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3. VENTILATION AND INDOOR AIR QUALITY

3.1. Ventilation in Modern Buildings

3.1.1. Ventilation

Ventilation can be defined as the deliberate supply of a clean outdoor air to a building or space to meet criteria associated with the use of that space. Clean outdoor air is provided to indoor spaces for several reasons including:

- provide oxygen for human breathing,
- dilution or removal of airborne contaminants,
- provide for thermal comfort,
- other reasons such as combustion appliances and for smoke control.

Ventilation dilutes air contaminants, carbon dioxide caused by human breathing exhalation and other air contaminants in occupied spaces. Building's ventilation can be either natural, mechanical or a combination of the two and can be selected according to the building requirements.

3.1.2. Natural Ventilation

Natural ventilation depends on wind and temperature difference to cause air movement between the inside and outside of a building, between enclosures within a building and within enclosures.

Ventilation air is generally delivered through openings of a particular size and distribution in the external facade of a building. Air moves in and out of these openings such as windows, doors, vents, and grilles. Natural forces such as wind, thermal and stack effects move the air. Openable windows and doors can be used in basic natural ventilation systems. Also, natural ventilation systems can be complex and controllable by means of engineered systems.

However, when a building or space cannot meet the building requirements with natural ventilation systems, a mechanical ventilation system is required.

3.1.3. Mechanical Ventilation

Mechanical ventilation depends on fans to cause air movement between the inside and outside of a building, between enclosures within a building and within enclosures. The outdoor air is essentially moved from outside to inside the building using fans in mechanical ventilation systems.

Mechanical ventilation systems are versatile and can be applied to almost any situation or condition to meet building requirements. It provides good control over airflows and an opportunity to filter outdoor and recirculating air streams. Mechanical ventilation can respond to the variable needs of time dependent occupation and can control building and enclosure pressures.

3.1.4. Hybrid and Mixed-Mode Ventilation

Mixed-mode ventilation systems use a combination of the natural and mechanical ventilation approaches but with independent operation and control between the two systems.

Hybrid ventilation systems use both natural and mechanical ventilation, or features of both, in an integrated system. Natural and mechanical ventilation forces can be combined or operated separately, with the operating mode varying depending on the needs of the building and occupants at any given time.

3.1.5. Health Effects and Exposure to Indoor Air Contaminants

People are exposed to different organic (i.e., microorganisms, pollens) and inorganic air contaminants (i.e., fine particles, gases) in the indoor building environment. Different internal and external sources of indoor air contaminants can be considered in the building environment (Fig.3.1).

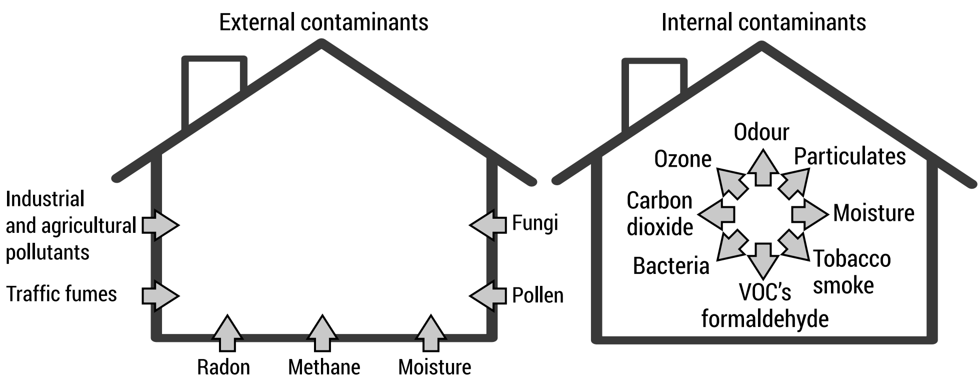

FIG. 3.1. Typical outdoor and indoor sources of contaminants (Source: own elaboration based on AIVC, 1996)

Exposure to indoor air contaminants can cause adverse health effects for occupants (WHO, 2010). Health effects can be acute or chronic and can differ from person to person. To limit the health risk, concentrations of individual substances in the indoor air should be controlled (Table 3.1) and this can be achieved using a variety of strategies including ventilation. Not all potentially dangerous chemicals are known, and many individual chemicals have not had safe exposure standards determined.

TABLE 3.1. Summary of WHO IAQ guideline limits for selected pollutants (Source: WHO, 2010).

Pollutant	Guideline limit	Averaging time	Comment
Benzene	No safe level	Lifetime	Carcinogen
Carbon monoxide	7 mg/m^3 10 mg/m^3 35 mg/m^3 100 mg/m^3	24 h 8 h 60 min 15 min	
Formaldehyde	100 μg/m^3	30 min	
Naphthalene	10 μg/m^3	1 year	
Nitrogen dioxide	40 μg/m^3 200 μg/m^3	1 year 1 hour	
PAH with benzo (α) pirenne as marker	No safe level	Lifetime	Carcinogen
Tetracloroethylene	250 μg/m^3	1 year	
Tricloroethylene	No safe level	Lifetime	Carcinogen

3.1.6. Reducing Indoor Air Contamination

There are several factors that influence the concentration of indoor air contaminants:

- External sources such as the level of air contaminants in the regional outdoor air and the location of outdoor air intake openings relative to local outdoor pollution sources.
- Internal sources such as the generation rate of air contaminants indoors, the level of air recirculation employed in a ventilation system, the level of air cleaning employed, and the level of contaminants generated within a ventilation system.

