TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria

DIPLOMARBEIT

A comprehensive multi-domain building performance indicator catalogue

ausgeführt zum Zwecke der Erlangung

des akademischen Grades eines Diplom-Ingenieurs

unter der Leitung von

Univ.Prof. Dipl.Ing. Dr.techn. Ardeshir Mahdavi

E259.3 Abteilung für Bauphysik und Bauökologie

Institut für Architekturwissenschaften

eingereicht an der Technischen Universität Wien

Fakultät für Architektur und Raumplanung

von

Nicolas Constantinou

01528053

Wien, November 2017

KURZFASSUNG

Die vorliegende Diplomarbeit enthält eine Auflistung von Indikatoren (Leistungsindikatoren) im Bereich der Bauphysik. Die enthaltenen Indikatoren gehört zu den Domänen Energieeffizienz, hygrothermisches Verhalten (Wärmeschutz, Feuchteschutz), thermische Behaglichkeit, Innenraumluftqualität, Beleuchtung und Bau- und Raum-Akustik. Die Auflistung befasst sich mit wissenschaftlichen Literatur und Fachliteratur, Normen und Richtlinien inbegriffen. Die Indikatoren wurde nach Domänen und untergeordneten sub- Domänen katalogisiert und klassifiziert. Jeder Eintrag wird von entsprechenden Angaben wie z.B. kurze Beschreibung, Literaturangabe, Berechnungsangabe und Bewertungskriterien begleitet. Diese Angaben erlauben den Benutzern dieser Auflistung von Indikatoren, Rückschlüsse über eine etwaige Eignung eines Indikators für spezifische Anwendungsfälle zu ziehen, beziehungsweise auf Basis dieser Grundinformationen weitergehende Recherchen anzustellen. Neben der beschriebenen Katalogisierung der Indikatoren enthält diese Diplomarbeit dazugehörige Informationen über den Einsatz der Indikatoren in der alltäglichen Berufspraxis von ArchitektInnen, IngenieurInnen und anderen StakeholderInnen sowie über deren Rolle im Bereich des „performance-based“ Assessment wie z.B. im Zuge von Gesetzen, Bauordnungen, Richtlinien und Zertifizierungsprogrammen. Diese umfassende Sammlung und Aufarbeitung der Indikatoren zeigt die Breite und Komplexität des Bereichs Gebäudeperformance auf. Als mögliches Anwendungsszenario dieser Arbeit ist vorstellbar, dass der Katalog im Zuge von Bauplanungs- und Realisierungsvorhabe als gemeinsame Datengrundlage aller involvierten Stakeholder zu verwenden, um ein sinnvoller und informierter Gespräch zu führen. Eine weitere Anwendungsmöglichkeit könnte der Einsatz zu edukativen Zwecken sein, um beispielsweise Auszubildende oder Studierende anwendungsbezogen an bauphysikalische Probleme und Fragestellungen heranzuführen, oder Fachleuten eine einfache und rasch anwendbare Methode des Wissensupdates zu bieten

Schlüsselwörter

Innenraumqualität, Gesundheit und Komfort, performance-basierte Gebäudebewertung, Leistungsindikatoren, Gebäude-Energieperformance, Tageslicht, Bau- und Raumakustik, Lärm, Thermischer Komfort

ABSTRACT

This thesis presents a catalogue of building Performance Indicators (PIs) in the domains of energy efficiency, hygro-thermal performance (air tightness, moisture protection), thermal comfort, indoor air quality, indoor visual environment (indoor lighting, daylight performance, glare, colour) and indoor acoustic environment (room and building acoustics, noise, speech perception, privacy). The catalogue covers scientific and professional literature, including standards, reference literature for professionals and regulation literature. The PIs are classified under performance domains and sub-domains. Each entry is accompanied by information that allows the user to draw useful conclusions on the tool's usability, suitability and effectiveness as well as to search for further information on the calculation and use of each tool. Moreover, the indicators are mapped to the everyday practice of professionals such as architects, engineers and other stakeholders, in regard to building codes, standards and certification programmes. This catalogue reveals the spectrum and complexity of performance based assessment in the building sector. It can be used by researchers and other professionals to help them choose between alternative indicators and by building sector stakeholders to help them set project goals and improve the communication between them. Additionally, the catalogue can be used for educational purposes, as an appropriate vehicle for trainees and students to explore the field of building science (building physics).

