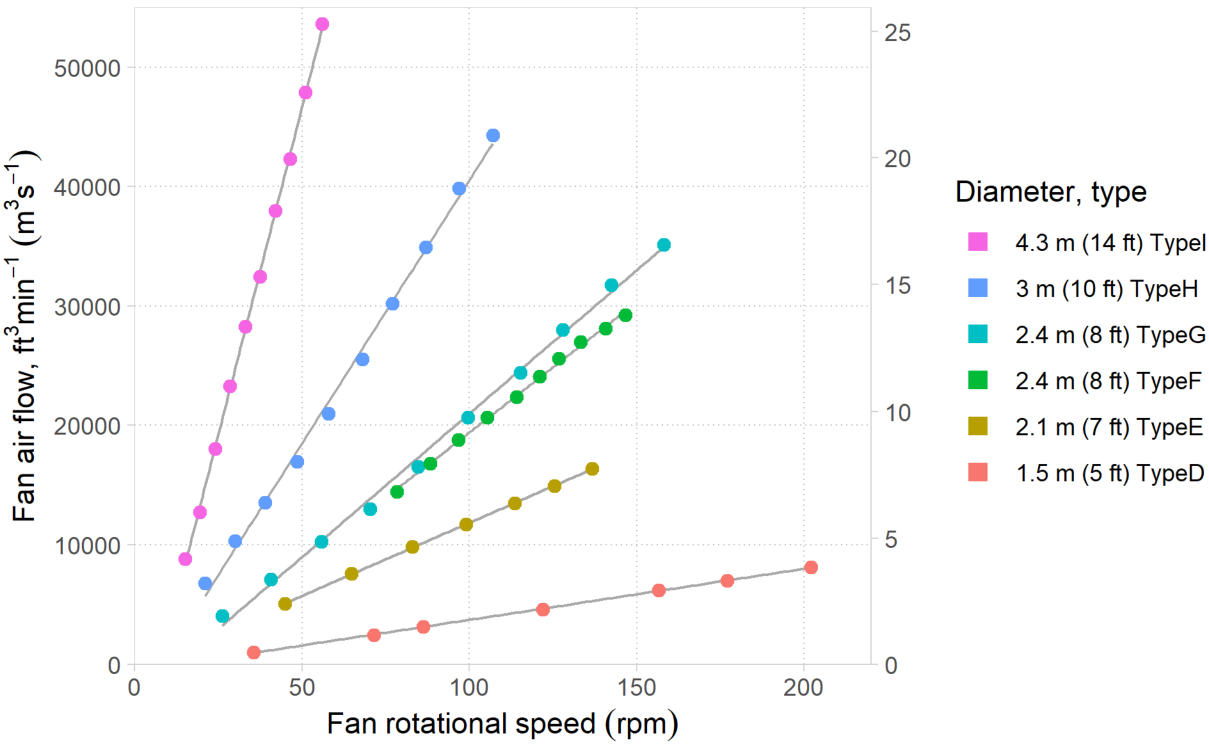


Figure 15: Fan rotation speed and fan air flow for fans of varying diameters

Power and fan efficacy

The power consumed by a fan increases in proportion to the cube of its rotational speed, while the airflow generated by the fan increases linearly with its rotational speed. Thus, fan efficacy - or the airflow per unit power consumed - decreases as fan speed increases. However, in many fan models, motor efficiency is poor at lower speeds, partially counteracting this effect. In the MAEDbS dataset, the typical (median) fan efficacy at the lowest operating speed of each fan is 165 cfm/W, while it is 79 cfm/W at highest operating speed. Note that the only way to make a direct energy performance comparison between one fan and another is to compare it under the same conditions - the same diameter and the same power (or the same airflow). This is because fans with lower-rated maximum airflows will have a better-rated efficiency even if they consume more power to provide the same airflow. Note that the US Department of Energy and Energy Star criteria – and the metric that shows up on the Energy Guide label - calculates the ceiling fan airflow efficacy using an average of the efficiency at different operating speeds, weighted according to the amount of time the fan is expected to operate at those speeds, including a standby power loss. This does not account for different maximum and minimum airflows between fans of the same diameter, so it can be misleading. As before, fans with lower maximum airflow will generally perform better in this efficiency metric. Figure 16 below highlights the issue, where three fans have the same 234 CFM/W efficacy, but there is a clear difference in performance between the fans due to the different range of airflows provided. The fan represented by the curve furthest to the left (least efficient, lowest maximum airflow) is rated as having the same overall efficacy as the fan furthest to the right (most efficient, highest maximum airflow).

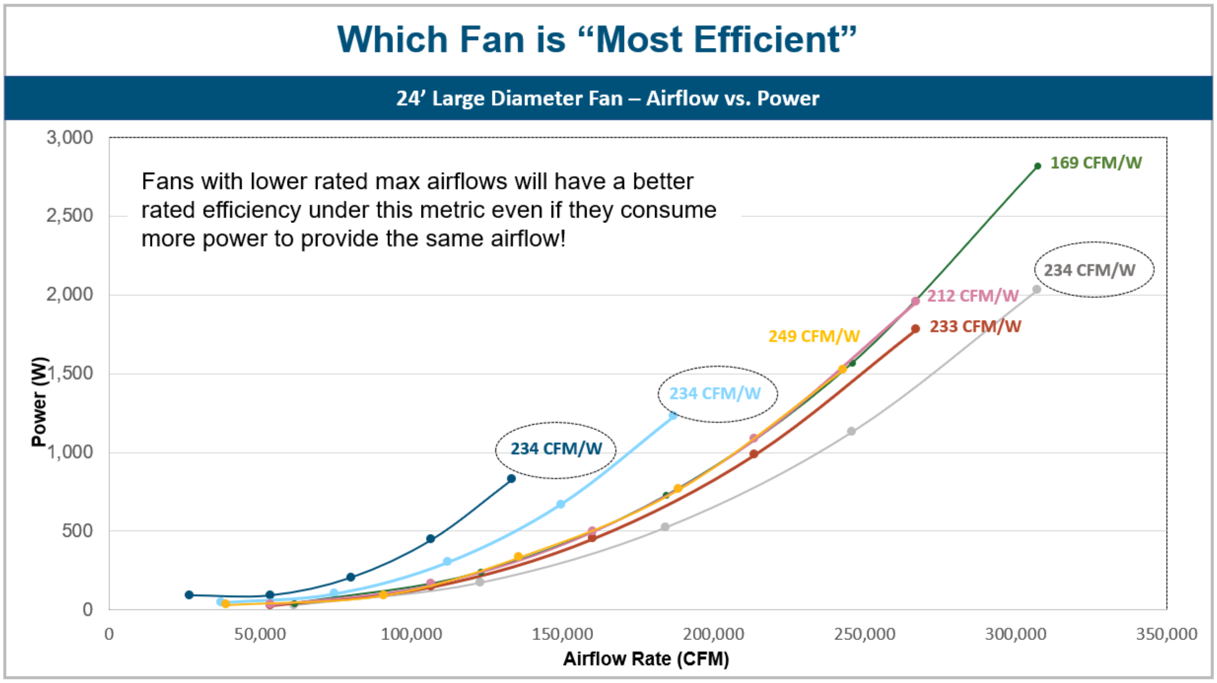


Figure 16: Fan efficacy versus total air flow and power

Fans that can turn down to a low rotational speed and maintain good motor efficiency at that speed can operate very efficiently under those conditions. There are a number of fans on the market with an efficacy of over 1000 cfm/W at their lowest operating speed. Other fans typically have a relatively high minimum speed, and often also have poor motor efficiency at that speed, and these fans benefit less from speed reduction. Generally, the ability of a fan to operate efficiently at lower speed improves as the diameter increases, as the Figure 17 below demonstrates.

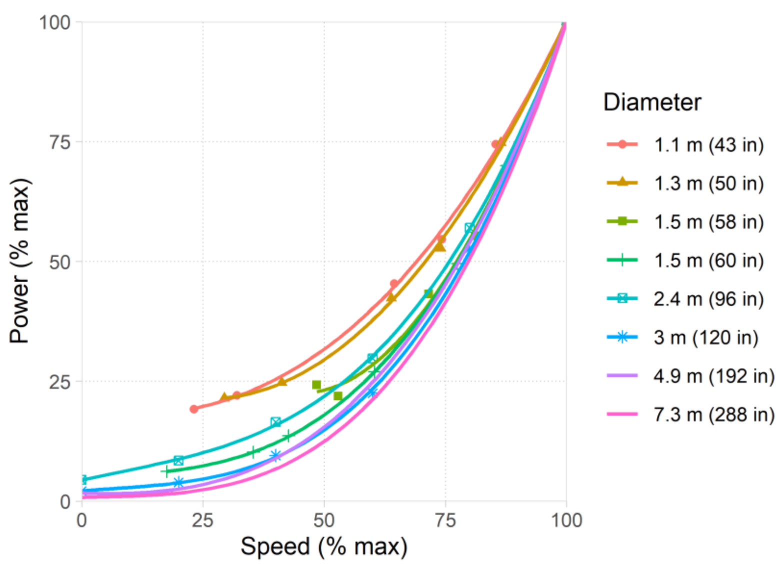


Figure 17: Relationship of power and fan speed settings for eight fans of different diameters (data from a selection of fans from MAEDbS)

However, there is considerable variation in performance between models of fans with the same diameter, as Figure 18 shows. This also demonstrates that there is a wide range of turndown ratios (minimum speed divided by maximum speed) among different fan models at the same diameter. Some fans can operate at or below 20% of their maximum rotational speed, while others cannot run below 50% of their maximum rotational speed. This is also apparent in the MAEDbS data, as shown in Figure 19.

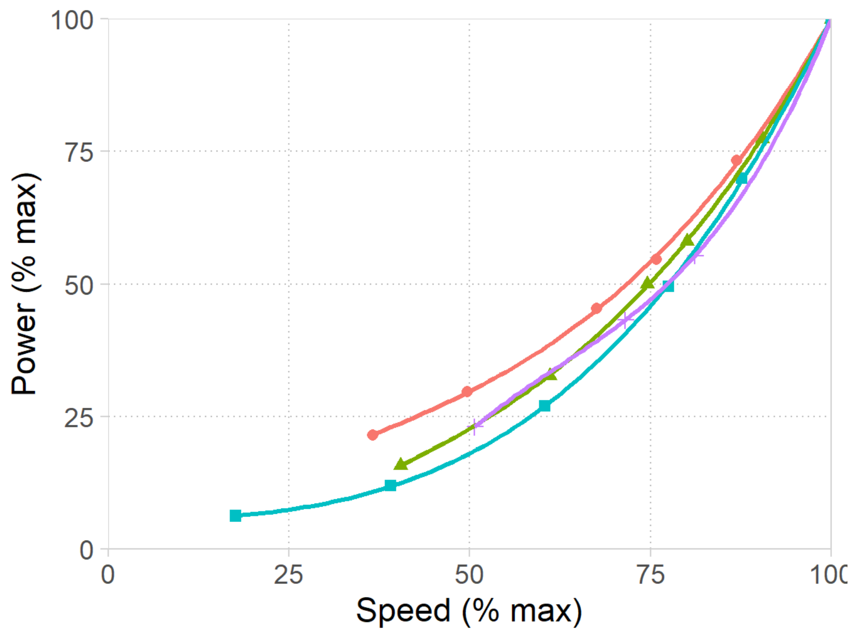


Figure 18: Relationship of power and fan speed settings for four different 5 foot (1.5m) diameter fans

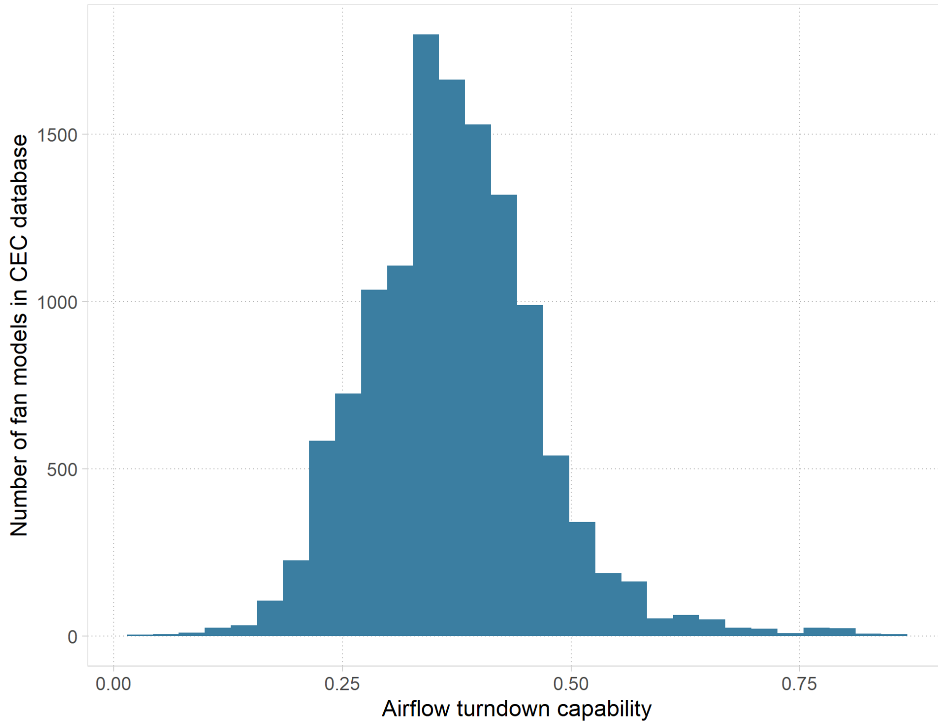


Figure 19: Minimum fan speed for ceiling fans in CEC database

Airflow

Drawing data again from the CEC's MAEDbS system, Figure 20 below is a random sample of the fans available in the database. This gives a perspective of the range of fan diameters and associated range of fan airflows available on the market today. The test methods for rating the airflow of these fans is federally regulated under 10 CFR 430 Appendix U. For standard fans, the rating is determined by a modified EnergyStar method, which infers airflow from an anemometer traverse below the fan. For large diameter fans (above 7ft), the rating is determined by the AMCA 230-15 test method, which infers airflow from a load cell measurement of fan.

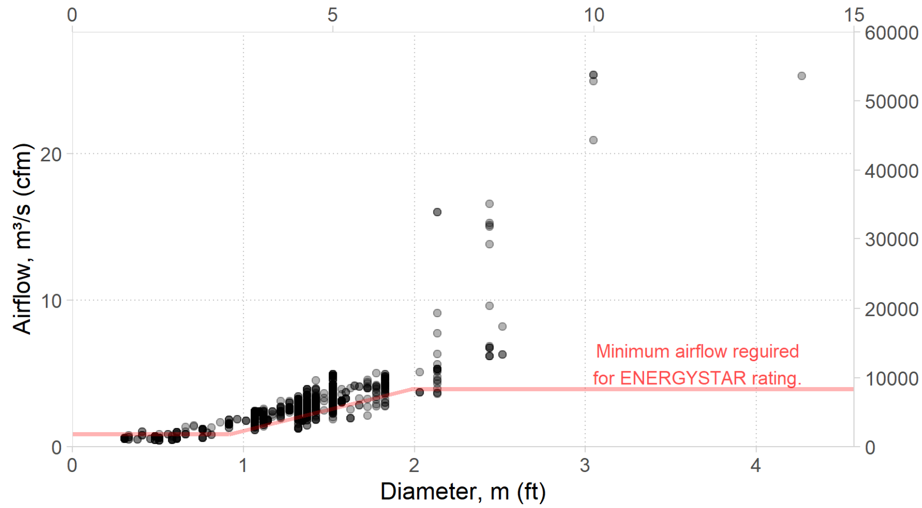


Figure 20: Airflow and fan diameter for ceiling fans in CEC database

Fan air speed

The fan air speed is calculated by dividing the rated airflow of the fan by its diameter. It represents the average airspeed that passes through the circle swept by the fan blades. Thus, as with rated airflow, fan air speed varies linearly with fan rotational speed. Fan air speed is a useful metric as it is more directly representative of the air speeds that will occur in the space. For example, the maximum airspeed at any location and height in the room will typically be within 1.3 to 1.5 times the fan air speed, and it will occur below the fan blade tip, slightly inside the fan blade diameter. That applies regardless of fan diameter. Unlike fan rotational speed, airflow, or power consumption, the concept of fan air speed is also very useful as it allows designers to directly compare fans with different diameters to one other. Fans with higher maximum fan air speeds will yield higher maximum air speeds in the room regardless of fan diameter. For example, Figure 21 shows a sample of fans from MAEDbS. By using the fan air speed as a metric instead of the rated airflow (see Figure 20), one can directly compare fans to each other even if the diameter differs substantially. This is useful in cases when the design target is the maximum airspeed directly underneath the fan.