In the many buildings ventilated by natural means, little can be achieved to avoid the ingress of contaminated air. Therefore, every effort is needed to ensure the quality of outdoor air. Nevertheless, urban pollution, especially from high traffic densities, remains a problem. In these areas, control measures include air filtration, air intakes and fresh air dampers and building air tightness.

Filtration is used primarily to remove particulates from the air. Almost all mechanical supply air intakes incorporate filters to prevent dust from entering the ventilation system. Activated carbon filters can remove gaseous pollutants while high specification (HEPA) filters enable the minutest of particles to be removed.

Air intakes must be located away from pollutant sources. Problems include street level and car parking locations. Also, air quality controlled fresh air dampers can be useful to control peaks occurring during the morning and evening in traffic pollution urban areas.

None of the above control strategies will be effective unless the building is well sealed from the outdoor environment to prevent contaminant ingress through air infiltration.

The preferred order and methods of controlling indoor air contaminants sources are summarized in Table 3.2.

TABLE 3.2. Preferred Methods to control indoor contaminant sources (Source: AIVC, 1996)

Method	Contaminant source
Source control	Emissions from avoidable sources (VOCs and formaldehyde from furnishings, tobacco smoke etc.)
Enclosure and ventilation at source	Pollutants generated by occupant activities (cooking, clothes washing and drying, use of office equipment etc.)
Dilution and displacement ventilation	Emissions from unavoidable sources (primarily metabolic pollution)

Once a contaminant has entered a space, it can only be diluted. Avoidable contaminant sources should therefore be eliminated. This means restricting potentially harmful sources of contaminants such as VOC's and formaldehyde, from furnishings and discouraging tobacco smoking.

Contaminants generated as part of the activity of occupants are usually highly localized. The dominant contaminant in residential buildings is water vapor generated by washing, clothes drying and cooking. Wherever possible source control should be applied, combined with the use of local extractors and cooker hoods to remove these pollutants at source. Similarly localised sources in the workplace should be directly vented to the outside.

General ventilation of a space is needed to dilute and remove residual pollution from unavoidable contaminant sources. Such sources should primarily be odor and CO_2 emissions from building occupants. The necessity to contain metabolic pollution to acceptable levels represents the minimum need for ventilation. A space in which high levels of metabolic products are measured indicates that the ventilation rate is insufficient. Often ventilation is used to dilute avoidable sources of pollutant. Apart from causing unnecessary pollution within such a space, the additional ventilation will result in increased space conditioning load.

3.1.7. Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants. IAQ is a measure of the condition of air in an indoor environment to provide health and comfort of building occupants.

According to the UNE 171330-1:2008 standard, (UNE 171330-1, 2008) Indoor Air Quality is defined as "the environmental conditions of indoor spaces, appropriate to the user and the activity, defined by the levels of chemical and microbiological contamination". IAQ is a part of Indoor Environmental Quality, IEQ, which includes also values of physical factors.

Optimum indoor air quality relies on an integrated approach to the removal and control of contaminants based on source control, filtration, enclosing pollutant sources and ventilating the occupied space (Fig. 3.2).

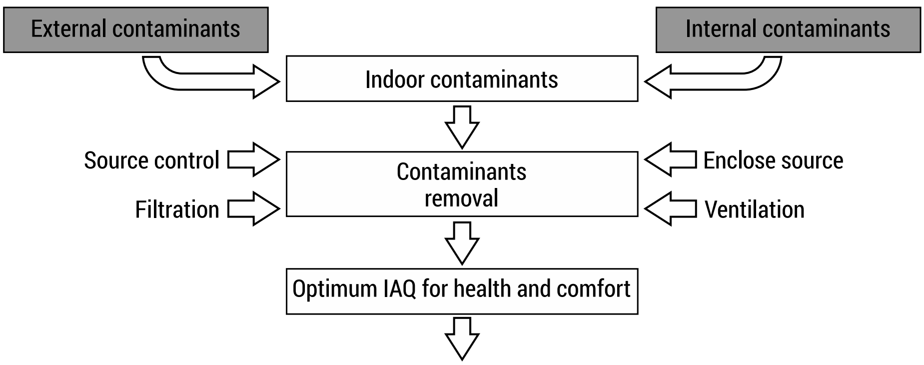

FIG. 3.2. Achieving Optimum Indoor Air Quality (Source: own elaboration based on AIVC, 1996)

Ventilation provides an effective measure to deal with unavoidable contaminants, but source control is the most efficient and, sometimes, the only method suitable for minimizing the effect of avoidable pollutants. Typical unavoidable contaminants are those associated with metabolism (carbon dioxide and odor) and essential occupant activities (e.g., cooking and washing). Avoidable sources include excessive organic emissions from furnishings and fittings, and pollutant emissions from poorly enclosed appliances.

3.2. Ventilation and Indoor Air Quality

The performance of ventilation is dependent on identifying and providing sufficient ventilation for controlling the dominant pollutant. In residential buildings this may be moisture whereas in densely occupied non-residential buildings it may be the occupants.

Provided the dominant contaminant is controlled, all other contaminants should remain below their 'safe' threshold concentration.

3.3. Ventilation Requirements

The ventilation requirements can be fixed depending on several criteria including the contaminant emission rate.