Keywords

indoor environment quality, health and comfort, performance-based building, performance criteria, performance metrics, performance indices, energy performance indicators, daylight metrics, acoustic measures, noise measures, thermal comfort indices

ACKNOWLEDGEMENTS

I wish to thank my advisor Univ. Prof. DI Dr.techn. Ardeshir Mahdavi and my co-advisor DI Dr.techn. Ulrich Pont for encouraging me to address this topic and for providing me with indispensable guidance.

Special thanks to my family for their unconditional support and encouragement in my academic and personal journey.

Contents

* Indicators marked with an asterisk are included in important international standards

1 Introduction

1.1 Overview

This catalogue is a record of building performance indicators and their use in the contemporary performance-based building sector. The indicators were collected through bibliographical research into varying types of sources including reference literature for professionals, scientific journals, standards, regulations and internal documents of important organisations.

In general terms, a Performance Indicator (PI) is a tool used to quantify the performance of a product in respect to a specific performance requirement. The performance requirements considered in this catalogue fall into the following domains of building science:

- Hygro-thermal performance (e.g. energy efficiency, thermal comfort, moisture protection)
- Indoor air quality
- Indoor visual environment
- Indoor acoustic environment

Each domain includes several performance requirements and each performance requirement can be addressed in different ways (and using various alternative Indicators) “each with its own merit and each requiring a different experimental set up or different model or different aggregation method”. (Augenbroe 2011, p. 19). Therefore, an abundance of performance indicators is found in scientific literature and in literature for professionals.

In addition to the catalogue, this publication maps the PIs into areas of the everyday practice of architects, engineers and other building sector stakeholders, to familiarise readers with practices in the performance-based building sector, to reveal the prevalence of certain indicators and to support the correct application of performance-based assessment. The indicators are mapped into the following spheres, discussed in detail in chapter 4:

- PIs in international Standards
- PIs in the Austrian building codes and standards
- PIs in Green Building rating and certification
- PIs in Energy Efficiency rating and certification

NOTE 1: Special care was taken to cite the original authors of each indicator. In case the original author was not known an important source is cited instead (e.g. standards). This catalogue does not introduce any new indicators.

NOTE 2: This review does not include all the relevant published performance indicators. Included are indicators represented in important standards, reference literature for professionals, compliance programmes and indicators that represent a unique category (as explained in section 2.1).

NOTE 3: This review is not intended as a reference for the calculation of the indicators or as a source for performance criteria (acceptable values etc.). Information on these is found in the original sources (e.g. scientific articles) or other relevant literature (e.g. standards, legislative directives).

NOTE 4: Standards and Legislation directives mentioned in this review are expected to be updated and in some cases withdrawn and replaced.

1.1.1 **Performance-based assessment**

Generally, PIs are used by stakeholders (engineers, developers, authorities, investors, scientists etc.) to understand the performance of products and to facilitate their development, comparison and optimization. PIs serve a significant role in both new and retrofit projects and are the foundation of performance-based design, procurement and assessment.

The use of performance based methods in the building sector is a relatively recent but increasing trend. Previously building regulations and pertinent literature focused on prescribing material properties and construction details as a means to ensure the adequate performance of the building elements and systems (Jasuja 2005). This approach is often described as a prescriptive method.

Today the emergence of major regulation frameworks, that use performance-based methods, such as the European Performance of Buildings Directive (EPBD), as well as the rising popularity of green building rating programs (e.g. BREEAM, LEED), shows that the building sector is moving towards more flexible and effective ways to address overall building performance.

In the performance domain of energy efficiency, the demand for sustainable solutions is driven by resource-related and environmental considerations.

The domains of thermal comfort, Indoor Air Quality (IAQ), indoor acoustic environment and indoor visual environment, regularly grouped under the term Indoor Environment Quality (IEQ), address comfort issues such as glare, overheating risk and odour control as well as performance issues such as speech intelligibility, privacy and fresh air distribution.