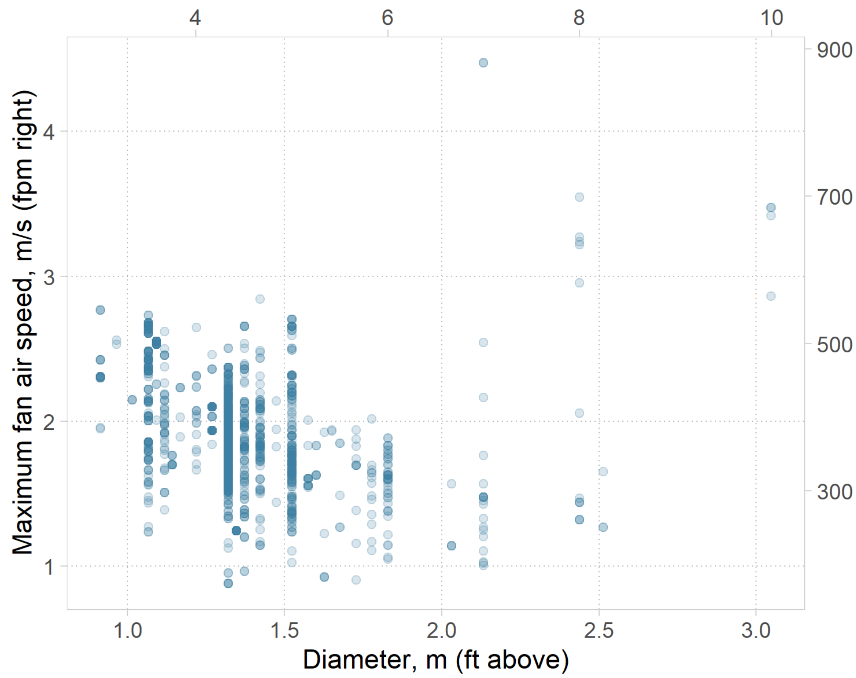


Figure 21: Maximum fan air speed and fan diameter for ceiling fans in CEC database

Levels of speed control

Most standard fans typically have a number of fixed fan speed levels. Though some of these fans have a wide range of speed levels (6 or more), the vast majority of fans have just 3. These are typically standard fans with AC motors, whereas DC motor fans tend to have more speed levels. Large diameter fans are typically variable speed regardless of motor type.

The minimum rotational speed on fans with just 3 speed levels is typically still quite high, and often the minimum speed may generate ~150 fpm seated average directly under the fan, equivalent to over 5 °F cooling effect. Having a high minimum speed can be problematic in some applications, such where there are occupants located directly under the fans for extended periods of time (e.g. an office) or when the fan is used to destratify a space in heating mode. The reason is that the minimum speed may generate too much of a cooling effect for the occupants when temperatures are mild or cool, and they cannot reduce the speed further without switching the fan off. In contrast, a high minimum speed is less of a concern in transiently occupied spaces, spaces where occupants can move freely around. Overall, in most applications, it is desirable to have more levels of speed control, particularly a minimum level that is slow enough that it generates low air speeds directly under the fan. A reasonable approximation is that the minimum fan air speed should be below 0.4 m/s (80 fpm), or a 3 °F cooling effect at the minimum allowed blade height, depending on the specifics of the application (see Applications section, below).

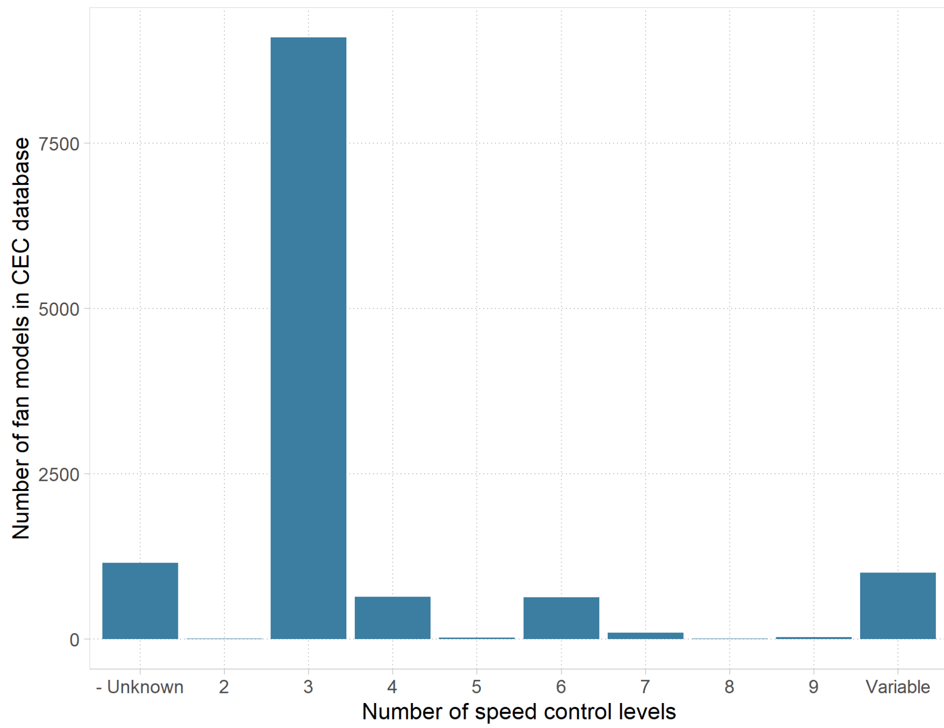


Figure 22: Number of speed control levels for ceiling fans in the CEC database

IP Rating, Damp Rated, and Wet Rated

For a motor, drive, and controller combination, it may be useful to check the IP (Ingress Protection) Rating of the fan defined by IEC Standard 60529. The IP rating describes how well an electrical enclosure keeps water and solids out. A direct drive or gear-driven fan with a higher IP rating means that the fan is suited to run in harsh environments or conditions, which may be required for the application under consideration.

Similarly, any ceiling fans in outdoor applications must be rated for outdoor use. UL (Underwriters Laboratories) provides “Damp Location” and “Wet Location” ratings for electrical products such as lighting and ceiling fans. Damp rated ceiling fans can be installed in covered locations where they may be exposed to moisture, but can not be directly exposed to water such as rain or a hose. Wet rated ceiling fans can be directly exposed to rain, or washed down with a hose.

Uniformity Of Air Speeds

The amount of variation of the air speeds in a space is an important design consideration. Figure 23 below shows the measured air speeds in a cross section through an 18 ft x 18 ft room with a 5 ft diameter ceiling fan located at the center of the room. The airflow ‘jet’ from the fan immediately narrows to a slightly smaller diameter than the fan blades. The jet then impinges on the floor, creating a stagnation point, and then spreads radially outwards along the floor. Smaller diameter fans have a relatively shallow spreading zone. For the case shown below, the airspeeds in the spreading zone are still high along the floor at a distance of one fan diameter from the fan center. However, the air speeds are almost unaffected by the fan at a height of 0.5 to 0.7 m at the same location. In contrast, larger diameter fans have a deeper spreading zone. For fans at or above 10 ft in diameter, the height of the spreading zone at a distance of one fan diameter from the fan center is approximately the height of an average person. However, large diameter fans have lower air speeds directly under the fan center, near the stagnation point. As Figure 24 shows, the larger the ratio of fan diameter to room size is, the more uniform the distribution of air speeds will be in the room.

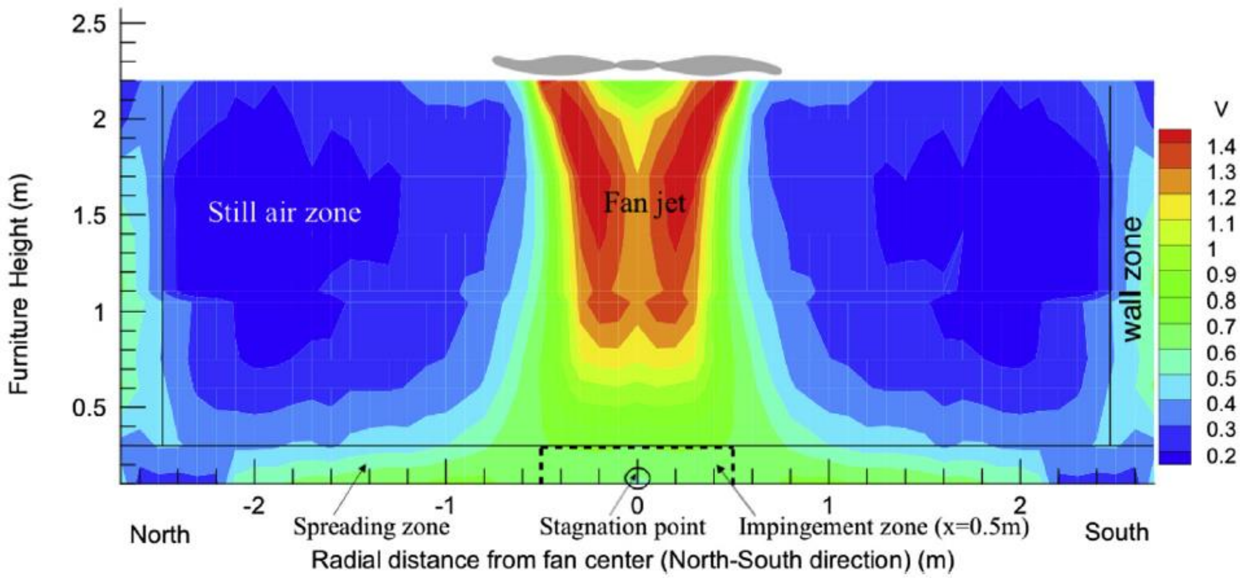


Figure 23: Example air speed distribution from a ceiling fan (Source: Gao, Y. et al., 2017)

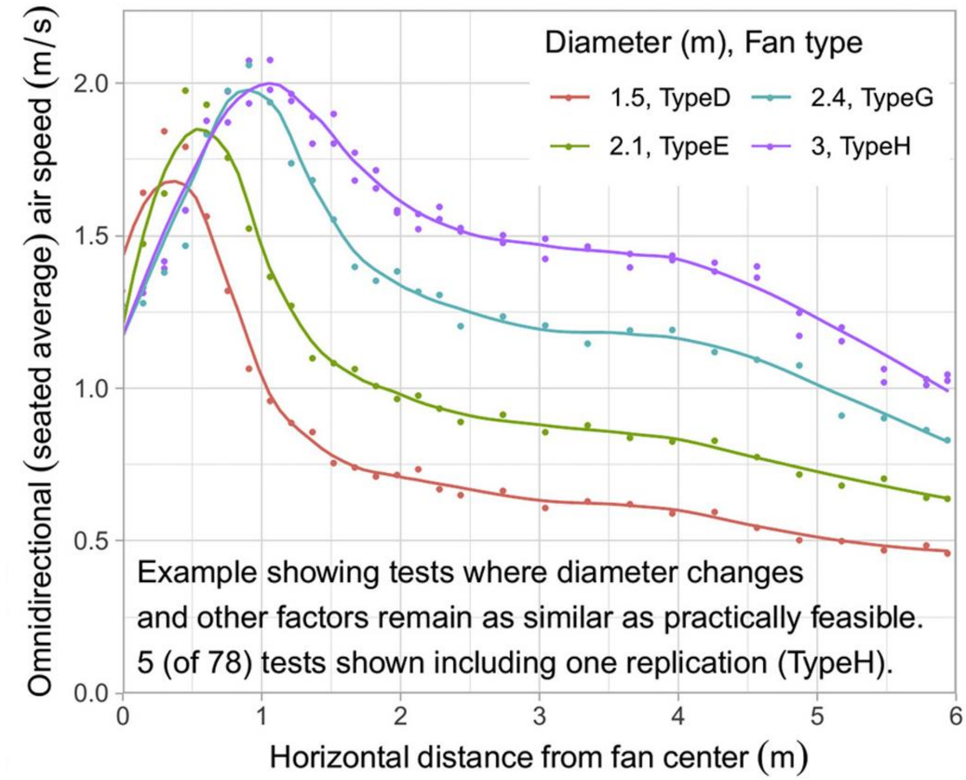


Figure 24: Air speeds over distance from the fan center (Source: Raftery, P. et al., 2019)

Whether this uniformity or variability is preferable, or whether neither is particularly relevant depends highly on the type of space and how the occupants use that space. Even under identical environmental conditions, occupant comfort needs vary significantly based on individual preference, clothing levels, metabolic rates, and their thermal history. In many cases the variability in air speeds created by a ceiling fan can help address these differences and overall improve occupant comfort. For example, in spaces where occupants can easily move around, such as a lobby, gymnasium or event space, variability is likely beneficial as the comfort needs of different occupants can be met by choosing their location in the space. Similarly, in spaces where there is some existing spatial thermal non-uniformity due to an architectural feature or varying activity levels in the space, targeting air movement accordingly may improve comfort. For example, the thermal comfort impact of increased solar radiation near a poorly shaded, highly glazed façade could be offset by locating ceiling fans near the façade. Other examples could be to locate ceiling fans over the audience above a dance floor area, or in front of the stove in a kitchen.

In contrast, in spaces where the occupants cannot easily move around, particularly those where occupants will be in those locations for extended periods, uniformity (or more granular control) is likely beneficial because there is no way of guaranteeing that the person who feels the warmest happens to be the one who is located where the air speeds are highest in the room. Examples here include a shared office with assigned seating. There are also applications where neither uniformity or variability is particularly relevant. For example, a private office where the single occupant has control over the fan speed.

The flow chart in Figure 25 below gives a quick guide through the different issues to consider regarding the air speed distribution in the space.

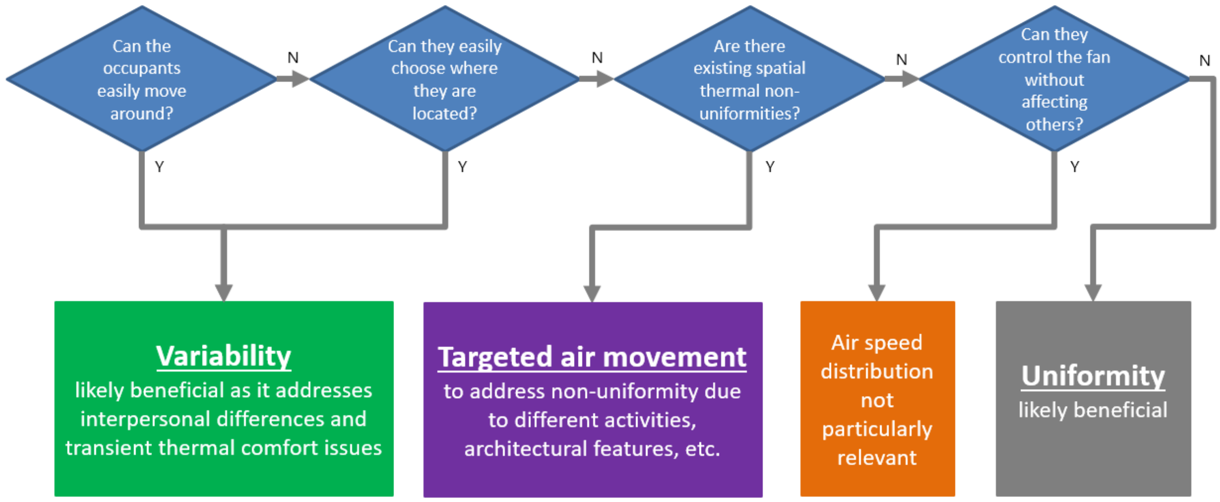


Figure 25: Flow chart of air speed and distribution considerations

Selecting Fan Sizes And Determining The Layout

Determining appropriate fan size and layout is critical to effective cooling from ceiling fans. The highest air speeds - and therefore the greatest cooling effects - from a ceiling fan are felt directly beneath the fan and dissipate the farther an occupant is from the fan. Air movement and the associated cooling effect are also impacted by obstructions such as furniture, partitions, or equipment. Any permanent obstructions should be considered in determining fan layouts, but spaces that may change in layout over time should take this into account for that particular application.

Considerations should also include the overall design intent for the ceiling fan application, including the desired air speed uniformity, and overall coverage of the space. Spaces that are likely to benefit from more uniformity will require larger fans or more fans than spaces that are likely to benefit from variability (see the Applications section below for recommended guidelines). Fan size and layout must also consider relevant code requirements (see Codes and Standards section below), and potential conflicts and spacing requirements from other building systems such as fire sprinklers and lighting equipment.

To maximize uniformity of air speeds in a space with standard ceiling fans, choose the largest possible fan that fits in the space while maintaining appropriate mounting height, and clearances from walls and other obstructions (see Fan Mounting Height and Clearances, below). For small, roughly square rooms such as residential spaces or private offices, where only one fan is required, a simple rule of thumb is that the fan diameter should be between 0.2 and 0.4 times the characteristic room width, as shown in Figure 26. For spaces with a single fan, as closely as possible given practical considerations, the fan should be centered in room to maximize air speed uniformity. Generally, a single fan centered in a space can effectively serve a rectangular space with an aspect ratio (length/width) of up to 1.5:1. Rectangular spaces with higher aspect ratios, or other unconventional shapes, benefit from multiple fans to ensure relatively uniform air speeds throughout the space. For rectangular (and other unconventional shapes), the characteristic width of the room is the square root of the floor area. For example, for an 18 ft x 25ft rectangular room, the characteristic width is 21 ft, and using the simple rule of thumb above yields fan diameters between 4.3 and 8.5 ft.