3.3.1. Air Flow Rate Required for Thermal Comfort (Heating And Cooling)

In a mechanically ventilated space, ventilation is also commonly used as part of the heating and cooling distribution system. The amount of ventilation to maintain an internal room air temperature of T_r is given by:

$$\dot{V} = \frac{\dot{Q}_{s,hg}}{\rho\, c_p \left(T_s - T_r\right)} \tag{3.1}$$

where $\dot{V}$ is required warm air ventilation rate (m^3/s), $\dot{Q}_{s,hg}$ is the room sensible heating load (W), ρ is the air density (kg/m^3), c_p is the specific heat capacity of air (1020 J/kg K) and T_s and T_r are the supply and room air temperatures respectively (°C).

A similar calculation approach is applied to cooling and again, the requirement to meet fresh air needs is essential. The flowrate for cooling is thus:

$$\dot{V} = \frac{\dot{Q}_{s,cg}}{\rho\, c_p \left(T_r - T_s\right)} \tag{3.2}$$

where $\dot{V}$ is required warm air ventilation rate (m^3/s), $\dot{Q}_{s,cg}$ is the room sensible cooling load (W), ρ is the air density (kg/m^3), c_p is the specific heat capacity of air (1020 J/kg K) and T_s and T_r are the supply and room air temperatures respectively (°C).

The above equations give an approximate flowrate only. It is assumed that the moisture contents (i.e., mass of water to that of air) of the supply and room air are the same. The room air temperature to be maintained in summer is commonly 22–24°C (offices), while the supply air temperature may be about 15°C. Ideally the same ventilation rate should apply in summer and winter so that the same ventilation system can be used.

3.3.2. Air Flow Rate Between Spaces for Pressurisation

Ventilation is often used to maintain pressure differences between spaces (e.g., in kitchen areas to prevent odors and water vapor from dispersing into other rooms).

Extract ventilation drives the contaminated air through the fan and out of a roof or wall mounted exhaust vent. The resultant under-pressure causes make-up air to come from adjacent spaces. It is important to ensure that the exhaust vent does not contaminate adjacent air supply intakes.

The flowrate to be maintained for pressurization may be obtained by assuming that the sum of the flowrates into and out of a space is equal to zero. Air is lost or gained by leakage from openings around doors, windows, gaps between surface interfaces and via 'leaky' surfaces and to/from a ventilation system via diffusers and grilles.

Pressurized spaces include operating theatres and cleanrooms (as used for the production and testing of integrated circuits), which need to be kept free of contaminants. Calculating flowrates due to pressurization are found using:

$$\sum_{i=1}^{N} \rho_i \dot{V}_i = 0 \tag{3.3}$$

where ρ_i is the air density (kg/m^3), $\dot{V}_i$ is the flowrate via path i (m^3/s) and N is the number of flow paths.

The flowrate $\dot{V}_i$ may be found using:

$$\dot{V}_i = 0.775\, A \sqrt{\Delta P} \tag{3.4}$$

where $\dot{V}_i$ is the leakage rate through openings (m^3/s), A is the leakage area (m^2) and ΔP is the pressure drop across the opening (Pa).

3.3.3. Air flow Rate Required for Removal of Contaminants

In simple mathematical terms the indoor air contaminant concentration of a space can be considered in terms of the relationship:

$$C_i = C_o + \frac{S}{\dot{V}} \tag{3.5}$$

where C_i is the indoor air contaminant concentration (μg/m^3), C_o is the outdoor air contaminant concentration (μg/m^3), S is a measure of contaminant source generation within the space (μg/m^3) and $\dot{V}$ is the outdoor air ventilation rate (m^3/s).

In terms of this relationship the objective of ventilation systems for contaminant control is to maintain C_i as close as possible to C_o. This can be achieved by maximising the outdoor airflow rate $\dot{V}$ and minimizing indoor contaminant generation rate S. The relationship $S/\dot{V}$ is therefore of paramount importance when considering the dilution performance of ventilation systems.

Additional terms would need to be added to this mathematical model to account for infiltration and exfiltration, the action of air cleaning devices, and internal sinks removing contaminants from the air.

Rooms may have one or more pollutant sources/types, different ventilation systems with specific supply and extract locations, given ambient conditions (e.g., temperature, relative humidity, local air speed) and normally it may be difficult to calculate transient and steady-state pollutant concentrations. However, if some simplifying assumptions can be made, then various equations can be used.

For a single room or space, the pollutant concentration for one pollutant source in one room can be found from the following dilution equation:

$$C_{(t)} = C_{(t=0)}\, e^{-\left(\frac{\dot{V}+S}{V}\right)t} + \frac{\dot{V}C_o + S}{\dot{V}+S}\left(1 - e^{-\left(\frac{\dot{V}+S}{V}\right)t}\right) \tag{3.6}$$

where $\dot{V}$ is the flowrate (m^3/s), C_o is the pollutant concentration in the outside air (μg/m^3), S is the pollutant release rate (μg/m^3), V is the room volume (m^3), t is the time (seconds or hours) and $C_{(t=0)}$ is the initial concentration of contaminant (μg/m^3).

The above equation is based on the following assumptions: (1) single pollutant source, (2) constant flowrate, (3) constant external pollutant concentrations, inside and outside pressures, and (4) pollutant and air completely mixed.