Improvements on the IEQ may lead to gains in productivity by reducing adverse health effects or directly improving worker performance (Fisk et al. 2000). For example, lower ventilation rates increase the prevalence of respiratory diseases (Seppänen et al. 2002). In another example, the transmission of irrelevant speech in open plan offices may distract workers and cause a drop-in productivity (Hongisto 2005).

1.1.2 **PIs and performance criteria**

Each PI is connected to a predefined unique calculation or measurement method that outputs a single value used to represent the performance of a building or a building system in respect to a performance requirement. The calculation of a PI is sometimes based on a model, such as the Fanger's PMV index for thermal comfort (see section 3.3.1), or on different aggregation methods of performance metrics (measurable quantities) over time or space, such as the Spatial Daylight Autonomy used to assess the effective use of daylight in indoor spaces (see section 3.9.5). In some cases, the indicator represents a single measurement of a physical quantity, such as the Illuminance level measured at a point (E_v) used to assess the provision of appropriate lighting over a task area (see section 3.8.1).

The calculation methods typically involve weighting factors to regulate the influence of different metrics on the overall performance output. For example, some noise measures used to evaluate the disruptive effects of noise, weight more heavily, noise levels at certain frequencies or noise levels occurring at night (see section 3.15.1). Additionally, normalisation factors are used to enable the assessment of the performance of non-identical products. For example, energy consumption is normalised per unit of area to help compare buildings of different sizes (see section 3.1.1).

Whilst sometimes the outputted single value is enough to understand the performance of a building or a building system (e.g. percentages, thermal sensation votes), in many situations the value must be considered in the context of a value system, often referred to as "performance criteria". Typical examples of such value systems are the following:

- Benchmarking: the PI value is used to compare the performance of the product to the performance of other products (e.g. EPIs).
- Perception votes: the (predicted) conditions are evaluated using the predicted opinion of the occupants or the predicted percentage of occupants dissatisfied (e.g. PMV, TSENS, PD_{AQ}).
- Percentages of performance: the performance of a product is defined as a ratio of the actual performance to the best possible performance. (e.g. STI, SII)
- Percentages of time/area: the performance of a product is defined as a part of the overall time or area that the performance was suitable or unsuitable. (e.g. zDA, sDA, CIBSE overheating risk)
- Acceptable/recommended range and design target values: the value must approximate a predefined value or fall within limits of acceptability (e.g. L_{Aeq}, C_{50}, G, SET*). The suitable range and design target values are sometimes defined in respect to other metrics (e.g. TOP and elevated air speed/relative humidity, see section 3.2.1).

Indicators are not necessarily connected to a single value system. For example, the Standard Effective Temperature (SET*) can be evaluated both as an environmental index (see section 3.2.3) and as a PMV index (see section 3.3.4).

1.2 Motivation

Whist there are plenty direct and indirect efforts to record building performance indicators, up until this moment, there is no other record that fulfils simultaneously all the following requirements:

- focuses on the indicators (recorded into a catalogue layout)
- is multi-domain
- is fairly comprehensive (see section 2.1)
- maps the indicators to professional practice, standards and regulations.

A short literature review pertinent to this subject is presented in section 1.3.

The first and most obvious use of this catalogue is to help users in professional and academic fields choose between alternative indicators. The need arises due to the fact that a given performance requirement may be addressed using alternative indicators. For example, daylight performance in buildings can be approached using daylight performance indicators such as the zonal Daylight Autonomy (zDA) or the spatial Daylight Autonomy (sDA). Both of these indicators measure sufficient daylight illuminance using a threshold value and both are measure how much of the time period the threshold value is exceeded. However, the zDA reports on how much of the time period the illuminance levels are sufficient whilst the zDA reports on how much of the area (or grid points) receive sufficient illuminance for a predefined amount on time (see sections 3.9.4 and 3.9.5). The spatial information conveyed by the latter indicator might be valuable for some users. In another example, thermal comfort may be calculated using indicators based on environmental variables such as the operative temperature (TOP) or indicators based on physiological models such as the Predicted Mean Vote (PMV) (see section 3.2.1 and 3.3.1). The PMV has been proven a very accurate index for HVAC serviced buildings (de Dear et al. 1998), however, the TOP is typically easier to implement because of the less parameters involved in the calculation. However, If thermal comfort is evaluated in transient thermal conditions, then the PMV is not applicable. In that case a heat balance index based on a different physiological model, such the Thermal Sensation (TSENS) index should be used (see section

3.3.3). Finally, if the building is depended on natural ventilation, using operable windows to adjust the indoor thermal environment and not mechanical systems, then indicators based on adaptive models (see section 3.4) are more accurate than indicators based on physiological heat balance (de Dear et al. 1998).