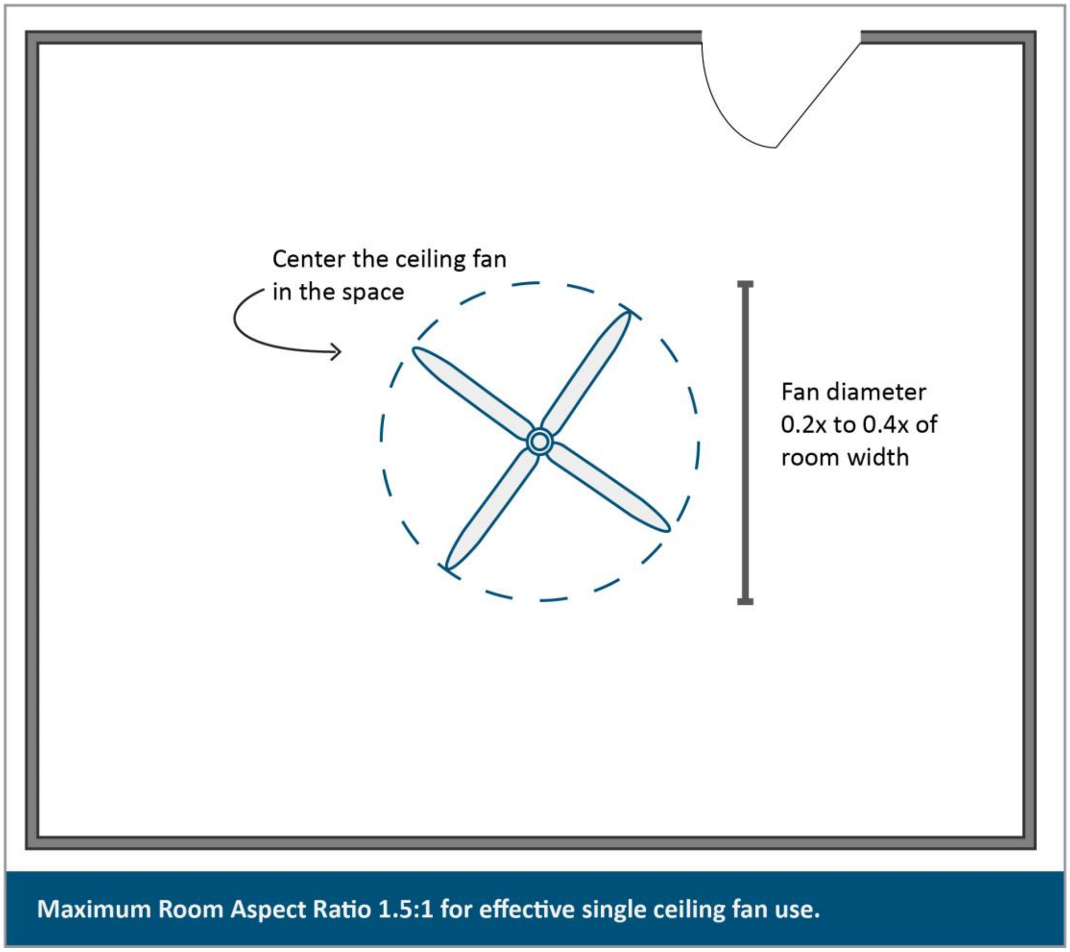


Figure 26: Recommended sizing and layout for single-fan applications

For spaces requiring multiple fans the overall layout should be determined by subdividing the space into multiple equal roughly square “fan cells”, and then centering a ceiling fan in each cell, as shown in Figure 27 below. Fan cell size is determined largely by the overall dimensions of the space, and the preferred size of ceiling fans to be used. In many cases there may be a variety of options for fan cell and fan diameter. Fewer large fan cells will require larger diameter fans, while a larger number of smaller fan cells will require smaller diameter fans. When all fans operate at the same speed, the individual fan cells within larger spaces will behave much like smaller spaces with a single fan, and as such should target an aspect ratio of no more than 1.5:1. Ratio’s above this value, it is likely possible and beneficial to create split this cell into two fan smaller cells with smaller aspect ratios. As with smaller single-fan spaces, fan diameters should be at least in the range of 0.2 to 0.4 times the characteristic width of the fan cell. Higher values will increase the uniformity of air speeds throughout the space. Fan-to-fan spacing should be determined based on centering the fan as much as possible within each fan cell, and should take into consideration needs for air speed uniformity in the space. Spaces with high uniformity requirements may necessitate larger fans and closer fan spacing.

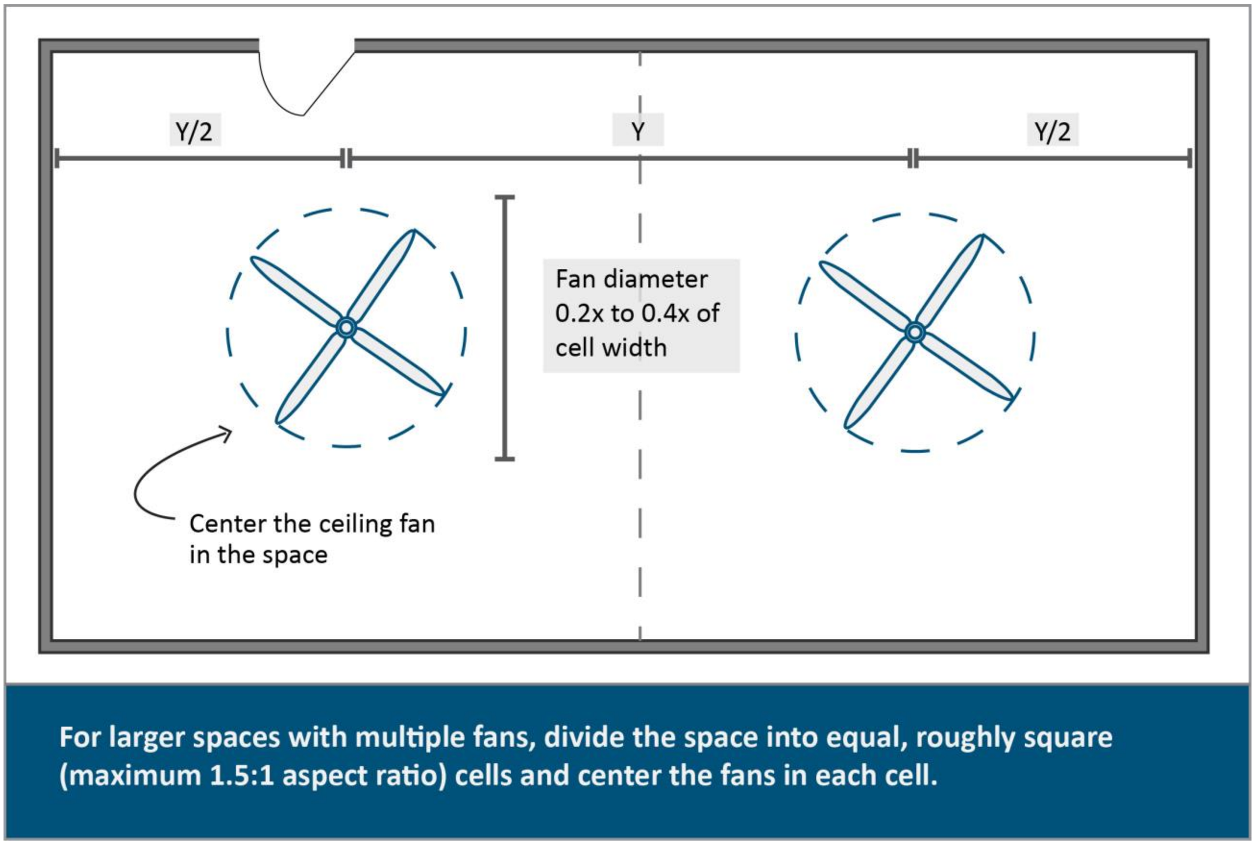


Figure 27: Recommended sizing and layout for multi-fan applications

Large spaces with high ceilings (at least 11 ft) should also consider large-diameter ceiling fans to maximize air flow and uniformity of air speeds (both horizontally, and vertically).

Another resource for determining optimal fan diameters and layouts is the CBE Ceiling Fan Design Tool, which allows users to specify the dimensions of a space and details of fan types to determine ideal layouts. More details on the tool are provided in the CBE Ceiling Fan Design Tool section below.

Fan Mounting Height And Clearances

Another key consideration for ceiling fan effectiveness is mounting height and clearances. Mounting heights and clearances from walls and other obstructions are determined based on both safety and performance considerations.

Standard ceiling fans must be mounted at least seven feet above the floor to prevent any accidental contact with blades. In addition, industry standards recommend fan blades be at least eight inches below the ceiling, though clearances of 12 inches or more are more optimal at providing air circulation into the swept area of the blades and avoiding 'starving' the fan. The distance between blades and the ceiling at which 'starvation' occurs increases with fan diameter. An approximation for this has the distance between the blade and the ceiling should be at least 0.2 times the fan diameter. For spaces with relatively low ceilings, "hugger" ceiling fans (see Fan Types section) are available without downrods to maintain adequate clearance, though these fans typically have poorer energy performance than standard fans mounted at an appropriate distance from the ceiling. In spaces with higher ceilings, standard ceiling fans should be suspended on downrods at eight to ten feet above the floor to adequately cool occupants. In addition, standard ceiling fans must be located so that the sweep of the blades is at least 18 inches from any vertical obstructions such as walls or columns, though clearances of two to three feet are often recommended to enable proper air circulation.

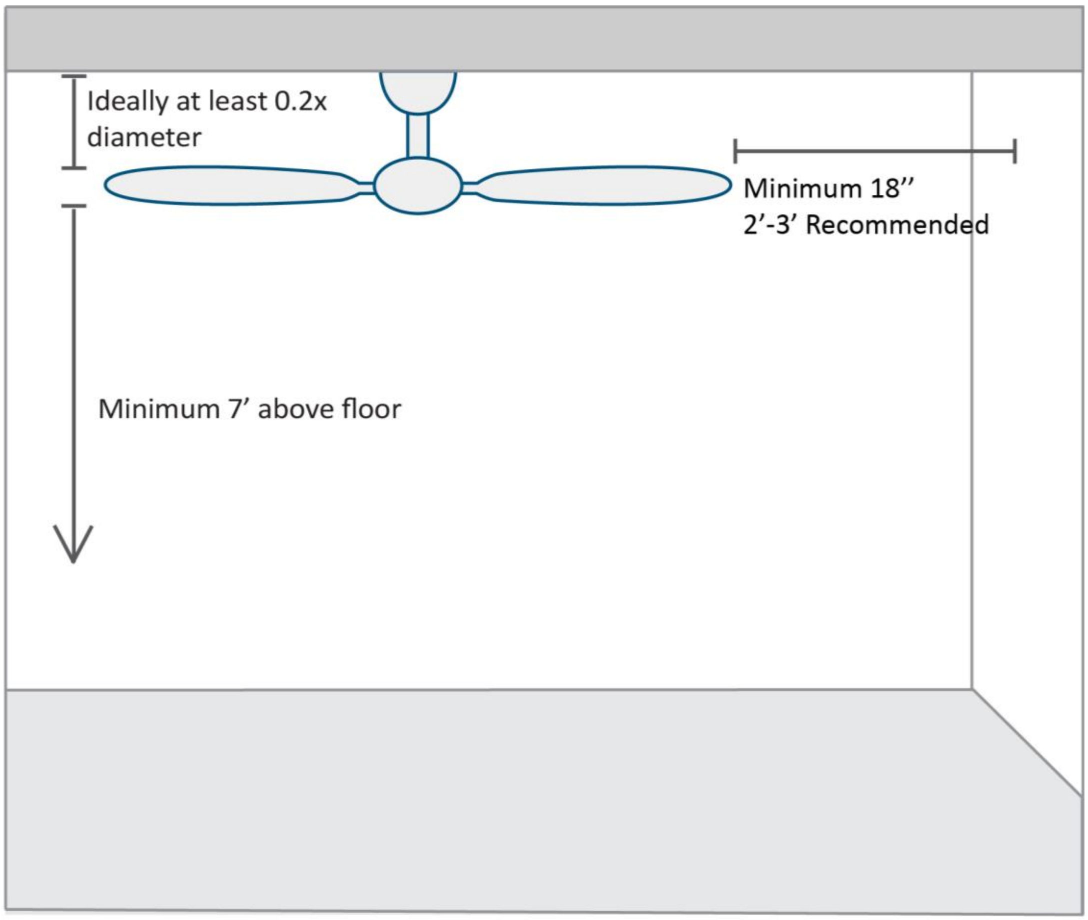


Figure 28: Minimum clearances for standard ceiling fans

Safety regulations require almost all large-diameter fans (above seven feet in diameter, see Fan Types section) to be mounted such that the blades are at least 10 feet above the floor. A small number of large-diameter ceiling fan models can be mounted below 10 feet, but these fan models have limited rotational speeds to comply with safety regulations, and as such provide limited maximum airflows. As mentioned above, large-diameter ceiling fans typically require a minimum distance from the ceiling of 0.2 times the fan diameter, though manufacturer recommendations may vary. Similarly, large diameter fans typically require at least three feet of clearance from any obstructions to the sides or below the fan blades for safety and the ensure proper air flow around the fan blades.

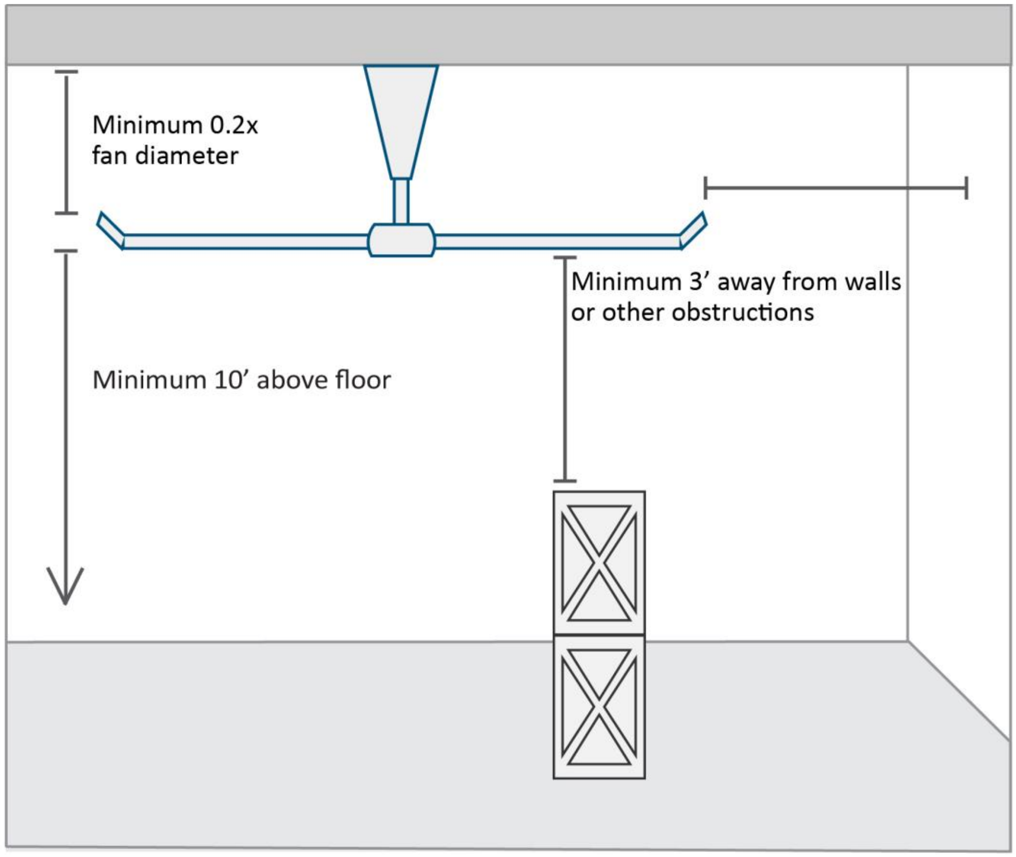


Figure 29: Minimum clearances for large diameter ceiling fans

In addition to distances from ceilings, floors, and walls, fan placement must also consider any other obstructions in a space, including lighting, mechanical equipment and ducts, fire sprinkler systems, warehouse storage racks, as well as any relevant code requirements (see Codes and Standards section below). For example, when planning an installation of large-diameter ceiling fans in a warehouse, fans should be mounted at least three feet above the highest level of any storage racks, stored items, and the tallest extent of any other equipment that may be used in the space such as forklifts. Fan placement and mounting height should also take into consideration any potential furniture placements, even though they may not be permanent. Cabinets or tall bookcases may interfere with fan operation, or cause safety hazards if located too close to ceiling fans.

Lighting

Whenever possible, lighting design and ceiling fan layouts should be developed in coordination. While many ceiling fans are available with built-in lighting, typical ceiling fan lights may be insufficient for many applications. Most applications will be best served by a lighting system that is independent of, or in addition to the ceiling fan(s).

The primary cause for concern when coordinating lighting systems and ceiling fans is the potential for a flicker or strobing effect caused by the fan blades passing through the beam of light, or intersecting with an occupant's line of sight to the light source. To avoid this, arrange ceiling fans and light fixtures so that the bulk of the light distribution does not intersect with the sweep of the fan blades. Ideally, light fixtures are suspended at the level of the fan blades or below them. Light fixtures should never be placed directly above ceiling fan blades, and point source and downlight fixtures should be located so that the beam angle does not intersect with the fan blades. More diffuse sources, such as fluorescent troffer-type fixtures may be somewhat less susceptible to strobing effects from interaction with ceiling fans, but placement should still be carefully considered in relation to ceiling fans.