If there is no contaminant source (i.e., $S = 0$), then the concentration will decay depending on the ventilation rate, i.e.

$$C_{(t)} = C_{(t=0)}\, e^{-\left(\frac{\dot{V}}{V}\right)t}. \tag{3.7}$$

If the initial concentration of the pollutant is zero, then the concentration is calculated using:

$$C_{(t)} = \frac{\dot{V}C_o + S}{\dot{V}+S}\left(1 - e^{-\left(\frac{\dot{V}+S}{V}\right)t}\right). \tag{3.8}$$

The time constant is the time taken to reach 63% of the steady state value. As the time, t becomes large or greater than four-time constants, the transient term becomes small and the above equation simplifies to the following equation:

$$C_{(t)} = \frac{\dot{V}C_o + S}{\dot{V}+S}. \tag{3.9}$$

The above can be rearranged to give a value for flowrate, i.e.

$$\dot{V} = S\frac{1 - C_{(t)}}{C_{(t)} - C_o}. \tag{3.10}$$

This can be simplified to (as $C_{(t)} \ll 1$)

$$\dot{V} = \frac{S}{C_{(t)} - C_o}. \tag{3.11}$$

The above formula can be modified to calculate a ventilation supply flowrate if the pollutant emission rate, the required room plus outside air contaminant concentrations and the ventilation system efficiency are known, i.e.:

$$\dot{V} = \frac{S}{\varepsilon_v\left(C_{(t)} - C_o\right)} \tag{3.12}$$

where $\dot{V}$ is the fresh air supply per person (m^3/s), S is the contaminant release rate (m^3/s per person), ε_v is the ventilation system efficiency.

3.4. European Regulation and Standards

A set of internationally harmonized procedures has been developed to assess the overall energy performance of buildings: the set of energy performance of buildings, EPB standards. The EPB standards has been proposed aiming at an international harmonization of the methodology for the assessment of the energy performance of buildings (Fig. 3.3).

The set of EPB standards play a key role to support the Energy Performance of Buildings Directive (EPBD, 2010) of the European Union. EU Member States are encouraged to consider applicable standards, from the list of EPB standards.

The EPBD aims to promote the improvement of the energy performance of buildings within the European Union, considering outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness (Article 1).

The first version of the EPBD was published in 2002 (EPDB, Directive 2002/91/EC). In the interest of clarity, the EPBD was recast in 2010 (EPDB, Directive 2010/31/EU). A revised version of the EPBD was published in 2018 (EPDB, Directive 2018/844/EU). Revised EPBD in 2018: stronger role of the EPB standards, from the amended (2018) text of EPBD Annex 1, point 1:

"*Member States shall describe their national calculation methodology following the national annexes of the overarching standards, namely ISO 52000-1, 52003-1, 52010-1, 52016-1, and 52018-1, developed under mandate M/480 given to the European Committee* *for Standardization (CEN). This provision shall not constitute a legal codification of those standards."*

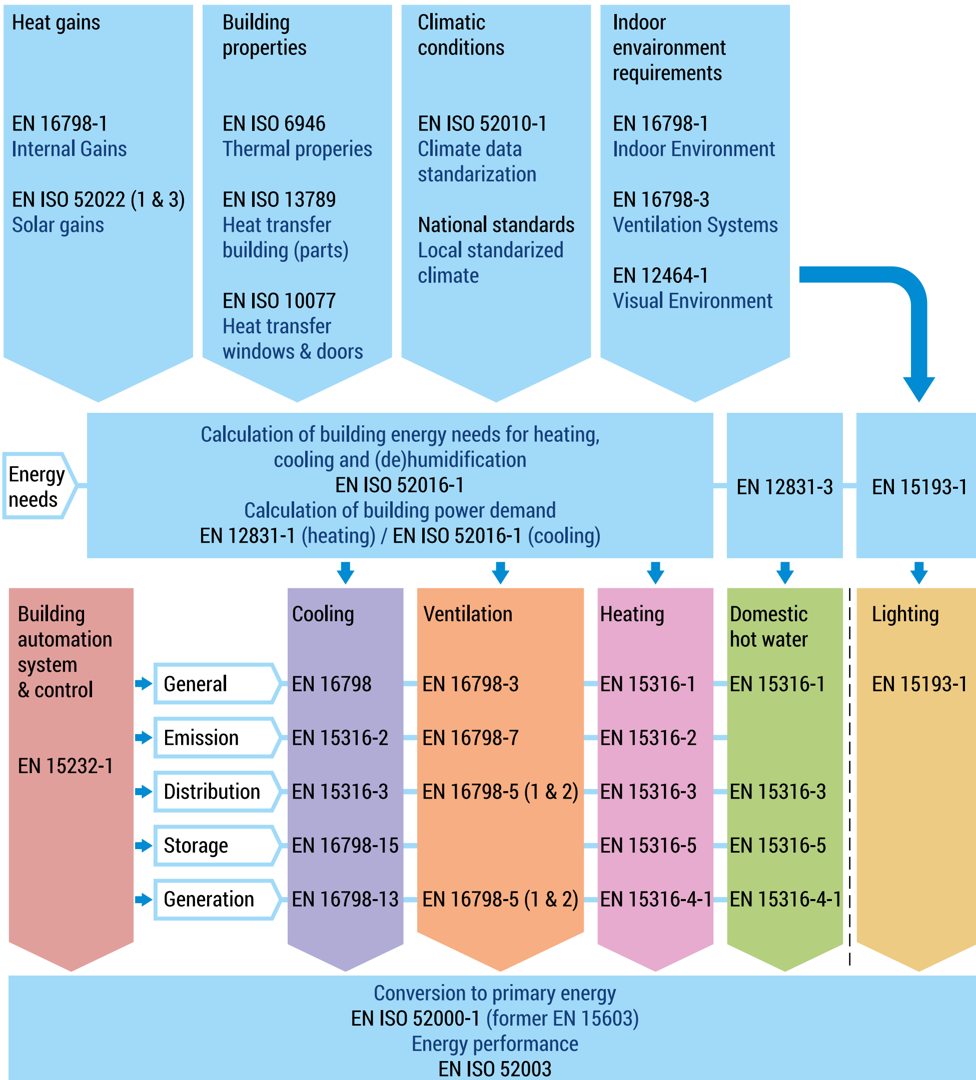

FIG. 3.3. Modular structure of the set of EPB standards (Source: Hogeling, 2016)

Although the new EPBD does not force the Member States to apply the set of EPB standards, the obligation to describe the national calculation methodology following the national annexes of the overarching standards will push the Member States to explain where and why they deviate from these standards. This will lead to an increased recognition and promotion of the set of EPB standards across the Member States and will have a positive impact on the implementation of the Directive.