Secondly, this catalogue can be used for educational purposes to help initiate students and professionals from other fields, to topics in the field of building science (building physics) and performance-based practice, quick and effectively, by exposing them directly to the "end-product" of these science fields. The end-products in this case are the PIs themselves. The PIs reveal information on the spectrum of the building performance sector, the nature and nuances of the performance requirements and their relation to the building's systems and components as well as information on the priorities of the various stakeholders (see section 5.1).

Additionally, the PIs help reveal the interdependence between different performance requirement and therefore the need for a comprehensive approach in evaluating building performance (Augenbroe 2011). For example, introducing fresh air to improve the perception of indoor air quality in high occupancy rooms may require increasing the ventilation rate (Fanger 1987). However, increasing the ventilation rate means higher air velocity and may therefor compromise the thermal comfort of the occupants by increasing the possibility of draught risk (see section 3.5.1). Several indicators could be used to measure and adjust these two requirements. For example, the Percentage of Dissatisfied (PD_{AQ}) due to Air Quality can be predicted using the number of occupants and the ventilation rate (see section 3.7.2). In case the ventilation rate must be increased, then the Draught rate (DR) or the Air Diffusion Performance Index (ADPI) can be used to evaluate the possibility of draught risk (see sections 3.5.1 and 3.7.9). Under specific conditions, the air distribution index (ADI) could be used to address simultaneously all of these requirements (see section 3.7.8).

Finally, this catalogue can serve as inspiration for stakeholders when setting the requirements of a project and help promote a more effective dialogue between them. An effective dialogue means, among other, that the stakeholders agree on the measures and measurement methods and that they understand the limitations in reaching performance targets caused by factors such as conflicting requirements and budget constrains (Augenbroe 2011).

1.3 Background

There are various direct and indirect records of building performance indicators in scientific and professional literature. Some focus on the indicators, whilst other referred to the indicators as part of a general narrative on building performance. Additionally, some record only the most commonly used indicators or indicators of a certain kind whilst other adopt a more comprehensive approach reviewing a wide range of indicators within a performance domain.

This chapter discusses part of this literature, that influenced this project. The literature is divided in two main categories: multidomain and single domain.

1.3.1 Multi-domain literature

Multi domain publications could be furthermore grouped into two categories. Handbooks issued by important organizations as reference literature for professionals and standards that provide performance criterial per category. ASHRAE Handbook: Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009) is an example of a publication belonging to the first category. The handbook provides a comprehensive overview on the workings of HVAC systems, including information on the physical mechanisms involved, performance issues and calculation methods. The publication is intended to inform professional in the HVAC industry, but the content is relevant to the whole of the building sector. A similar example is the Indoor Environment Handbook, co-published by RIBA Publishing, part of the Royal Institute of British Architects (RIBA). The publishers intend to promote "best practice and quality professional guidance on sustainable architecture" (Bluyssen 2009). The publication provides information on historical context, physical mechanisms, performance evaluation and legal framework regarding health and comfort in buildings. Similarly, Hasselaar (2006) discusses heath performance in houses covering indicators and tools especially in the area of indoor air quality. Another multidomain publication that focuses on performance issues is the "Building performance simulation for design and operation" (Hensen et al. 2011). This publication discusses the role of simulation in performance-based design in the various domains. Performance indicators per domain are mentioned as part of this narrative.