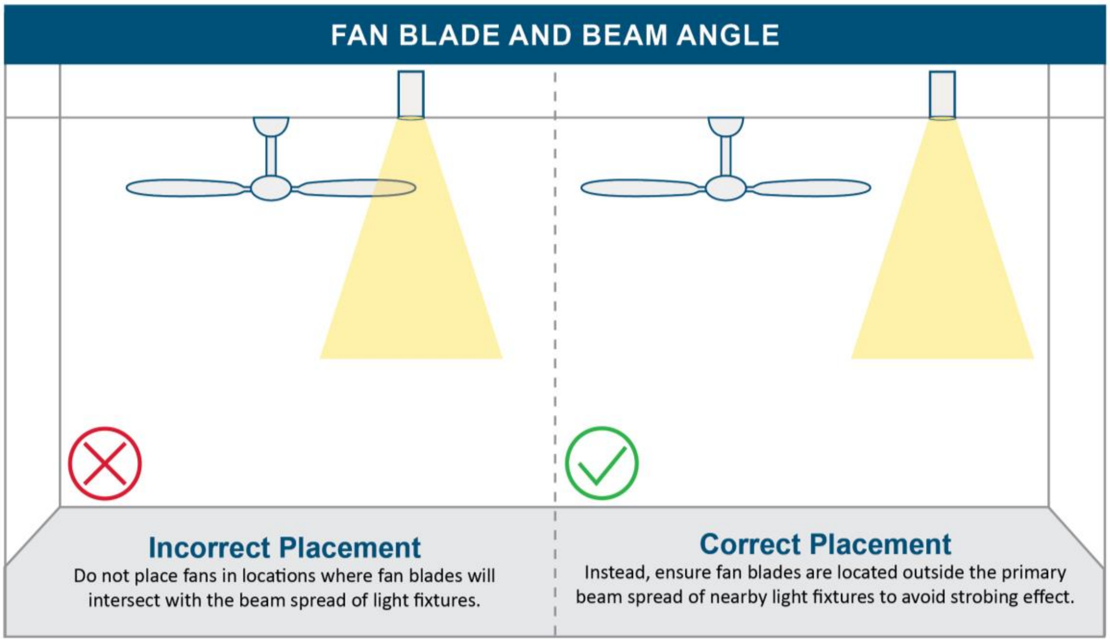


Figure 30: Fan blades and light fixture beam angle, ensure that fan blades do not intersect with the beam spread of light fixtures

Generally, any recessed ceiling fixtures and fixtures that emit light above the level of the fan blades should be located as far as possible from the ceiling fan while still maintaining appropriately uniform light levels. When working with uniform arrangements of recessed troffers in a ceiling grid, fans should be roughly centered between four fixtures.

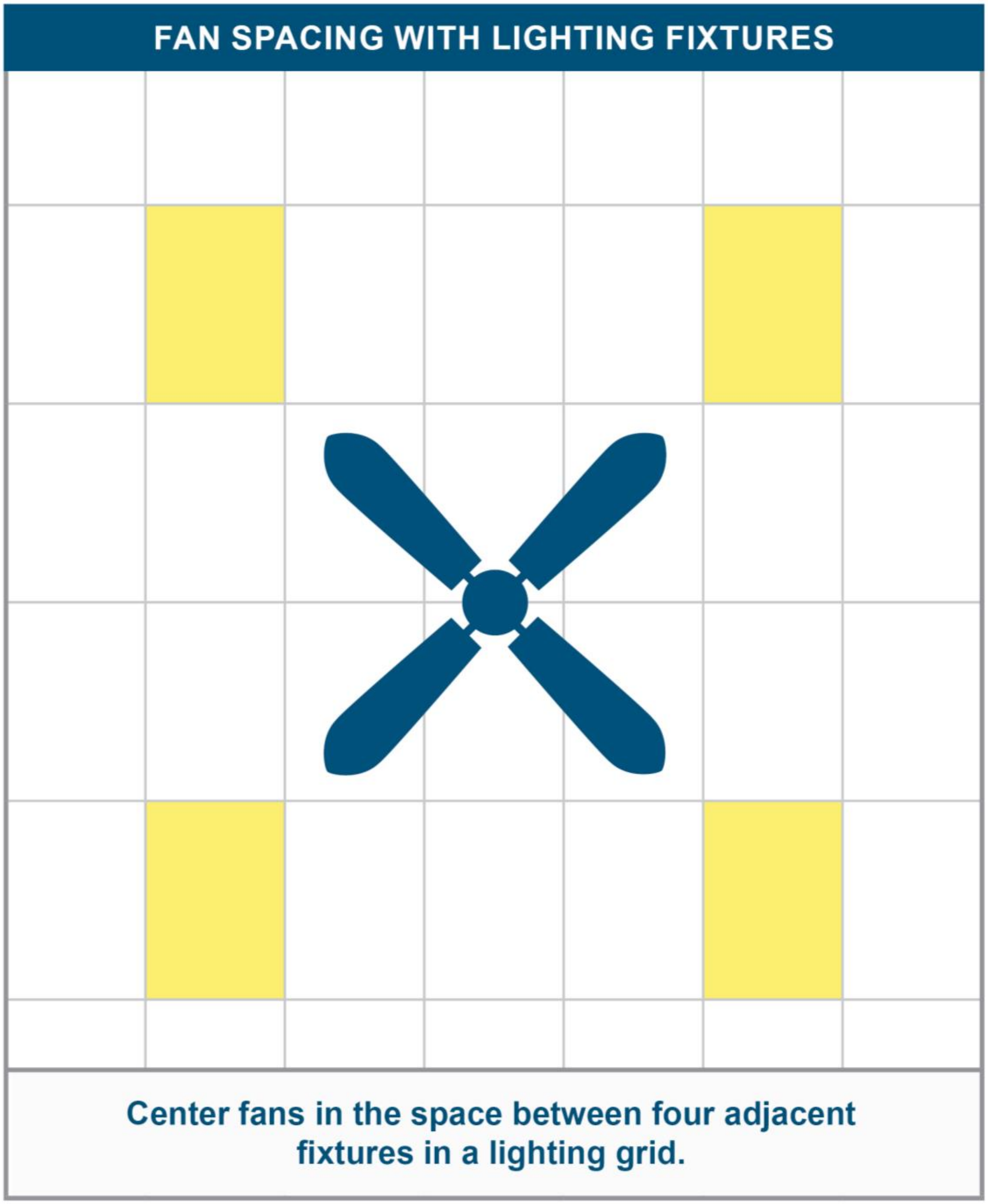


Figure 31: Center ceiling fans in the space between four adjacent light fixtures in a uniform lighting grid

Lighting fixture choice should also be carefully considered in relation to ceiling fans. For example, air movement from ceiling fans may cause suspended light fixtures to sway or swing. However, fixtures suspended on solid conduit or pipe mountings (such as high-bay fixtures in industrial and warehouse settings) may be beneficial as they can be mounted roughly at the same level as the fan blades to eliminate the risk of any strobing. As always, follow manufacturer recommendations and the guidelines in this document for minimum clearances around fan blades to ensure safety and proper fan operation.

For best results, ceiling fan and lighting layouts should be developed in careful coordination to optimize both air speed and light distribution in a space. For new construction, the project team should budget and plan for the time required to co-ordinate these elements, and others (sprinklers, etc.), with the relevant members of the design team.

CONTROLS

Controls for ceiling fans run the gamut from basic manual on-off and speed controls, to fully automated onboard controls that are also integrated with the building automation system. In any scenario the design and specification of ceiling fans must address a variety of controls considerations. Will the fans be fully manual or automated? Will occupants have control over the fans, and if so how and where? If the fans are automatically controlled, what will the setpoints or triggers be? How much variation in fan speeds is necessary for the application? How will ceiling fan controls interface with the HVAC system? These questions must all be considered when planning controls for ceiling fans.

Control needs and priorities will vary from application to application. The following sections provide guidance through the most common decisions related to controls when designing and specifying ceiling fans.

User Interface

One of the most important control considerations for implementing ceiling fans is how the occupants will control the fans. Typical user interface options are listed below. Note that it is common for ceiling fan installations to combine several of the control types listed below in a single application.

- Pull Chain: adjust a fan’s speed or light level by pull chain located on the fan. Typically, each fan will have two chains, one for the light, and one to turn the fan on or off and adjust the fan speed, typically through just 3 speed levels. Typically only used in residential applications.
- Wired Wall Control: slide controls or knobs on the wall connecting to wiring in order to control fan speed and light levels. Wall controls may be preferable for fans with greater fan speed variability or dimmable lighting.
- Wireless Remote Control or Detachable Wall Control: wall control or remotes tuned to create a frequency combination enabling wireless control of fan speed and light levels. Like wired wall controls, wireless controls can support greater fan speed variability and dimmable lighting. Wireless controls eliminate the need for hardwired connections, which can be costly in retrofit scenarios, but they also typically use batteries that will need to replaced regularly, and if detachable, they can be lost or misplaced.
- Wi-Fi or Bluetooth Connectivity via Phone App or Internet: some fans have smartphone apps or web interfaces that use Bluetooth or Wi-Fi networks to control fan speed, light levels and other settings. This may be especially advantageous for controlling multiple fans in a space or throughout a buildings, but may be less ideal for spaces where multiple people will need access to fan controls. Additionally, note that many fan models can be retrofit with a controller that adds Wifi or Bluetooth control capabilities.
- Building Automation System Interface: some fans may also be controlled through building automation system interface. This approach may be ideal for applications where access to fan control needs to be limited to building management and maintenance staff, such as assembly and hospitality spaces.

Figure 32: Examples of ceiling fan wall controls (Images courtesy Elaina Present)

A sample of ceiling fan controls are shown above, demonstrating that many are not particularly clear to the user. For example, the controls are not labeled as controlling the ceiling fan and as such are indistinguishable from a dimmable light switch in many cases.

For any space it is important to ensure that wall mounted fan controls are:

- Clearly visible to the occupant(s)
- Located near the fan they control

- Located near the thermostat in the room
- Intuitive (e.g., levels increase vertically from off to maximum speed)
- Clearly labeled as a ceiling fan control (to differentiate from the lighting controls).

Types Of Control Automation

In addition to the user control interfaces listed above, there are a range of options and strategies for ceiling fan control automation. Listed below are some automation strategies that can be implemented for ceiling fans. As with control interfaces, many of these automation strategies can be used in combination. However, the automation options available for any given application will sometimes depend on the capabilities of the chosen ceiling fan model.

- Manual: no automation, fan control is fully manual based on occupant inputs
- Schedule: a schedule may be set for when the fans are operating, typically at a fixed speed. For example, if a room is generally only used during weekday business hours, a schedule could be set to automatically turn on each weekday morning and turn off at night.
- Automation based on occupancy: occupancy controls ensure that a fan only operates when the space is occupied. Ceiling fans only provide a cooling sensation if an occupant is there to feel it.
    - Wall switch “vacancy” or “occupancy” sensing
    - Integration with building automation system (BAS) occupancy sensors (e.g. via power relay, 0-10V input or BACnet interface to fan)
    - On board occupancy sensors
- Temperature sensing: fans can be programmed to turn on at certain temperature thresholds, and increase speed with temperature, automating the thermal comfort control in a similar manner to a thermostat for a traditional HVAC system.
    - Manufacturer provided wall controller with built in temperature sensor (or remote temperature probe)
    - Integration with BAS temperature sensor (e.g., via 0-10 V input, or BACnet interface to fan)
    - On board temperature sensing
- Learning Behaviors and/or Preferences: some ceiling fans are equipped with programming that learns user preferences over time. For example, if a user frequently turns off the fan when the room temperature drops to 74°F the fan will “learn” this user preference and start to automatically turn off at 74°F.

Additional Considerations For Choosing A Control Type

There are a few things to consider when choosing a control mechanism for ceiling fans:

Amperage Restrictions

The amperage of a wall control unit may limit the number of ceiling fans that can be controlled together at once. For example, a wall control unit with an amperage of 5 amps could only control at most 5 fans at once if the load of one fan is about 1 amp.

In general, the number of fans that may be in a space at once is limited by the National Electric Code standards. The standard mandates that a circuit breaker not carry more than 80% of its rated current.

This means that for a standard circuit breaker with 15-20 amperage, the circuit breaker will only allow about 12 fans (80% of 15).

To allow for more fans to be controlled at once, fans are often daisy-chained together. When fans are daisy-chained, a control device controls one master fan and the rest of the fans are controlled by the master fan by a variable-frequency drive.

Remote Control Receivers

When using wireless wall controls or remote controls, each fan that is controlled must have a receiver. Additionally, for each new fan desired to be controlled simultaneously with the existing fans, a new receiver must be purchased. The frequency settings must then be reset in order for the receiver and remote control to match.

Integration With Building Controls And Sequences Of Operation

Ceiling fans can be integrated with a BAS through a number of mechanisms. True integration requires speed control of the fans and this is typically achieved using either a 0 - 10 V input or a BACnet interface. Here, the fan may respond to zone temperature, acting as the first stage of cooling for a zone before the HVAC system begins to operate in cooling mode. For example, for a zone with a fan and a VAV box, the fan comes on first at 74 - 75 °F providing the first stage of cooling to the occupant. The fan speed increases with zone air temperature until reaching 78 – 80 °F, at which point the VAV box begins to modulate to maintain that setpoint, providing the second stage of cooling. Operating the VAV box at this higher cooling setpoint has significant energy savings potential. The following figures provide control schematics for both the HVAC system and the ceiling fan. Note that some ceiling fans have onboard sensing and controls that allow for fan speed and temperature automation without integration with the BAS.

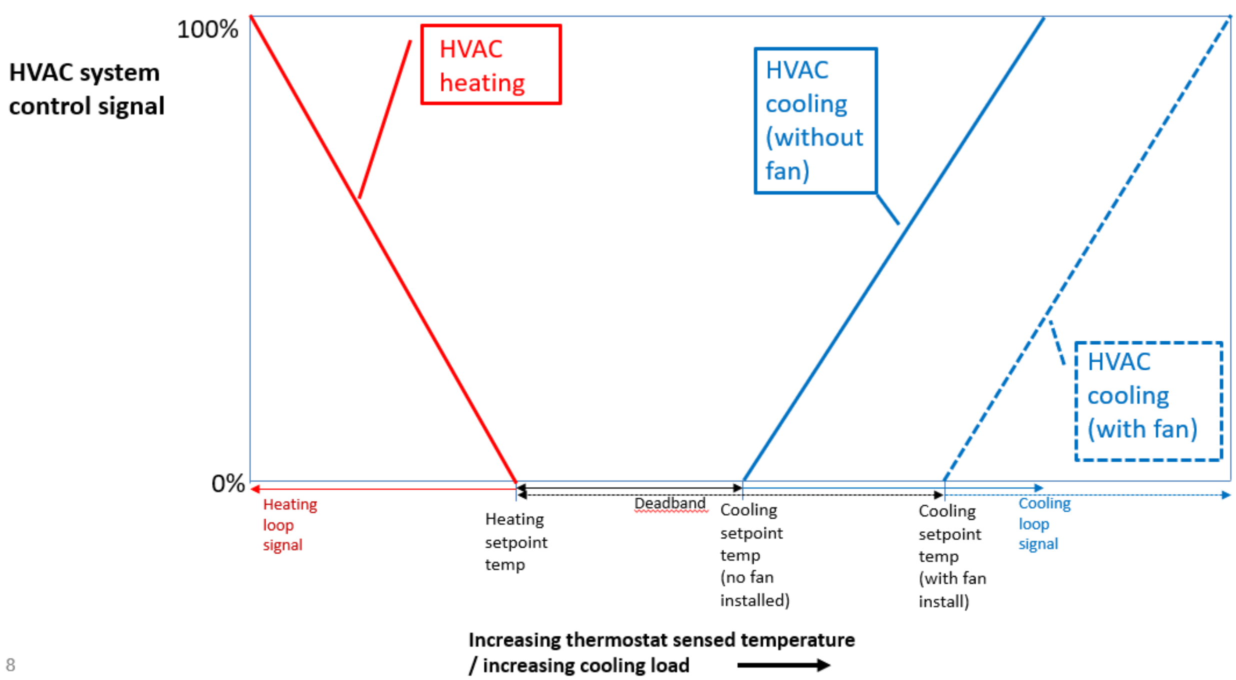


Figure 33: Example HVAC control schematic with without ceiling fans

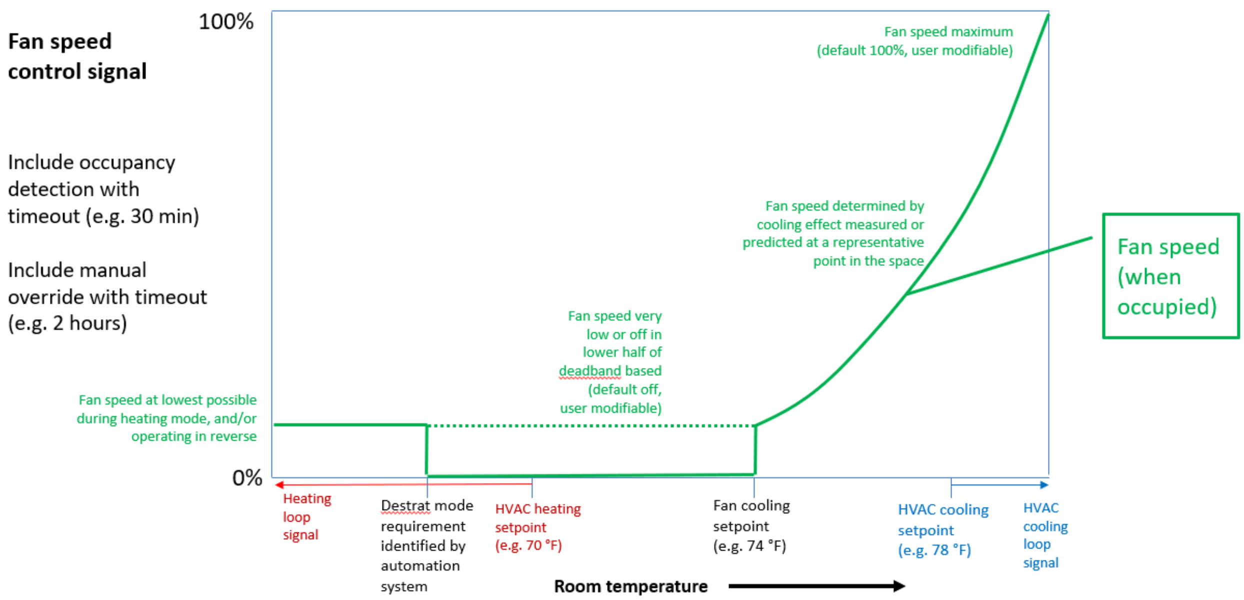


Figure 34: Example ceiling fan control schematic

A lower cost, simpler alternative to automatically control the ceiling fan based on temperature is to use a relay to switch power on or off to the fan(s). The fans then operate at a fixed preset speed. This only provides on/off control, and as such can only be effective over a small range of temperatures without a 'typical' occupant in the space experiencing conditions that are either too warm (insufficient air movement) or too cool (excessive air movement). This approach may be most applicable for designs that either:

- use the ceiling fans predominantly to mix the air the space and aim for relatively low air speeds (e.g. <= 50 fpm) in the occupied zone. Example applications include: destratification in heating, or air mixing to reduce the need for distribution ductwork.
- are for spaces where variability in air speeds is likely beneficial (e.g. the occupants can easily move within the space, such as a lobby, event space, or hallway).