The set of EPB Standards is used to calculate the energy demand and energy use of a building with its installations. So, it is needed to determine:

- The heat gain: external and internal gains entering the building.
- Building properties: thermal properties of the building envelope and materials of all building elements.
- External climate: the climatic data such as temperatures, humidity, solar data, location/ orientation of the building etc.
- Indoor environment: the indoor environmental requirements (IEQ) like indoor temperatures, humidity, ventilation rate, lighting, and the related assumptions for the user behavior.

The standards regarding technical building system under EPDB such as ventilation system, are shown in Table 3.3.

TABLE 3.3. Technical Building Systems under EPBD (Source: EPDB, 2010)

Sub-Modules	M3 Heating	M4 Coolling	M5 Ventilation	M6 Humidification	M7 Dehumidification
General Needs	EN 15316-1	EN ISO 16798-9	EN 16798-3	EN 16798-3	EN 16798-3
Maximum Load and Power	EN ISO 52016-1 EN 12831-1	EN ISO 52016-1	EN ISO 52016-1	EN ISO 52016-1	
Ways to Express Energy Performance	EN 15316-1	EN ISO 16798-9	EN 16798-3	EN 16798-3	EN 16798-3
Emission & Control	EN 15316-2 EN 15500-1 EN 12098-1 EN 12098-3 EN 12098-5	EN 15316-2 EN 15500-1	EN 16798-7 EN 15500-1	EN 16798-5-1 EN 16798-5-2	EN 16798-5-1 EN 16798-5-2
Distribution & Control	EN 15316-3 EN 12098-1 EN 12098-3 EN 12098-5	EN 15316-3 EN 16798-5-2	EN 16798-5-1		
Storage & Control	EN 15316-5 EN 12098-1 EN 12098-3 EN 12098-5	EN 16798-15			

Sub-Modules	M3 Heating	M4 Coolling	M5 Ventilation	M6 Humidification	M7 Dehumidifi-cation
Generation & Control	EN 12098-1 EN 12098-3 EN 12098-5 EN 15316-4-1 EN 15316-4-2 EN 15316-4-3 EN 15316-4-4 EN 15316-4-5 EN 15316-4-8	EN 16798-13 EN 15316-4-2 EN 15316-4-5	EN 16798-5-1 EN 16798-5-2	EN 16798-5-1 EN 16798-5-2	EN 16798-5-1 EN 16798-5-2
Load Dispatching & Operating Conditions	EN 15316-1	EN ISO 16798-9			
Measured Energy Performance	EN 15378-3				
Inspection	EN 15378-1	EN 16798-17	EN 16798-17	EN 16798-17	EN 16798-17

The general framework and procedures of EPB Standards is set in EN ISO 52000-1 (EN ISO 52000-1, 2017). Indoor environmental input parameters for the design and assessment of energy performance of buildings are regulated in EN 16798-1 (EN 16798-1, 2019) and EN 16798-3 (EN 16798-3, 2017) also used for the performance requirements for ventilation and room-conditioning systems.

Calculation methods for the determination of air flow rates in buildings including infiltration are given in EN 16798-7 (EN 16798-7, 2017). Other calculation methods for energy requirements of ventilation and air conditioning systems, requirements of ventilation systems and control for heating, ventilating and air conditioning applications are given in EN 16798-5-1 (EN 16798-5-1, 2018), EN 16798-5-2 (EN 16798-5-2, 2018) and EN 15500-1 (EN 15500-1, 2017) respectively. Guidelines for inspection of ventilation and air conditioning systems are given in EN 16798-17 (EN 16798-17, 2017).

3.4.1. Indoor Environmental Quality

Indoor environmental quality (IEQ) refers to the quality of a building's environment in relation to the health and wellbeing of those who occupy space within it. IEQ is determined by four main parameters: thermal comfort, indoor air quality, visual comfort, and acoustic comfort, see Figure 3.4.