In the category of standards, a commonly referred to publication is ISO 15251. This standard intends to provide input parameters for energy efficiency assessment but is commonly used as a general reference on performance criteria and assessment methods of indoor environmental. A similar source of performance criteria is the CEN/CR 1752 and the ASHRAE Standard 189.1. The latter is intended to be used for the design of high performance green buildings. Green building performance criteria can be also found in literature accompanying green building rating programs such as BREEAM and LEED. This type of literature suggests indicators and performance criteria and would typically reference other pieces of literature (e.g. the LEED program references the ASHRAE standards). Finally, belonging to this category is a series of publications by the "PERFECTION coordinated action" that recorded indicators and relevant literature (e.g. standards and regulations) in a systematic way and developed a framework for the evaluation of the overall quality of the indoor environment (Steskens et al. 2010).

However, none of these multi-domain publications provides a comprehensive record of the indicators in each domain. They focus mostly on a narrow group of commonly used indicators and indicators prescribed in regulations. A more comprehensive record of PIs is found in single domain literature.

1.3.2 Single-domain literature

Single domain literature could be grouped into three categories: standards and reports, handbooks and scientific articles. In the first category, almost all major standardisation organisations (ISO, CEN, ASTM, ANSI etc.) provide standards that inform on the use of indicators, calculation methods and performance criteria per performance category, building system etc. For a comprehensive review see section 4.1. A similar reference source, especially for performance criteria, are reports from international organisation such as the WHO (e.g. reports on air quality and community noise) and the European commission (e.g. ECA indoor air quality and its impact on man).

The handbook category, contains several domain-dedicated publications with comprehensive and well edited material. For example, in acoustics, the "Handbook for sound engineers" (Ballou 2008) and the "Springer Handbook of acoustics" (Rossing 2007) include chapters dedicated on measuring the attributes of performance spaces (for music and speech). These chapters present information on the theory of measurement, the acoustic attributes of performance spaces and recommended values. Beranek (2004) published a ranking of 100 concert halls and opera houses along with measurement of their acoustic attributes using various acoustic indicators (objective acoustic measures). Conserving the visual environment, perhaps one of the most comprehensive resources in the field is the "IES The Lighting Handbook 10TH" (DiLaura et al. 2011). In the domain of energy efficiency, the International

Energy Agency (IEA) published a series of comprehensive reports (IEA 2008, IEA 2010) on building codes and energy efficiency policies. The reports include information on the different performance-based and prescriptive methods (e.g. energy performance certification) used to assess energy efficiency in the various countries. Similarly, an ECOFYS report (Hermelink et al. 2013) discusses policies on Nearly Zero Energy Buildings (NZEB) and their implementation.

Still, perhaps the most focused discussion on the nature and capacity of performance indicators is found in scientific articles.

In the domain of energy performance Balaras et al. (2014) and Shengwei et al. (2012) discuss the different indicators, the calculation methods connected to them and their use in voluntary or compulsory compliance programs.

In the domain of thermal comfort Epstein et al. (2006), Taleghani et al. (2013) and Gauthier (2013) review approaches to thermal comfort assessment featuring information on physical mechanisms of thermal comfort and records of performance indicators along with implications in their use (e.g. sensitivity to specific variables). Cheng et al. (2012) discuss the characteristics and performance of thermal physiological models in a comprehensive review. Humphreys et al. (1998) and de Dear et al. (1998) published the fundamental references into the adaptive model indices. Borgeson et al. (2010) and Psomas et al. (2015) review exceedance and overheating indices. Carlucci (2013) published an analytical record of long term indices and tested their capacity through an extensive experimental process.

In the domain of the visual environment Carlucci et al. (2015) offer a comprehensive review of all possible visual environment sub-domains where indicators are recorded and classified in an analytical manner. The layout of that review inspired the layout of this catalogue in terms of the representation of the indicators and the classification approach. Wienold et al. (2006) and Bellia et al. (2008) review glare indices for glare from artificial source and glare from daylight. Reinhart et al. (2006) review daylight metrics and their use in popular rating programs.

In the domain of the acoustic environment Lacatis et al. (2008) published a concise chronologic record of room acoustic indicators. Cerdá et al. (2011), Soulodre et al. (1995) and Bradley (2010) discuss in detail the various room acoustic indicators, their calculation and their capacity. Griesinger (1999) reviews objective measures (performance indicators) focussed on spaciousness and listener's envelopment. Seddeq (2012) and Gover et al. (2011) discuss indicators used to assess speech privacy. Finally, Tocci (2000) presents a comprehensive review of room noise criteria (e.g. noise rating curves).