Fan operation can also be tied to occupancy sensors in the zone, preventing unnecessary operation, energy use, and maintenance. Lastly, note that in some cases, it may be beneficial to operate fans even when unoccupied, such as pre-cooling applications that benefit from increased convection from surfaces in the space due to the air movement generated by the fans.

Airflow Direction

All fans sold in the USA are required to be reversible, and thus, fans can run in either direction – forwards, blowing downwards towards the floor, or in reverse, blowing upwards towards the ceiling. Many standard ceiling fans will have a switch on either the wall switch, remote control, or on the motor housing to change the direction between downwards and upwards. For some models this functionality will be provided in the control system or smartphone app. Most applications are for fans blowing downwards, as this is by far the more common and the more efficient way of creating air movement in the occupied space. Reversing a fan so that it blows upwards against the ceiling requires that the space containing the fan (or fans) is bounded by a ceiling and walls on all sides. This creates a similar recirculation cell as blowing the fan downwards, but it avoids creating a region of high air speeds directly under the fan. Running fans in reverse has the effect of creating a much lower, but much more uniform air speed distribution in the space, which can be desirable in some applications.

One application of running fans in reverse is to mix air the room when elevated air speed in the occupied zone is not desirable. One example is destratifying spaces in the heating season. Many fans have a relatively high minimum rotational speed and if these fans run in the downwards direction, the resulting air speeds may cause a draft on the occupants directly below the fan. This can be remedied by running the fan in reverse. Note here that there are also fans that have a very low minimum speed, allowing them to run forwards without creating a draft on the occupants, while still effectively de-stratifying the space. This uses less power to destratify than a fan with a higher minimum speed running in reverse. Another application of running fans in reverse is when elevated airspeed in the region directly under the fan is perceived as excessive for some reason, such as causing paper to blow off a desk.

The ratio of air flow through a fan in the upwards vs. downwards direction depends on the fan type and associated blade geometry. Some fans have highly optimized blade designs that blow downwards efficiently. Here, the blade geometry is not symmetrical when the fan reverses direction, and these do not generate as much airflow at the same rotational speed and power when operated in reverse. Other fans, such as those with a less efficient but symmetrical blade geometry (e.g., flat blades) or those whose blades can be inverted and re-attached to the fan (making the blade geometry symmetrical in reverse), will generate approximately the same airflow operating in reverse.

For context, based on full scale laboratory testing the area weighted average air speed for seated and standing occupants with a fan blowing upwards ranged from 30 to 70% that of the same fan blowing downwards at the same speed in the same room. In cases where the blade geometry is symmetrical (flat blades, or inverted blades), the area weighted average airspeed was approximately 60-70% that of the downwards case. Obstructions in the flow from the fan (e.g., furniture, ceiling obstructions, etc.) will likely have a significant effect on these percentages.

Figure 35: Brock Environmental Center, Virginia Beach, VA (Photo: copyright Big Ass Fans)

Occupant Interface and Education

A key part of the success of any ceiling fan installation is ensuring that occupants understand the purpose and use of the ceiling fans.

In cases with regular occupants (as opposed to spaces with transient occupants such as lobbies or event spaces) who do not have direct control over the fan operation, occupants should be informed about the purpose and operation of the ceiling fans. Ideally, spaces where occupants do not have direct control over fan operation should also allow for flexibility so that occupants may find a location within the space that best suits their comfort preferences.

In applications where occupants have access to fan controls, it is also helpful to post information or instructions encouraging occupants to adjust ceiling fan settings when they are too warm, rather than reducing thermostat setpoints. Two examples of occupant interface information plaques are provided in the images below. Figure 36 shows a simple plaque with basic recommendations, while Figure 37 is an example of more detailed user information.

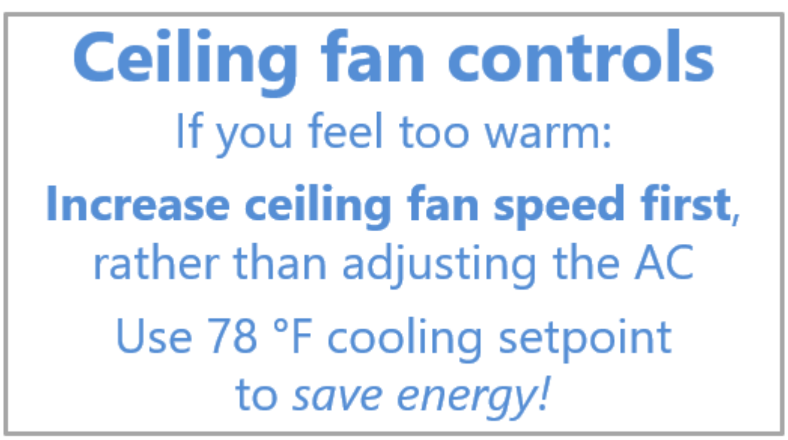


Figure 36: Example of simple information plaque that can be posted near fan controls and thermostats to encourage ceiling fan use and energy savings

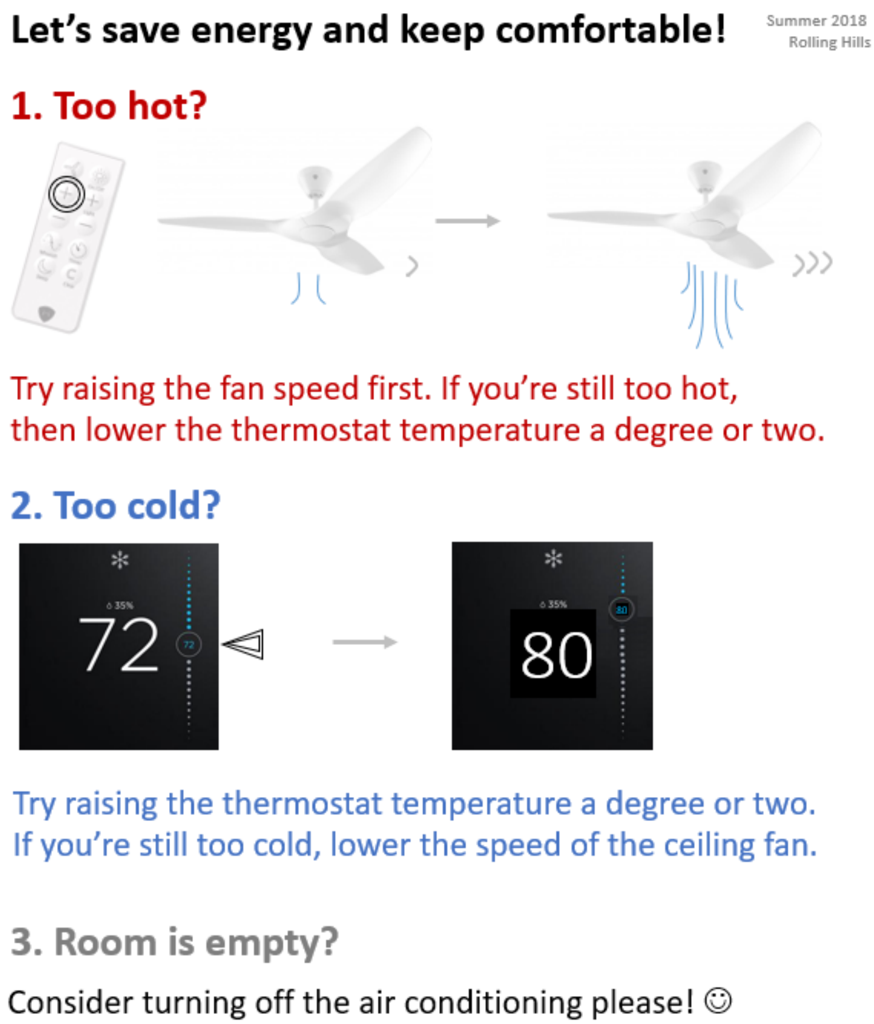


Figure 37: Example of a more detailed information plaque for occupant interface and control recommendations

Figure 38: High School Gymnasium, San Marcos, CA (Architecture: LPA Architect, Photo: copyright Cris Costea)

Applications

Ceiling fans are effective for comfort cooling and air circulation in nearly all scenarios and applications. Table 3 below outlines some key considerations for ceiling fan applications based on the design intent for each space.

The table is divided into four primary design intent categories as follows:

- Single occupant – designs where the goal of the ceiling fan is to provide thermal comfort for a single primary occupant
- Uniformity – multi-occupant spaces where occupants do not have flexibility in their location, and where uniform air speeds and consistent thermal comfort experience is the primary goal
- Variability – multi-occupant spaces where occupants have flexibility in their location and can choose their preferred conditions, more variability in air speeds and thermal comfort conditions is preferred
- Targeted – spaces with inconsistent or transient occupancies, inconsistent thermal conditions, and/or spaces with specific thermal requirements

For each design intent category, the table provides example application types, example target air speeds, and additional considerations for each type of approach.

Table 3: Recommended Guidelines for Ceiling Fan Applications

Design Intent	Application Examples	Target Maximum Air Speed	Comments
Single occupant Provide ceiling fan cooling directly to the occupant, taking into consideration furniture configuration / space layout, locate fan directly above occupant where possible	• Office – Private • Residential	High to very high	• Provide local manual control • Ensure fan is capable of turning down to a low fan air speed. • Ceiling fan locations should consider potential/planned furniture locations
Uniformity For multi-occupant spaces where locations are fixed or inflexible, maximize uniformity and coverage at relatively low air speeds throughout the occupied subzones of the space to ensure consistent experience for all occupants.	• Assembly / Event Spaces – Fixed • Classrooms and conference rooms (See Figure 13) • Dining Areas • Offices – Shared, Assigned Seating (See Figure 1) • Retail	Low to medium	• Prioritize uniformity and coverage to provide consistent conditions throughout the occupied subzones of the space • For offices and classroom spaces, ensure maximum design air speed will not blow papers off desks (approx. 150 fpm, can be as low as 80 for lightweight paper) • For dining and retail, separate airspeeds for subzones containing diners versus servers, or clerks versus shoppers, may be created to account for their different activity levels and cooling needs. (see targeted category below)

Design Intent	Application Examples	Target Maximum Air Speed	Comments
Variability For spaces where occupants have the flexibility to move around the space and choose their preferred conditions, allow variable air speed conditions within the space, up to medium air speeds. Uniformity is a lower priority.	• Assembly / Event Spaces – Flexible • Cafeterias (See Figure 39: DPR Construction, Sacramento Office. (Architecture: SmithGroup, Photo: copyright Chad Davies)) • Gymnasium / Exercise Areas (See Figure 38) • Offices – Shared, Hoteling / Unassigned	Medium	• For office spaces, ensure maximum design air speed will not blow papers around

Design Intent	Application Examples	Target Maximum Air Speed	Comments
Targeted For spaces with inconsistent or transient occupancies, inconsistent thermal conditions, and/or spaces with specific thermal requirements, target ceiling fan strategies to the specific needs of the space. Consider providing different air speed conditions for different occupant types. For example, permanent occupants in a space (e.g., receptionists in a lobby) may have different thermal comfort requirements than temporary occupants who are passing through the space. Similarly, fans can be used to address inconsistent thermal conditions in a space, such as areas of high solar heat gain near windows, or areas where occupants can be expected to have notably different metabolic rates.	• Assembly / Event Spaces – Transitional • Lobbies • Agricultural / Livestock • Industrial Production / Manufacturing • Kitchens (commercial) • Outdoor • Gymnasium / Exercise Areas – directly over areas or equipment where occupants likely will have high metabolic rates	Low to high; depending on application and occupancy, target may vary throughout the space	• Allow flexibility or ensure lower air speeds for any permanent occupants in the space (receptionists, etc.) • Maximum target air speeds in agricultural, industrial, and warehouse applications will depend on whether the space has other mechanical cooling (unconditioned spaces may require higher maximum air speeds)

Figure 39: DPR Construction, Sacramento Office. (Architecture: SmithGroup, Photo: copyright Chad Davies)

Figure 40: Bluescope Buildings, North Carolina, USA (Photo: copyright Big Ass Fans)

CODES AND STANDARDS

The following sections summarize building code requirements related to ceiling fans, as well as several safety considerations and design best practices.

The requirements and considerations outlined below are derived from model codes that have been adopted as part of the California Building Code. Other states may have different code requirements, and municipalities within California may have additional code requirements beyond the statewide building code. Always consult local codes to confirm requirements as they apply to a specific project.

Fire Code Requirements

The primary concern with ceiling fans in relation to the fire code is the interaction with fire sprinklers. For the most part, standard ceiling fans in typical residential and nonresidential applications have few limitations in relation to fire sprinklers, while large-diameter ceiling fans require a higher degree of integration with fire suppression systems.

The California Fire Code (Title 24, Part 9) cites the requirements of the National Fire Protection Association's NFPA 13, "Standards for the Installation of Sprinkler Systems,"[3] and NFPA 13R, "Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies,"[4] to govern the use of fire sprinklers in buildings.

Per NFPA 13 in most nonresidential applications, for ceiling fans less than 60 inches (1.5m) in diameter where the blades are less than 50% of the swept area in plan view, fire sprinklers can be located without regard to the fan blades.[5] Since the above requirement specifically calls out "fan blades," there may be cases where other parts of the ceiling fan, such as motor housing or mounting pendants (or fan blades that are less than 50% open in plan view), are considered obstructions to fire sprinklers. In most cases, for any motor housing, mounting pendant, or other part of the fan that is 18" or less below the level of the sprinkler deflector, the so-called "rule of three" applies, where sprinklers must be placed away from the obstruction a minimum distance of three times the maximum dimension of the obstruction, up to 24".[6] In other words, if the motor housing of a ceiling fan is 7" in diameter, any fire sprinklers should be located at least 21" from the motor housing. In the 2019 version of NFPA 13, for extended coverage sprinklers and residential sprinklers, this requirement is increased to a distance of four times the maximum dimension of the obstruction, up to 36".[7]

For low-rise residential applications, NFPA 13R requirements are more explicit about sprinkler locations in relation to obstructions such as ceiling fans. In these cases, the standards require pendant sprinklers to be a minimum of 3 feet from any ceiling fan[8], and sidewall sprinklers to be at least 5 feet from any ceiling

---

[3] https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13

[4] https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13R

[5] NFPA 13 2016 sections 8.6.5.2.1.10, 8.7.5.2.1.6, 8.8.5.2.1.9, 8.9.5.2.1.6; NFPA 13 2019 sections 10.2.7.2.1.10, 11.2.5.2.1.9, 12.1.10.2.1.9

[6] NFPA 13 2016 section 8.6.5.2.1.3; NFPA 13 2019 section 10.2.7.2.1.3

[7] NFPA 13 2019 sections 11.2.5.2.1.3 and 12.1.10.2.1.3

[8] NFPA 13R 2016 and 2019 section 6.4.6.3.4.1

fan.[9] Though the standards do not explicitly state where those distances are measured from, this is typically interpreted at being the distance from the center point of the ceiling fan.