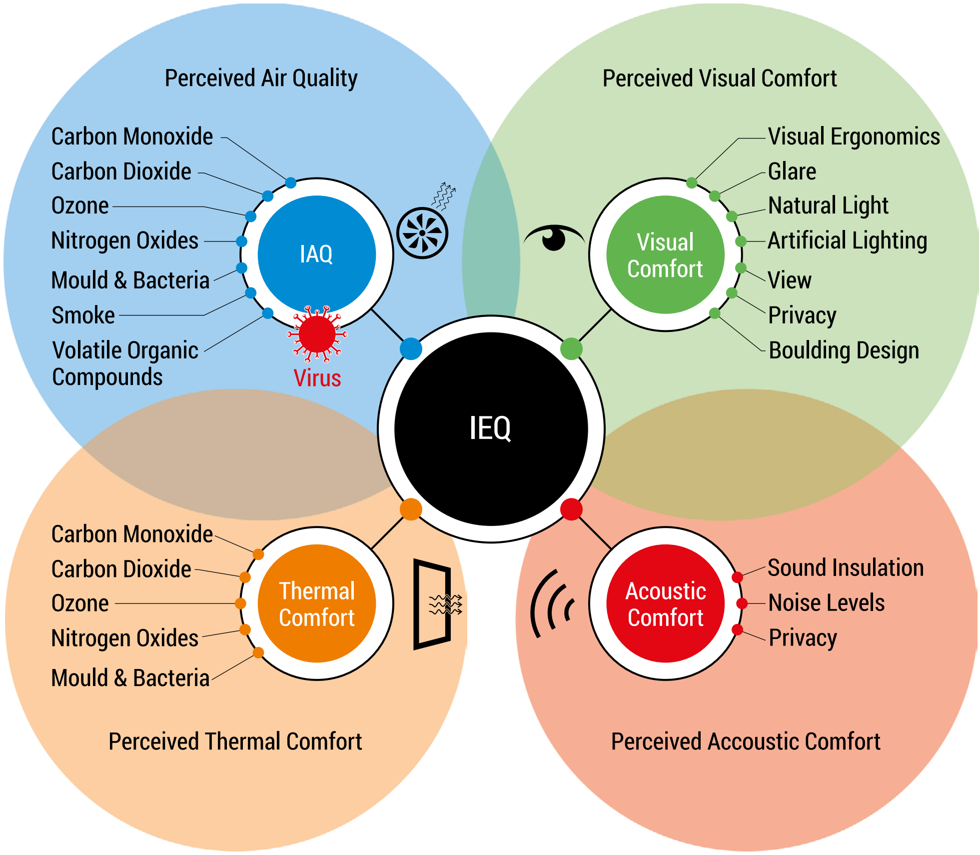

FIG. 3.4. Indoor environmental quality (Source: own elaboration based on AIVC, 1996)

3.5. The European Standard 16798

This document specifies requirements for indoor environmental parameters for thermal environment, indoor air quality, lighting and acoustics and specifies how to establish these parameters for building system design and energy performance calculations.

This European Standard includes design criteria for the local thermal discomfort factors, draught, radiant temperature asymmetry, vertical air temperature differences and floor surface temperature. It is applicable where the criteria for indoor environment are set by human occupancy and where the production or process does not have a major impact on indoor environment.

This European Standard specifies occupancy schedules to be used in standard energy calculations and how different categories of criteria for the indoor environment can be used. The criteria in this European Standard can also be used in national calculation methods. It sets criteria for the indoor environment based on existing standards and reports listed under normative references or in the bibliography. It does not specify design methods but gives input parameters to the design of building envelope, heating, cooling, ventilation, and lighting.

3.5.1. Categories of Indoor Environmental Quality

Categories of indoor environmental quality for design and operation in buildings are given in the European Standard EN16798-1 (EN16798-1, 2019), as shown in Table 3.4.

TABLE 3.4. Categories of indoor environmental quality (Source: EN 16798-1, 2019)

Category	Level of expectation	Contaminant source
IEQ_{I}	High	Should be selected for occupants with special needs (children, elderly, person with disabilities).
IEQ_{II}	Medium	The normal level used for design and operation
IEQ_{III}	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.

Table 3.5 describes some of the aspects and criteria used in EN 16798-1. The criteria are meant to be used in standard energy calculations for offices, schools, dwellings, and other indoor environments that are primarily meant for human occupancy.

TABLE 3.5. Example criteria from EN 16798-1:2019 (Source: Boerstra, 2019)

IEQ aspect	Building/space type	I	CategoryII	III
Temperature range winter	Residential buildings (bedrooms)	21-25[°C]	20-25[°C]	18-25[°C]
	Offices (landscape layout)	21-23[°C]	20-24[°C]	19-25[°C]
	Schools (classrooms)	21-23[°C]	20-24[°C]	19-25[°C]
Temperature range summer	Residential buildings (bedrooms)	23.5-25.5[°C]	23-26[°C]	22-27[°C]
	Offices (landscape layout)	23.5-25.5[°C]	23-26[°C]	22-27[°C]
	Schools (classrooms)	23.5-25.5[°C]	23-26[°C]	22-27[°C]
Maximum CO_2 level (delta CO_2 conc.)	Residential buildings (bedrooms)	380	550	950
	Offices (landscape layout)	550	800	1350
	Schools (classrooms)	550	800	1350
Minimum lighting level Em	Residential buildings (living room)			
	Offices (landscape layout)		500 [lux]	
	Schools (classrooms)		500 [lux]	

IEQ aspect	Building/space type	I	CategoryII	III
Maximum system noise level LAeQ	Residential buildings (bedrooms)	25 [dB]	30 [dB]	35 [dB]

The standard does so not by specifying design methods – leaving manufacturers free to provide their own – but instead it gives parameters that needs to be respected in the design and operation of heating, cooling, ventilation, and lighting systems.

3.5.2. Input Parameters for Ventilation Design in Buildings

Source control, ventilation, or filtration/air cleaning systems are used to control Indoor air quality. Source control is a key strategy for maintaining acceptable indoor air quality. It is assumed that pollutants emissions are constant in each time period.

Three different methods are specified as design parameters for indoor air quality: a method based on perceived air quality, a method based on limit values for substance concentration and a method based on predefined ventilation airflow rates.