For larger format fans, NFPA 13 lays out more detailed requirements as follows:[10]

- Fans must be no more than 24 feet in diameter
- Each fan must be approximately centered between four adjacent sprinklers
- The vertical distance from fan blade to sprinkler deflector must be at least 3 feet
- All fans must be interlocked to shut down immediately upon receiving a waterflow signal from the alarm system in accordance with the requirements of NFPA 72

While this section covers requirements as they apply in the California Fire Code, adapted from NFPA Standards, specific requirements may vary by local jurisdiction. Always consult local codes for requirements for a specific project.

Seismic Requirements

In many applications, standard ceiling fans attached directly to a structural ceiling do not require any further seismic bracing or restraint. However, applications with large-diameter ceiling fans, suspended ceilings, long suspension rods, or other special conditions may require additional seismic support.

Seismic considerations and requirements are especially relevant for installations of ceiling fans in California. Per the California Building Code, nonstructural components that are permanently attached the structure, such as ceiling fans, must be installed to resist the effects of earthquake motions in accordance with the ASCE 7 standard (from the American Society of Civil Engineers).[11] The exact requirements in ASCE 7 will vary depending on the size, weight, and configuration of the fan, the strength of the expected seismic forces for the area, and the building type where it is installed.

In addition to the specific requirements in ASCE 7, there are some general best practices for all applications and scenarios. The Federal Emergency Management Agency's (FEMA) document, "Reducing the Risks of Nonstructural Earthquake Damage – A Practical Guide" recommends that all suspended fixtures, such as lighting and ceiling fans, have positive attachment to the structure to avoid falling hazards.[12] Ceiling fans should never be supported on a suspended ceiling grid or ceiling tile. In addition, the California Department of the State Architect (DSA) has issued code interpretations pertaining to suspended fixtures such as ceiling fans, stating that fixtures with rigid suspension pendants must be attached to the structure using a device allowing movement in any direction (i.e., a ball and socket

[9] NFPA 13R 2016 and 2019 section 6.4.6.3.5.1

[10] NFPA 13 2016 sections 11.1.7 and 12.1.4.1; NFPA 13 2019 sections 19.2.7 and 20.6.7.1

[11] 2016 California Building Code, Part 2 Volume 2, Section 1613.1

[12] Section 6.4.9.3 https://www.fema.gov/media-library-data/1398197749343-db3ae43ef771e639c16636a48209926e/FEMA_E-74_Reducing_the_Risks_of_Nonstructural_Earthquake_Damage.pdf

joint),[13] and requiring bracing where any pendant fixture passes through a suspended ceiling.[14] Some manufacturers, such as Big Ass Fans, also suggest lateral restraint using guy wires that are at least ¼ inch (6.35 mm) in diameter for large-diameter fans.

As always, consult local building codes to determine specific requirements.

Energy Code Considerations

As of this writing, only Florida and Hawaii have energy code requirements for ceiling fans, as part of the "Tropical Zone" options of their Residential Building Codes. In both states, this option requires that no more half of the occupied area is air conditioned, the occupied space is not heated, renewable energy for at least 80% of the service water heating load, operable fenestration, and ceiling fans or ceiling fan rough-ins in every bedroom and in the largest non-bedroom space, among other requirements.

To date, ceiling fans have not been included in the California Building Energy Efficiency Standards (Title 24, Part 6) as a compliance option for thermal comfort control. Although ASHRAE Standard 90.1 has some options for increasing assumed cooling setpoints in conjunction with strategies such as ceiling fans, this strategy has not yet been included in the California Energy Standards. There have been previous proposals for Codes and Standards Enhancement (CASE) studies to develop options for residential comfort using unconventional strategies in some coastal climate zones in California. These proposals use cooling load avoidance strategies as a first priority, including passive solar strategies, advanced envelopes, and night cooling, supplemented by non-compressor-based cooling strategies, such as evaporative cooling or ceiling fans, when needed. This proposal was most recently presented as part of the 2013 Standards development process but has never been pursued by the CEC or the California investor-owned utilities.

Although these strategies proposed for residential comfort remain viable, there are several barriers to adoption in the Energy Efficiency Standards. One of the primary barriers has been a lack of widely accepted standards for measuring cooling effect from these unconventional strategies such as ceiling fans. Without accepted methods for modeling the cooling load avoidance, or measuring the cooling effect of these strategies, there has been no reliable method for determining the potential energy savings or cost effectiveness in accordance with standard CASE proposal procedures.

However, the development of new standards such as ASHRAE Standard 216, and updates to existing standards such as the proposed addendum to ASHRAE Standard 55, described in the sections above, will help to address this barrier. With the development of industry standards for measuring performance characteristics of ceiling fans (ASHRAE 216) and defining the use of ceiling fans as a potential thermal comfort control strategy (proposed addendum to ASHRAE 55), California has new resources to cite in developing cooling comfort models for ceiling fans. These new standards re-open the opportunity to develop comfort compliance options for the less used cooling strategies, such as ceiling fans, in future revisions to the Energy Efficiency Standards.

---

[13] DSA IR 16-9, section 2 https://www.dgs.ca.gov/DSA/Publications

[14] DSA IR 25-2, section 3.1 https://www.dgs.ca.gov/DSA/Publications

ASHRAE 216 And Fan Testing Procedures

A new standard currently under development, ASHRAE Standard 216, "Methods of Test for Determining Application Data of Overhead Circulator Fans", is intended to provide standardized performance data for the application of overhead circulation ceiling fans in indoor spaces. The room airspeed distribution test results can be used to calculate occupant thermal comfort and to demonstrate compliance with the thermal comfort requirements of ASHRAE Standard 55. This standard includes requirements for test instrumentation, the features of test rooms features, and measurement procedures. It also includes calculation procedures for a number of performance metrics relevant to thermal comfort application of overhead circulator ceiling fans such as uniformity, room average cooling effect, heating draft risk, and comfort cooling efficacy.

Once adopted, this standard will provide a consistent, industry-standard practice for determining ceiling fan performance characteristics. Manufacturers will be able to use Standard 216 test procedures to test their products and provide standardized performance data for use in specification and simulation of fan performance. Standard 216 test procedures should also be used for any full scale fan test mock-ups. In conjunction with the proposed Addendum C to ASHRAE Standard 55 (described above), this new standard will support the implementation of ceiling fans as thermal comfort features in buildings.

As of this writing, the proposed Standard 216 is still in draft form pending final adoption.

Costs

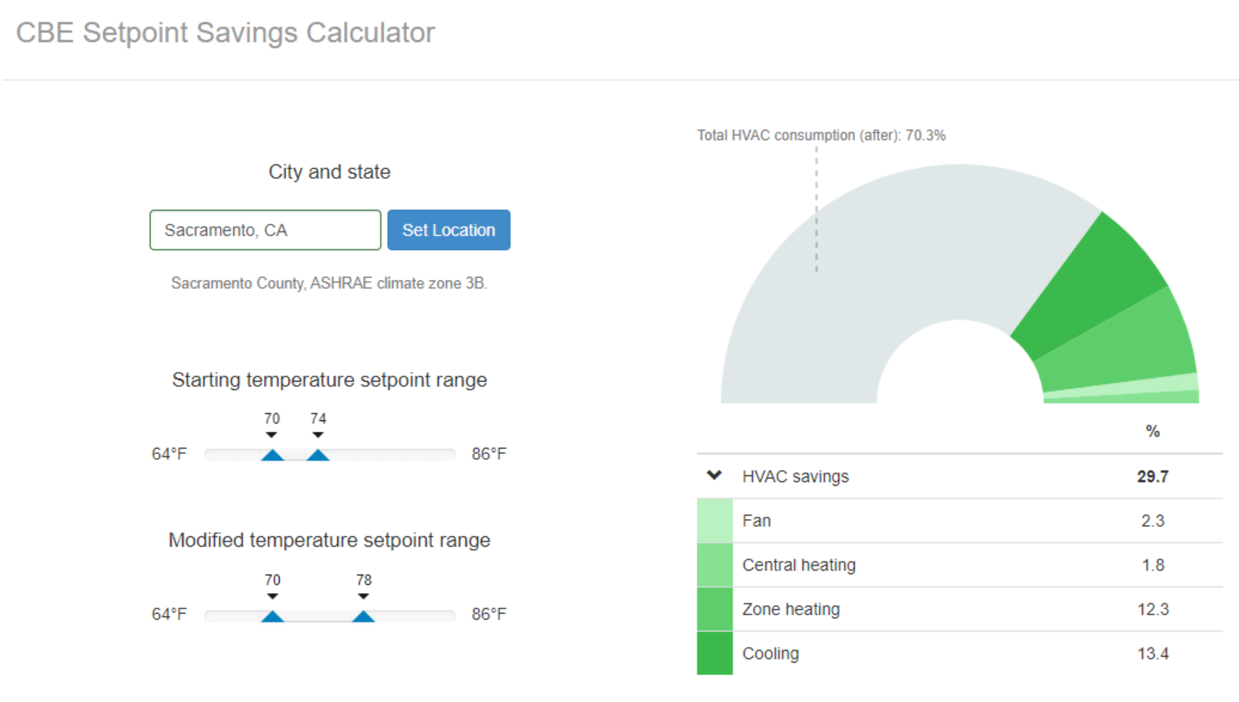
Like many building products, ceiling fan costs can vary widely depending on size, material, motor type, and other characteristics. Standard ceiling fans can range from less than $100 for basic off-the-shelf models to over $1,000 for more specialized fans with more decorative features, higher quality materials, and/or automated onboard control systems. In general, fans with DC motors tend to be more expensive than fans with AC motors, but DC motors also tend to be more energy efficient, quieter, and more durable than AC motor fans due to better bearings and build quality. A wide range of high quality, efficient standard fans with DC motors are currently available from $400 upwards. Large-diameter ceiling fans start at approximately $3,000 and increase in cost with fan diameter and performance characteristics. There is relatively little difference in performance between DC and AC motors for the larger motor sizes associated with large-diameter fans.

Installation costs can vary widely depending on the fan (assembly time, weight and diameter), the space conditions, and whether the installation is new construction or a retrofit. Very approximately, it can take a professional anywhere from 30 minutes to 3 hours to assemble and install a single ceiling fan depending on the selected model and site conditions. On the low end of that estimate, the time required to install a ceiling fan is simply the labor cost to assemble the ceiling fan and connect it to an existing junction box. On the other hand, a variety of factors can make ceiling fan installations more complicated, and therefore more expensive. The need for additional structural bracing in spaces with suspended ceilings, the need for additional people to handle and install larger fan models, running new wiring for power and controls in retrofit scenarios, and the need for mechanical lifts for installations in spaces with high ceilings are just a few of the factors that can add complication and cost for ceiling fan installations. In retrofit scenarios, if there is already an electrical box in place, installation costs may be minimal, but if new wiring and junction boxes are needed, the installation is likely to be more complicated and more costly.

As an example, for a recent research project which installed 99 fans in different sites throughout the California Central Valley, retrofit installation costs (including permit costs) ranged from an average of $427 per fan for installations in the residential demonstration units to $677 per fan for one of the community buildings in the demonstration project with eight-foot suspended tile ceilings. These high costs account for the relatively high costs of labor and permits in California, as well as site-specific conditions that made the installations more complicated. Some of the fans in spaces with suspended ceilings required additional bracing, and several of the residential applications required entirely new wiring and electrical boxes which added to installation costs. Variations in these installation costs also take into account external factors beyond the fan installation, such as long travel times to the demonstration sites (several hours each way), and the size and efficiencies of each of the installation projects (e.g., larger jobs had lower average per fan costs since external factors are averaged over a larger number of fans).

Modeling, Simulation and Energy Savings Estimation

To demonstrate the energy savings potential of ceiling fans in a whole building energy model, simply increase the cooling setpoint based on the estimated cooling effect for the considered scenario, while maintaining the same heating setpoint. Models will generally show approximately 10% reduction in total HVAC savings per °C increase in cooling setpoint (5% per °F), through a combination of cooling and associated transport energy savings (e.g. fan), as well as heating energy savings. The reason for heating energy savings is that when the cooling setpoint is higher, temperatures in the space tend to be warmer during the day than without ceiling fans, and this reduces morning warmup (and sometimes reheat) energy consumption. For rapid estimates, the CBE Setpoint Savings Calculator will estimate the energy savings for a particular location in the USA for a commercial office building based on EnergyPlus models. The web tool can be found here: comfort.cbe.berkeley.edu/energycalc



There are secondary effects that can also be modeled, but are only relevant in certain scenarios:

When ceiling fans operate, they increase convective heat transfer from surfaces in the space, such as floors, walls and windows. In most cases this increase has a small effect on the overall resistance of surface and can be ignored. However, there are scenarios where it may be important, such as:

- Where there is a poorly insulated envelope and a significant percentage of the spaces heating/cooling load is due to conduction through that envelope. For example, a space with a lot of single glazed windows.
- Where the surface temperatures are likely to differ substantially from the air temperature in the space. For example, direct solar radiation on a floor surface, a radiant heating/cooling system, or a zone with a lot of exposed thermal mass.

In these cases, this effect can be roughly approximated using equations derived from experiments on very high volume flow rate radial ceiling diffusers[15]: $h_{wall} = 1.208 + 1.012 \cdot ACH^{0.604}, h_{downstream\,surface} = 2.234 + 4.099 \cdot ACH^{0.503},\ h_{upstream\,surface} = 3.873 + 0.082 \cdot ACH^{0.98}$where h is the convective heat transfer rate of the wall/floor/ceiling (W/m^{2}K) and ACH is the air change rate (room volume divided by the fan airflow).

The minimal power consumed by the ceiling fans themselves can be added as a plug load, with a schedule similar to that of the lighting system. In modeling software where you can define the fraction heat emitted by radiation vs convection, a high convective value is likely appropriate here (e.g. 0.9). In modeling software where you can define the relationships between plug loads and other variables, defining a cubic relationship between ceiling fan power consumption and air temperature, starting minimum power consumption at 23 °C (74 °F) and ending at the design cooling effect and associated fan power is a reasonable assumption. However, modern ceiling fans typically consume very little power in the context of a building's typical electrical loads (small fractions of a watt per unit floor area) and this additional modeling step is unlikely to have a significant effect on results. It is likely more appropriate to use a fixed average plug load and focus modeling efforts on more influential components of the model.

Lastly, depending on the system, if ceiling fans and elevated temperatures are used throughout the building, it may be reasonable to modify other HVAC controls based on higher indoor cooling setpoints, generating further energy savings. For example, increasing the supply air temperature leaving the air handling unit, and increasing the water temperature leaving the mechanical cooling equipment serving the cooling coils in that unit.

[15] See the Ceiling Diffuser Algorithm in EnergyPlus documentation, or the paper: D.E. Fisher, C.O. Pendersen, Convective heat transfer in building energy and thermal loan calculations, ASHRAE Transactions., 103 (1997) 137-148.

CBE Ceiling Fan Design Tool

To help determine optimal ceiling fan arrangements, CBE developed an online Ceiling Fan Design Tool. The tool allows users to input room dimensions, design air speed ranges, and other parameters to determine optimal ceiling fan placement. The tool includes characteristics for a range of default ceiling fan options, or users can input specific details of other ceiling fan models to determine appropriate layouts. In addition to providing recommended fan layouts, the tool provides estimate for airspeeds (minimum, average, and maximum), cooling effect (minimum and maximum), and airspeed uniformity for each proposed layout, as shown below in Figure 41. The tool also provides visualizations for the overall ceiling fan plan for the space, as well as ceiling fan “cell” plan and section showing details on airspeeds within each fan cell, and ideal mounting heights, as shown in Figure 42 and Figure 43.

The CBE Ceiling Fan Design Tool takes into account many of the design factors discussed in the sections above. For more details on how the tool functions, please consult the online User Guide.