A. Method based on perceived air quality

The method based on perceived air quality is used to reduce health risk from a specific air pollutant. The perceived air quality calculation is proposed using the equation:

$$\dot{V}_{tot} = n\,\dot{V}_p + A_R\,\dot{V}_B\,, \tag{3.13}$$

where $\dot{V}_{tot}$ is the total ventilation rate for the breathing zone (l/s), n is the design value for the number of the persons in the room, $\dot{V}_p$ is the ventilation rate for occupancy per person (l/s person), A_R is the floor area (m^2) and $\dot{V}_B$ is the ventilation rate from building (l/s m^2) (Table 3.6).

TABLE 3.6. Ventilation rates defined in EN 16798-1:2019 (Source: EN 16798-1:2019)

		Minimum ventilation rate			
Category	Expected percentage of dissatisfied	Per non-adapted person [l/s person]	For very low-polluted building [l/s m^2]	For low-polluted building [l/s m^2]	For non-low-polluted building [l/s m^2]
		$\dot{V}_p$	$\dot{V}_B$	$\dot{V}_B$	$\dot{V}_B$
I	15	10	0.5	1	2.0
II	20	7	0.35	0.7	1.4
III	30	4	0.2	0.4	0.8
IV	40	2.5	0.15	0.3	0.6

B. Method based on limit values for substance concentration

The method based on limit values for substance concentration aims to reduce or dilute a particular substance. The required ventilation rate for dilution of an air contaminant is defined as:

$$\dot{V} = \frac{S}{\varepsilon_v \left(C_i - C_o \right)} \tag{3.14}$$

where $\dot{V}$ is the ventilation rate required for dilution (m^3/s), S is the generation rate of the substance (μg/s), C_i is the guideline value of the concentration of the substance (μg/m^3), C_o is the concentration of the substance (μg/m^3) in the supply air, ε_v is the ventilation system efficiency. Typical values for ventilation effectiveness as defined in EN 16798-4:2017 (EN 16798-4, 2017) are shown in Table 3.7.

TABLE 3.7. Typical values for ventilation effectiveness as defined in EN 16798-4:2017 (Source: EN 16798-4:2017)

Air difusión	Cold jet Δθ<0K		Hot jet		
	Effective velocity	**Ventilation effectiveness**	**Δθ (supply-indoor)**	**Low ceiling**	**High ceiling**
Mixing horizontal jet	>1,5 m/s	0.9 – 1.1	<10[°C]	0.8 – 1.0	Not advised
	<0.5 m/s	0.7 – 0.9	>15[°C]	0.4 – 0.8	Not advised
Mixing vertical jet	All diffusers	0.9 – 1.1	<10[°C]	0.6 – 0.8	0.8-1.0
			>15[°C]	0.4 – 0.8	
Displacement ventilation		1.0 – 2.0		0.2 – 0.7	Not advised

If the building has a demand-controlled ventilation system (DCV) the maximum design ventilation rate will correspond to the calculated maximum concentration of contaminant. The ventilation rate can vary between the maximum and minimum ventilation rates specified. Considering a standard CO_2 emission rate of 20 l CO_2/h person the default design CO_2 concentrations above outdoor concentration are given in Table 3.8 for non-adapted persons.

TABLE 3.8. Default design CO_2 concentrations above outdoor concentration assuming a standard CO_2 emission of 20 l CO_2 /(h person) as defined in EN 16798-1:2019 (Source: EN 16798-1:2019)

Category	Corresponding CO_2 concentration above outdoors in ppm for non-adapted persons
I	550 (10)
II	800 (7)
III	1350 (4)
IV	1350 (4)

The above values correspond to the equilibrium concentration when the air flow rate is 10, 7, and 4 l/s per person for category I, II, III and IV respectively and the CO_2 emission is 20 l CO_2 /h person. The default outside concentration average can be assumed 400 ppm.

C. Method based on predefined ventilation airflow rates
Method based on predefined ventilation airflow rates uses a pre-defined minimum ventilation airflow rate estimated to meet needs for perceived air quality and health of occupants. An example is given in Table 3.9 according to EN 16798-1:2019. (EN 16798-1, 2019).

TABLE 3.9. Default design air flow rates for offices and non-adapted persons defined in EN 16798-1:2019 (Source: EN 16798-1:2019)

Category	Design air flow rate for the office building	
	l/(s person)	l/(s m^2)
I	20	2
II	14	1.4
III	8	0.8
IV	5.5	0.55

If the ventilation rates are given by person and by surface area, the higher total ventilation rate should be used as ventilation design rate.

3.5.3. Classification and Certification of the Indoor Environment in Buildings

As shown in Annex G of EN16798-2 2019 (EN 16798-2, 2019), the indoor environment in a building can be classified by:

- Criteria used for energy calculations (new buildings).
- Whole year computer simulations of the indoor environment and energy performance (new and existing buildings).
- Subjective response from occupants (existing buildings).

By dynamic computer simulations it is possible for representative spaces in a building to calculate the space temperatures, ventilation rates and CO_2 concentrations. The distribution between four categories is done by a floor are weighted average for 95% of the building spaces. An example is shown in Figure 3.5.

Quality of indoor environment in % of time of occupancy in four categories				
Percentage	5	7	68	20
Thermal Environment	IV	III	II	I
Percentage	7	7	76	10
Indoor Air Quality	IV	III	II	I

FIG. 3.5. Example of classification by footprint of thermal environment and indoor air/quality/ ventilation (Source: EN 16798-2, 2019)

Long term measurement of selected parameters for the indoor environment can be carried out measuring parameters such us temperature, ventilation rate, CO_2 concentrations. These parameters are measured in representative spaces over a whole year or representative time period. The data are analysed and represented in a similar way that shown in Figure 3.5.

3.5.4. Rating of the Indoor Environment in Buildings

There is no widely accepted method for rating the overall level of indoor environmental quality (IEQ), although several different approaches are proposed by standards, guidelines, and certification schemes. To fill this void, a new classification rating scheme called TAIL (Wargocki, 2021) was developed to rate IEQ in offices and hotels undergoing deep energy renovation during their normal use; the scheme is a part of the energy certification method developed by the EU ALDREN project (ALDREN Project 2017-2020). Their quality levels are determined primarily using Standard EN-16798-1 and World Health Organization (WHO, 2010) air quality guidelines and are expressed by colors and Roman numerals to improve communication.

The TAIL scheme standardizes rating of the quality of the thermal (T) environment, acoustic (A) environment, indoor air (I), and luminous (L) environment, and by using these ratings, it provides a rating of the overall level of IEQ. Twelve parameters are rated by measurements, modelling, and observation to provide the input to the overall rating of IEQ. TAIL indicators are describing thermal (T), acoustic (A), indoor air quality (I) and visual-luminous (L) environment parameters (Table 3.10):

- (T) Air temperature defines how the thermal environment affects human thermal comfort.
- Sound pressure level to characterize airborne noise.
- Ventilation rate, relative humidity, CO_2, benzene, formaldehyde, PM2.5, radon, and visible mold. All of them chosen for their availability of IAQ guidelines values and relevant permissible exposure levels.
- (L) Illuminance and daylight factor as lighting is essential for performing work and good room darkening is essential for sleep quality.

TABLE 3.10. ALDREN-TAIL indicators (Source: Wenjuan, 2020)

T Thermal environment	A Acoustic environment	I Indoor air quality	L Luminous environment
Air temperature	Sound pressure level	CO_2 Ventilation rate Air relative humidity Visible mold Benzene Formaldehyde PM2.5 Radon	Daylight factor Illuminance

The measured values at each measuring point during working hours are compared with their defined ranges (Wenjuan, 2020), and their quality levels are determined. The quality level of each parameter defining TAIL are obtained by calculating the interim rating at each of the eight measuring locations:

$$Interim\,rating = \frac{\sum_1^k R_k O_k}{n}, \quad (3.15)$$

where R is the rank for the specific quality level k ($R = 1$ for green level, $R = 2$ for yellow level, $R = 3$ for orange level and $R = 4$ for red level); O is the number of observed rooms for the specific quality level k; k is the number of quality levels ($k \leq 4$); n is the total number of the rooms where measurements are performed.

The final quality level of each of the four TAIL components at the building level are determined by the worst interim rating for the thermal environment (T), acoustic environment (A), indoor air quality (I), and the luminous environment (L). The overall rating of IEQ is determined by the worst level of the four TAIL components.

Figure 3.6 shows an example of the TAIL level of a building:

- The thermal environment in the building (T) was qualified at the yellow level because the indoor air temperature varied between 20 and 24°C during more than 94% of the working hours in 5 rooms. The thermal environmental quality could be improved to the green level if the indoor temperature had been reduced to 23°C during midday.
- The acoustic environment in the building (A) was qualified at the green level because the sound pressure was lower than 35 dB(A).
- The indoor air quality in the building (I) was qualified at the orange level mainly because CO_2 concentrations in the measured rooms often exceeded 1200 ppm, and there were high concentrations of formaldehyde. The indoor air quality could be improved by increasing the air change rate in highly occupied spaces.
- The luminous environment in the building (L) was qualified at the orange level because the median daylight factors in the selected rooms were between 1.7%

and 3%, and the illuminance levels in the measured rooms were often higher than 500 lux at the desk height. The visual environment could be improved by renovating sun protection systems and reducing artificial lighting.

Since the lowest quality level among TAIL components was orange, the overall quality level of IEQ and the overall rated TAIL level was also orange, which is represented by the Roman III in the middle of the TAIL indicator for this building (Fig. 3.6).

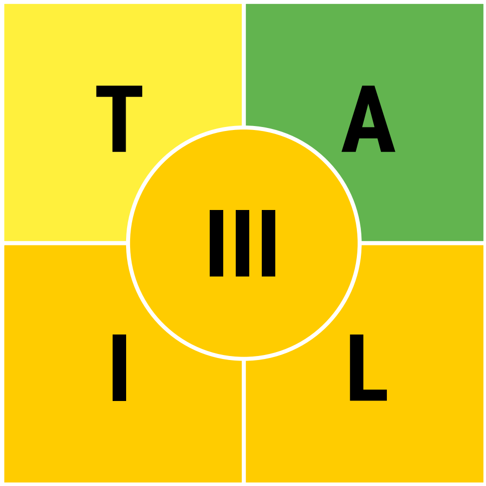

FIG. 3.6. Classification of a buildings using TAIL (Source: Wargocki, 2021)

TAIL creates an incentive to improve IEQ. It allows qualitative and quantitative assessment of non-energy benefits resulting during the process of a deep energy retrofit. The TAIL index focuses on office and hotel buildings to be aligned with the ALDREN procedure, but the intention is to use it in any type of building.

Being measured before the renovation, the TAIL index helps to identify the possible components to be improved on the energy renovation, making the latter even more beneficial for the building and its occupants. In case of measurements done after the energy renovation, the TAIL index 'after' compared to the TAIL index 'before' helps in showing that the renovation has not degraded the IEQ in the building or whether the IEQ improved.

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