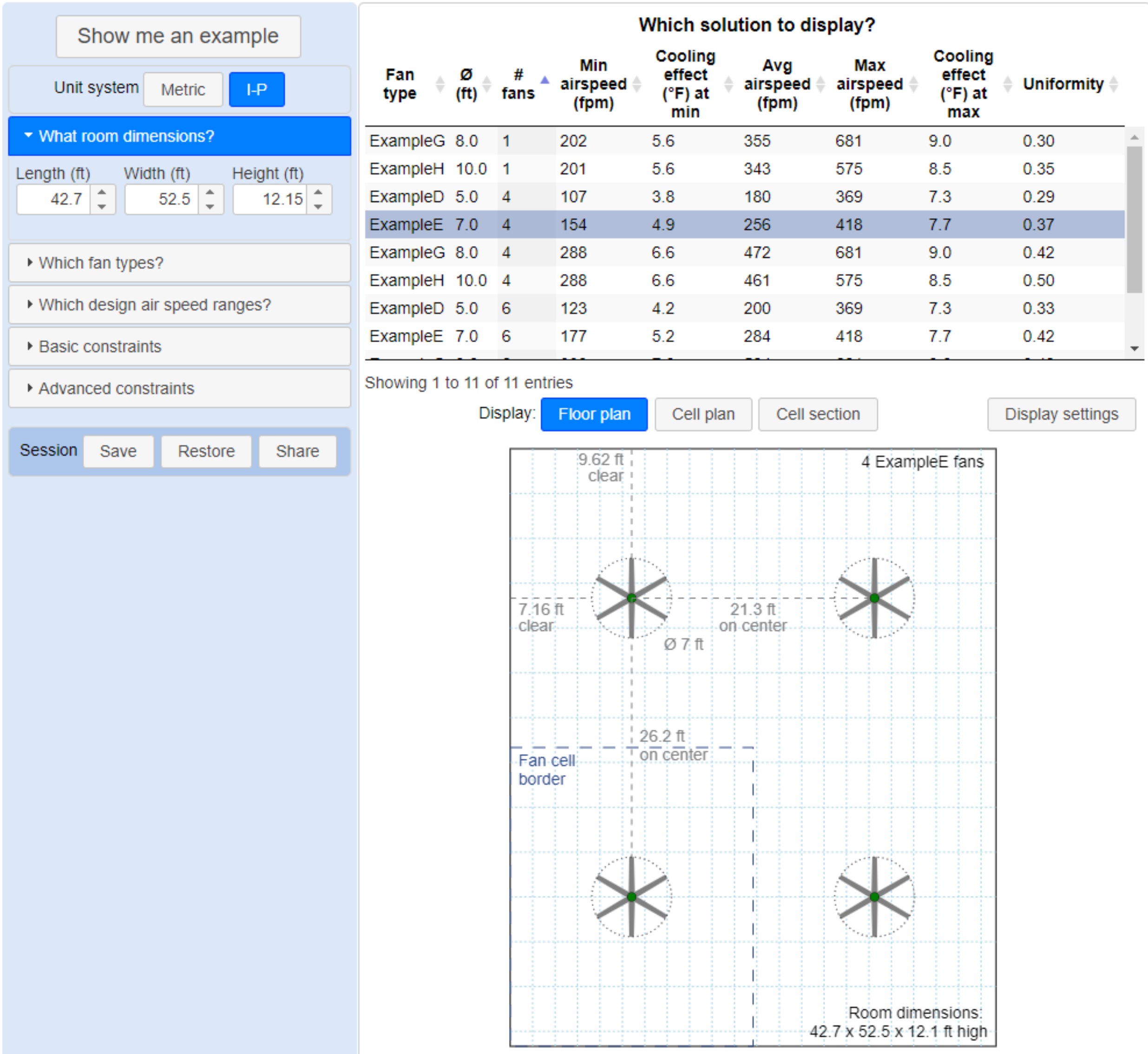


Figure 41: Example CBE Ceiling Fan Design Tool outputs

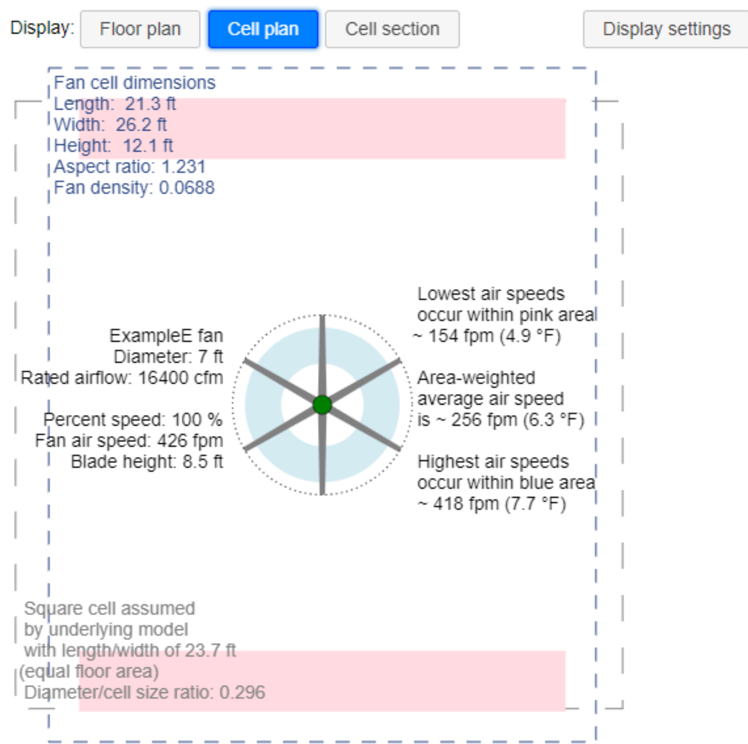


Figure 42: Example cell plan from CBE Ceiling Fan Design Tool

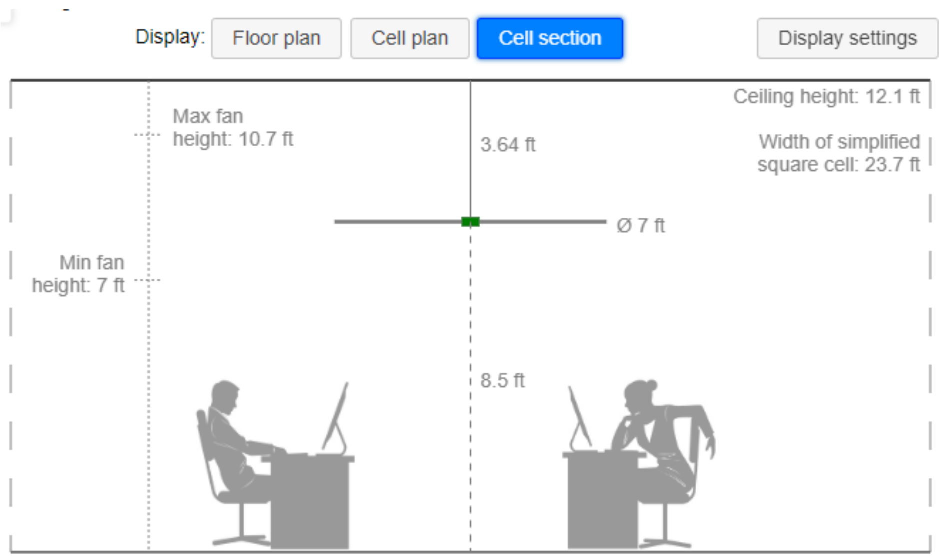


Figure 43: Example cell section from CBE Ceiling Fan Design Tool

Acknowledgements

The California Energy Commission's Electric Program Investment Charge Program and the Center for the Built Environment financially supported the work to develop this guide (EPC-16-013). Gwelen Paliaga and Therese Peffer contributed to initial scoping of the document, and Edward Arens and David Lehrer performed editorial review. Kristen Bellows, Mia Nakajima and Paul Raftery developed the graphics used throughout the guide. Additionally, a large number of people and organizations kindly provided photographs used throughout this guide, and we thank them for their contributions: Elaina Present, PAE, HOK, Big Ass Fans, EHDD Architecture, LPA Architect and SmithGroup.

Additionally, much of the content in this guide is a direct outcome from research performed under broader EPIC Fan project (EPC-16-013), which has had a wide range of contributors:

Hui Zhang, Gail Brager, Therese Peffer, Dana Miller, Sonja Salo, Lindsay Graham, Marta Delgado, Carlos Duarte, Ed Arens, Wenhua Chen, Yingdong He, Maohui Liu, Tom Parkinson, Elaina Present, Stefano Schiavon – *Center for the Built Environment (CBE)*

David Douglass-Jaimes, Gwelen Paliaga, Mia Nakajima, Abhijeet Pande – *TRC*

Jay Fizer, Christian Taber, Michael Smith, Jayme Webb, Michael Harp, Justin Risner – *Big Ass Fans*

Sebastian Cohn, Mitch Green, Andy Brooks – *Alliance for Energy Affordability (AEA)*

APPENDIX: DESIGN, SPECIFICATION, AND INSTALLATION CHECKLIST

Outlined below is a checklist of considerations and tasks to ensure a successful and effective ceiling fan installation.

Design airspeeds

- ☐ Determine occupancy type and design intent for each space – is air speed variability, targeted air movement, or uniformity most beneficial?
- ☐ Determine the design air speed location, based on occupancy, design intent, and application – under the fan, average in room, or farthest from the fan?
- ☐ Determine the design air speed and associated cooling effect needed for the application

Fan selection

- ☐ Determine the range of fan diameters that will meet blade and ceiling height constraints
- ☐ Determine fan location and/or layout that meet design performance criteria established above, and meets required clearances from any obstructions
- ☐ Select fans for high efficiency – but only directly compare one fan's power consumption to another fan at the same diameter and same airflow!
- ☐ Confirm that the selected fan has a sufficient number of fan speed levels (e.g. 5 or more) to meet the design performance criteria
- ☐ Confirm that the fan has sufficient turndown capability (e.g. 30% or less) to meet the design performance criteria
- ☐ Confirm that the fan has acceptably low noise level at design condition
- ☐ Confirm that the fan is of good build quality to reduce future maintenance issues
- ☐ Consider total equipment and install cost when selecting ceiling fans as the installation cost is typically a substantial component of overall cost.

Ceiling co-ordination

- ☐ Ensure that time is allocated for ceiling plan co-ordination with relevant project team members and that all relevant team members are aware there are ceiling fans in the design.
- ☐ Ensure that the fan layout is coordinated with the lighting design to prevent conflict (flicker, strobing, etc.)
- ☐ Ensure that the fan layout is coordinated with fire sprinkler locations and alarm strobe lights, and that the fan layout meets all applicable fire code requirements
- ☐ Confirm that fan layout and locations meet all structural requirements, and can accommodate necessary mounting locations, diagonal bracing, guy wires, etc.
- ☐ Coordinate fan layout with mechanical considerations such as supply and return vents, chilled beams, radiant panels, etc.
- ☐ Coordinate fan layout with any other ceiling systems considered in the space (projectors, acoustic elements, etc.)

HVAC design

- ☐ Consider increasing zone design cooling conditions (temperature and absolute humidity) to those enabled by the ceiling fans
- ☐ Consider reducing distribution ductwork and number of diffusers to reduce first costs and pressure drops
- ☐ Consider downsizing mechanical equipment and duct mains
- ☐ Determine if destratification is needed in heating mode
- ☐ If supplying ventilation air from the ceiling during heating operation, account for improved ventilation effectiveness in heating due to ceiling fan destratification.

Controls and UI

- ☐ Ensure fan control is near the fan(s) it controls and is clearly visible to occupants.
- ☐ Ensure the control is intuitive (increasing speed levels vertically from off to max, etc.)
- ☐ Consider adding a label/plaque describing controls, design intent, and recommended operation. At a minimum, there should be some indication on/near the control to indicate that it controls the fan.
- ☐ Consider including occupancy and/or temperature-based automation
- ☐ Confirm that any automated sequence of operations reflects the design intent, prioritizing ceiling fans first, then HVAC, with relevant setpoints suggested for both systems.

Functional testing

- ☐ Ensure installation contractor scope includes a functional mockup test with one fan to confirm user interface and controls function as intended

APPENDIX: ADDITIONAL RESOURCES AND REFERENCES

Useful websites and tools:

- CBE fan related research: cbe.berkeley.edu/research-category/indoor-environmental-quality/fans
- CBE Fan Tool: cbe.berkeley.edu/fan-tool
- CBE Comfort Tool: comfort.cbe.berkeley.edu
- CBE Setpoint Savings Calculator: comfort.cbe.berkeley.edu/energycalc
- CEC MAEDbs – database containing information on ceiling fans on the market: cacertappliances.energy.ca.gov
- Large selection of fans from multiple manufacturers, and resources for fan selection: http://www.hansenwholesale.com

Other ceiling fan design guides:

- Asia Pacific Research Initiative for Sustainable Energy Systems 2013 (APRISES13). Office of Naval Research, Grant #: N00014-14-1-0054. Ceiling Fan Study: Final literature and market report: http://bit.ly/2SinVwS

Relevant scientific publications:

- Arens E., S. Turner, H. Zhang, and G. Paliaga. 2009. Moving air for comfort. ASHRAE Journal, May 51 (25), 8 – 18. https://escholarship.org/uc/item/6d94f90b
- Chen, W. 2017. Experimental and numerical investigations of indoor air movement distribution with an office ceiling fan. Building and Environment 130, 14-26. https://escholarship.org/uc/item/37s8h4w4
- Gao, Y., H. Zhang, E. Arens, E. Present, B. Ning, Y. Zhai, J. Pantelic, M. Luo, L. Zhao, P. Raftery, and S. Liu. 2017. Ceiling fan air speeds around desks and office partitions. Building and Environment. November. www.escholarship.org/uc/item/3pq2j9mh
- Lipczynska, A., S. Schiavon, and L. Graham. 2018. Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics. Building and Environment 135. https://escholarship.org/uc/item/80b3458w
- Liu, S., A. Lipczynska, S. Schiavon, and E. Arens. 2018. Detailed experimental investigation of air speed field induced by ceiling fans. Building and Environment 142, 342-360. September. https://escholarship.org/uc/item/2mk3n264
- Melikov, A.K. and J. Kaczmarczyk. 2012. Air movement and perceived air quality, Building and Environment 47, 400–409. https://doi.org/10.1016/j.buildenv.2011.06.017.
- Parkinson, T., P. Raftery, and E. Present. 2020. Spatial uniformity of thermal comfort from ceiling fans blowing upwards. Published in ASHRAE Winter Conference, Orlando. February. https://escholarship.org/uc/item/5fs9q6fq
- Present, E., P. Raftery, G. Brager, and L. Graham. 2019. Ceiling Fans in Commercial Buildings: In Situ Airspeeds & Practitioner Experience. Building and Environment 147, 241-257. January. https://escholarship.org/uc/item/84h3z7nx
- Raftery, P., J. Fizer, W. Chen, Y. He, H. Zhang, E. Arens, S. Schiavon, and G. Paliaga. 2019. Ceiling fans: Predicting indoor air speeds based on full scale laboratory measurements. Building and Environment 155, 210-223. May. https://escholarship.org/uc/item/4p479663
- S. Schiavon, A.K. Melikov. 2008. Energy saving and improved comfort by increased air movement. Energy and Buildings 40, 1954–1960. https://escholarship.org/uc/item/6xg815xj.

- S. Schiavon, B. Yang, Y. Donner, V.W.-C. Chang, W.W. Nazaroff. 2017. Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons. Indoor Air 27, 690–702. https://escholarship.org/uc/item/7f01n291.
- T. Hoyt, E. Arens, H. Zhang. 2015. Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings. Building and Environment 88, 89–96. https://escholarship.org/uc/item/13s1q2xc
- Wang, H., H. Zhang, X. Hu, M. Luo, G. Wang, X. Li, and Y. Zhu. 2019. Measurement of airflow pattern induced by ceiling fan with quad-view colour sequence particle streak velocimetry. Building and Environment 152, 122-134. April. https://escholarship.org/uc/item/2v88v264
- Zhai, Y., C. Elsworth, H. Zhang, E. Arens, Y. Zhang, L. Zhao. 2015. Using air movement for comfort during moderate exercise. Building and Environment. https://escholarship.org/uc/item/6018h6wz

APPENDIX: CASE STUDIES

See the following pages for example case studies.

Ceiling Fans Case Study

Photo: Michael David Rose

Photo: Michael David Rose

OVERVIEW

Location: Santa Cruz, CA
Project Size: 40,000 ft^2
Construction Type: New Building
Completion Date: 2017
Building Type: University Campus
Climate Zone: 3C
Total Building Cost: $54 million

Owner: UC, Santa Cruz
Architect: EHDD
General Contractors: Swinerton Builders
Structural Engineer: Mar Structural Design
Mechanical Engineer: Taylor Engineering
Civil Engineer: GHD Engineering

Thoughtful design of a world-class research facility highlights the benefits of ceiling fans in naturally ventilated spaces in ensuring occupant thermal comfort in educational settings.

COASTAL BIOLOGY BUILDING

The Coastal Biology Building brings together faculty and staff to support research and teaching on ecology and evolutionary biology. The LEED Gold Certified building is set on a 97-acre site with easy access to wetlands and other important natural habitats for field-based learning. The University of California, Santa Cruz worked with EHDD to deliver world-class facilities for marine and ocean health research located near the Monterey Bay National Marine Sanctuary.

The two-story building is a state-of-the-art facility that includes a 125-seat classroom and two smaller classrooms, 20 primary research laboratories, a core seawater laboratory, seminar and meeting rooms, and 43 research offices. The HVAC systems for many spaces in the building, including the main lecture hall, function without compressive cooling. The integrated facade strategy uses electrochromic glazing, operable windows, and easy-to-operate ceiling fans to ensure above-average occupant comfort in warmer temperatures in summer. The success of this strategy is reflected in the building earning a perfect score in the LEED Indoor Environmental Quality category.

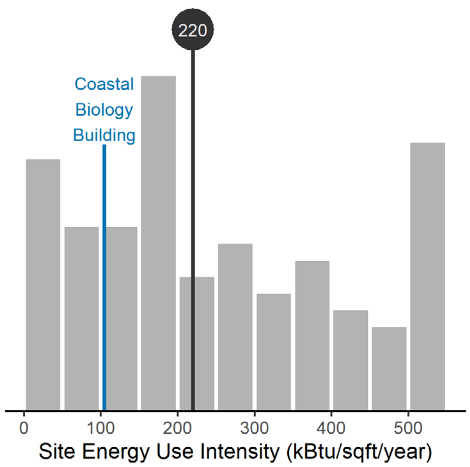


Figure 1. Energy use for both the main building and greenhouse is below 75% of laboratory and college buildings from the same climate zone in the Building Performance Database (BPD). The Site EUI of 105 is over 50% less than the mean EUI of 220.

Energy Performance

In keeping with the sensitive nature of the site, the building was designed with a context-appropriate agricultural vernacular with an emphasis on low energy use. The whole building site energy use intensity (EUI) of just 105 kBtu/ft² is 50% less than the average EUI performance of 118 laboratory and college buildings in the 3C climate zone within a federal database of over 230,000 buildings. This places the building in the top 25% of that dataset in terms of energy performance (Figure 1). In addition, it exceeds the best-practice targets in ASHRAE's Standard 100-2015 Energy Efficiency in Existing Buildings. The use of efficient high-volume, low-speed ceiling fans helped to ensure that the cooling systems consume only 1% of predicted electricity energy of the building.

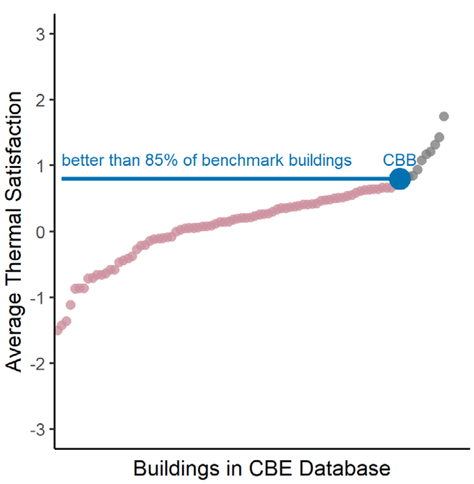


Figure 2. Satisfaction with the thermal environment at CBB is higher than 85% of classroom and laboratory buildings in the CBE Occupant Survey database.

Thermal Comfort

From the outset, Taylor Engineering wanted to pursue low-energy options to cool the mixed-use building. The cool coastal climate of the campus allowed them to design the HVAC system for the seminar space using an efficient single-zone air handler without a cooling coil. The seminar room has a ductless HVAC design, made possible by the use of ceiling fans to mix the air throughout the room and uniformly cool the occupants. Survey results show occupants' thermal satisfaction is well above that of comparable buildings in the CBE database (Figure 2). Figure 3 shows the mean score on the seven-point satisfaction scale was +0.8, well above the thermal comfort benchmark of +0.2 in the 112 classrooms and laboratories in the CBE database, placing it in the top 15% of buildings in that dataset.

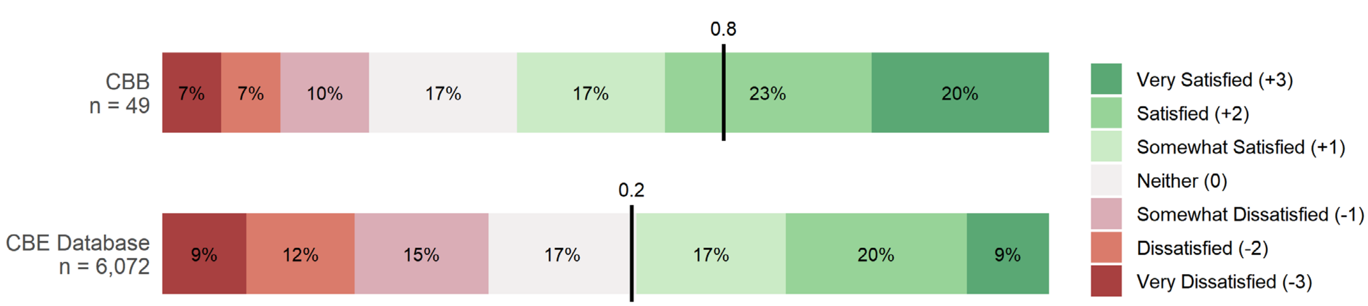


Figure 3. 60% of occupants in the Coastal Biology Building (CBB) rated their indoor temperature as satisfactory. The mean thermal satisfaction vote of +0.8 places it in the top 15% of classrooms and laboratories for thermal comfort in the CBE Occupant Survey database.

CBE
CENTER FOR THE BUILT ENVIRONMENT

This case study is part of a project focused on energy and occupant factors within the larger study of Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort. It is being led by Paul Raftery at UC Berkeley Center for the Built Environment (CBE) and funded by the California Energy Commission (EPIC Project 16-013).

Ceiling Fans Case Study


Photo: Nic Lehoux

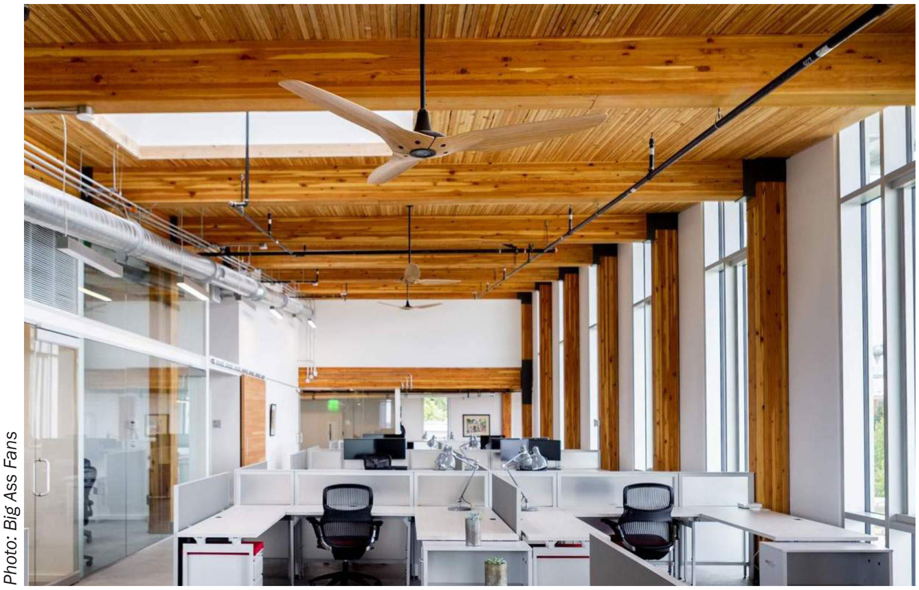


Photo: Big Ass Fans

OVERVIEW

Location: Seattle, WA
Project Size: 52,000 ft^2
Construction Type: New Building
Completion Date: 2013
Fully Occupied: 100%
Building Type: Office
Climate Zone: 4C
Total Building Cost: $32.5 million

Owner: Bullitt Foundation
Architect: Miller Hull Partnership
Development Partner: Point32
General Contractors: Schuchart, Foushee
Structural Engineer: DCI Engineers
MEP Engineering: PAE
Civil Engineer: Stantec
Commissioning: Keithly Barber Associates
Solar Team: Northwest Wind and Solar
Water Systems: 2020 Engineering
Landscape Architect: Berger Partnership

Ceiling fans are a key part of the strategy in achieving world-class commercial building performance and delivering a comfortable indoor environment for office workers.

THE BULLITT CENTER

The Bullitt Foundation, a nonprofit philanthropic organization with a focus on the environment, worked with local real estate firm Point32 to deliver a building at the cutting-edge of sustainable architecture. The building was the vision of CEO Denis Hayes to create "the greenest urban office building in the world", receiving the Sustainable Building of the Year award from World Architecture News in 2013.

The building uses a mixed-mode cooling, heating and ventilation strategy. To help meet the low energy targets, ceiling fans were combined with automated windows for passive cooling and to provide natural ventilation and fresh air. Fans use only 2% of end use energy but allow higher cooling setpoints to reduce HVAC reliance. This system was estimated to offset about 750 hours of annual cooling. Occupants use the fans to provide thermal comfort and ensure the building operates sustainably. The result is far above average thermal satisfaction and world-class energy performance.

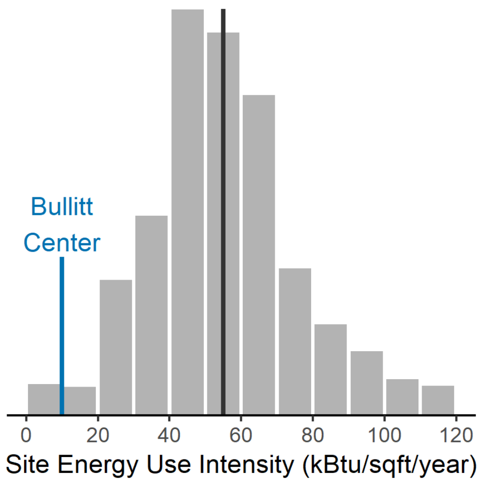


Figure 1. The Bullitt Center is placed in the top 2% of office buildings from the same climate zone in the BPD. The Site EUI of 10 is over 80% less than the mean EUI of 55.

Photo: Nic Lehoux

Energy Performance

The Bullitt Center was designed to have exceptionally low energy use to meet zero net energy targets and Living Building Challenge standards. The whole building site Energy Use Intensity (EUI) of just 10 kBtu/ft^2 is over 80% less than the average EUI performance of 1,142 offices in the 4C climate zone within the Building Performance Dataset (BPD). This places it in the top 2% of those buildings in terms of energy performance (see Figure 1). While that dataset includes a mix of construction age, the Bullitt building's energy use is also significantly lower than a new code building in the same year, and best-practice in ASHRAE's Standard 100-2015 Energy Efficiency in Existing Buildings by approximately 70%. The mechanical engineers used efficient ceiling fans to help reduce HVAC energy and meet the ambitious design goals.

Thermal Comfort

Aiming for low energy use targets required PAE Consulting Engineers to think creatively about ways to reduce HVAC energy consumption. Sensors and controls coordinate the windows to optimize thermal comfort and outside air, thereby reducing reliance on mechanical cooling. The use of ceiling fans help to lower energy use and enhance occupant comfort by cooling occupants much quicker than a centralized system can. The results of the thermal comfort survey show a 50% increase in occupant satisfaction with the temperature over the average building in the CBE database (see Figure 2). The mean score on the 7-point satisfaction scale was +0.8, well above the thermal comfort benchmark of 0.0 in the 500 offices in the CBE database, placing it in the top 15% of commercial office buildings in that dataset.

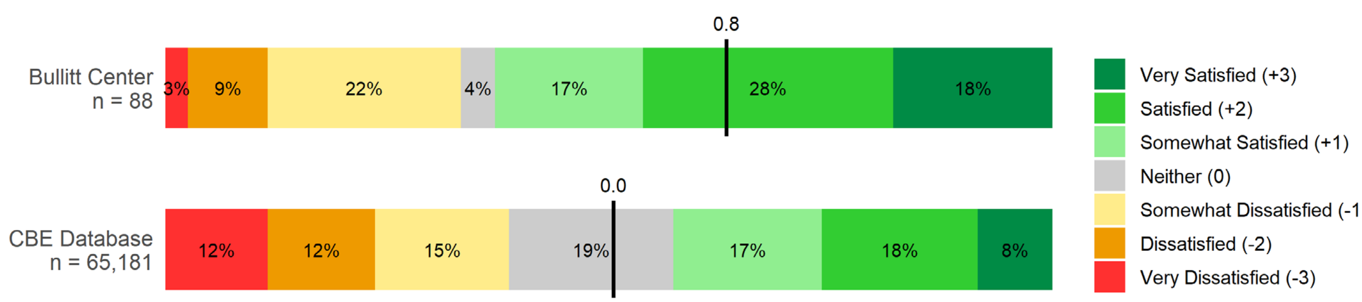


Figure 2. Over 60% of occupants in the Bullitt Center rated their indoor temperature as satisfactory. The mean thermal satisfaction vote of 0.8 places it in the top 15% of commercial office buildings for thermal comfort in the CBE Occupant Survey database.

This case study is part of a project focused on energy and occupant factors within the larger study of Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort. It is being led by Paul Raftery at UC Berkeley Center for the Built Environment (CBE) and funded by **the** *California Energy Commission (EPIC Project 16-013).*

Ceiling Fans Case Study

Photo: Community Preservation Partners

Photo: Dana Miller

OVERVIEW

Location: Stockton, CA

Project Size: 50,565 ft^2

Construction Type: Renovation

Completion Date: 2007

Fully Occupied: 112 units

Building Type: Senior Living Facility

Climate Zone: 3B

Owner: WNC & Associates

Energy retrofits of a senior living facility shows how ceiling fans integrated with air conditioning can deliver thermal comfort improvements and energy savings for community housing.

FRANCO CENTER

The Franco Center Apartments is a five story senior living facility in Stockton, CA. Constructed in 1967 and renovated in 2007, it is built of solid concrete masonry with no additional insulation. The first floor is made up of retail spaces, community rooms for the residents, and office space for staff. The residential spaces occupy the second through fifth floors, with studios and 1-bedroom units on floors two through four, and 2-bedroom units on the fifth floor.

The Franco Center is located in a hot climate, where the ASHRAE 1% summer design conditions are 97.9°F. Thirty-five ceiling fans were installed in the common areas of the building to demonstrate how smart ceiling fans with on-board sensors for occupancy and temperature can reduce energy usage and increase thermal comfort in flexible mixed-use spaces. Elevated air speeds from the fans improved occupant comfort, allowing thermostat cooling setpoints to be increased to save HVAC energy use. This project demonstrates how simple retrofits can deliver impressive results for both energy and comfort.

Energy Performance

The first-floor common room is served by two compressors and nine fan coil units with a total capacity of approx 400 MBtu/hour. Cooling setpoint temperatures were increased by 5-8°F to 76°F after the ceiling fans were installed. Electricity monitoring equipment established baseline energy use before and after the fan installation. Measurements over two summers (Figure 1) show air conditioning energy use increased with outdoor air temperature as expected. The same relationship was seen after installing the ceiling fans, but the total energy use decreased by approx 60% on average. This saved approx $1000 per month in electricity during summer. These savings were achieved by extending the temperature deadband, made possible by coordinating the fans and air conditioning to maintain or improve comfort.

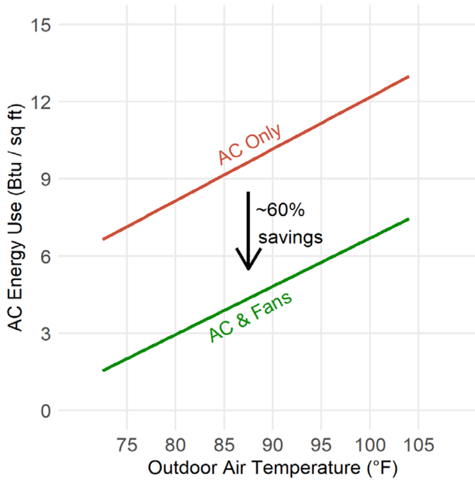


Figure 1. HVAC energy use in the common room was reduced by 60% by raising setpoints and using fans to cool occupants when temperatures were above 74°F. Source: Dana Miller.

Thermal Comfort

Thirty-five ceiling fans were installed in the common room in a grid arrangement to ensure even distribution of air speeds. They were programmed to start at 74°F during occupancy, while the air conditioning was changed to start at approximately 76°F. Thermal comfort surveys were completed by occupants before and after the ceiling fans were installed. Figure 2 shows 92% of surveyed occupants reported being comfortable at 80°F with the ceiling fans running. This is an improvement in thermal comfort over the earlier survey without the fans, even though the temperature in the common room was 8°F warmer. This demonstrates that cooling setpoints can be higher while providing similar or improved occupant comfort by using efficient ceiling fans, substantially reducing energy use and cost.

Photo: Dana Miller

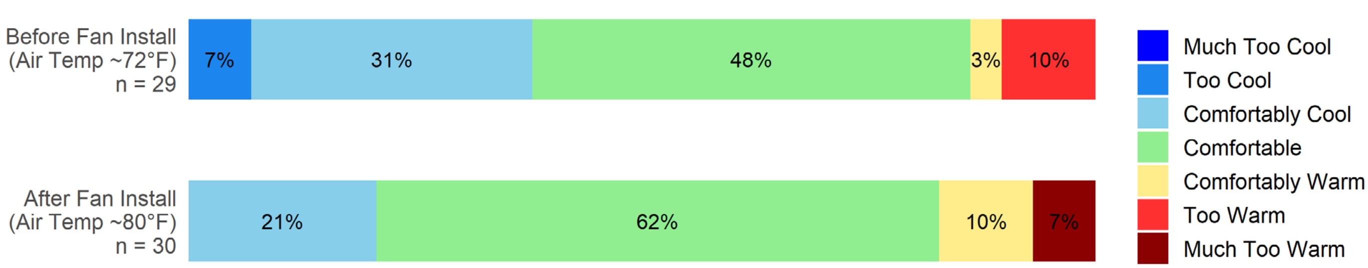


Figure 2. Over 90% of surveyed occupants in the Franco Center Apartments rated their indoor environment as comfortable after the ceiling fans were installed. This is an increase in occupant comfort from the earlier survey even though it was 8°F warmer. Source: Dana Miller.

This case study is part of a project focused on energy and occupant factors within the larger study of Integrating Smart Ceiling Fans and Communicating Thermostats to Provide Energy-Efficient Comfort. It is being led by Paul Raftery at UC Berkeley Center for the Built Environment (CBE) and funded by **the** *California Energy Commission (EPIC Project 16-013).*