2 Method

2.1 Content selection and representation

The indicators where collected through the means of bibliographical research into different types of sources, such as books, scientific journals, standards, internal documents of organisations (e.g. reports), building codes and regulations etc. The performance requirements considered in this catalogue are included in the following domains:

- Hygro-thermal performance (energy efficiency, condensation issues, thermal comfort etc.)
- Indoor air quality
- Indoor visual environment
- Indoor acoustic environment

New performance indicators belonging to these building science domains are introduced continuously into scientific and professional literature to address (among other):

- different performance requirements
- different aspects within a performance requirement
- advancements in scientific understanding
- shifting priorities of stakeholders (political, environmental, economic etc.).

An effort was made to represent all “common” and “essential” PIs and to cover comprehensively the performance requirements (and their sub-categories) belonging to the these domains. However, not all published PIs are represented. Priority was given to indicators:

- represented in important standards (ISO, CEN, ASTM, ANSI etc.)
- represented in reference literature for professionals (e.g. best practice guides and handbooks issued by important organisations e.g. RIBA, ASHRAE)
- represented in compliance programmes (building codes, rating schemes etc.)
- and indicators that represent a unique category of performance requirement (e.g. privacy indicators for open plan offices).

Furthermore, priority was given to indicators of overall performance that support performance-based assessment methods and measure conditions influenced by the performance of the building as a whole (or building systems) and not building components or material properties. The latter category of indicators (e.g. thermal transmittance (U-values), volatile organic compounds (VOC), sound absorbing coefficients (α) of materials) are regularly represented in compliance programs but are part of prescriptive methods of assessment that are not considered in this catalogue.

The performance indicators are recorded in a uniform style using the data fields of Table 1. The title of each entry appears on the content list which then function as an index, to help users locate each tool. The title includes the name of the indicator, the abbreviation and the units (if they exist).

NOTE: If an indicator is included in an important standard, then an asterisk follows the title to help the user distinguish immediately those indicators in the content list (index).

E.g.

3.12.1 Reverberation time (T) [s] *

Each catalogue entry includes a small description of the indicator, its numerical expression (if applicable) and information on performance criteria. E.g.:

3.9.5 Spatial Daylight Autonomy (sDA) [%]

This long-term daylight performance indicator, proposed by the Illuminating Engineering Society IES (2012), calculates the percentage of area where the illuminance levels exceeds a threshold (typically 300lx) for a minimum percentage of the analysis time (typically 50%). The indicator depending on the criteria is stated as such: e.g. $sDA_{300/50\%}$. The sDA is calculated using Equation 67:

$$\mathrm{sDA}_{\mathrm{x/y\%}} = \frac{\sum_{\mathrm{i}}(\mathrm{wf_i} \cdot \mathrm{DA})}{\sum_{\mathrm{i}} \mathrm{p_i}}$$

where DA is the Daylight Autonomy at a certain grid point, wf_i is equal to 1 when the DA threshold is equal or exceeded (otherwise 0) and p_i is a point on the grid.

The LEED certification system assigns 2 points for 55% and 3 for 75% for most spaces and 1 point for 75% and 2 for 90% for healthcare.

Table 1 Data fields used for the representation of PIs

Information	Comment
Name of indicator and Symbol	The name of the indicator is the title of each entry and appears on the context list. The symbol of the indicator is also part of the title. e.g. Daylight Factor (DF)
Unit	The unit is also included in the title of each entry and appears in the content list. Not all indicators have units. e.g. Reverberation time (T) [s]*
Short description	A short text description of each indicator accompanies all entries. The description may include the following information: • Relevant literature (e.g. source scientific literature, standards) • type on measurement (e.g. long/sort term, point/plane/volume) • aggregation method (e.g. average, sum) • objective of the measurement (e.g., speech intelligibility, effectiveness of the ventilation system) • calculation method • context of application
Numerical expression	Shows the aggregation of metrics, weighting factors and normalisation logic of the indicators
Evaluation (performance criteria)	• Recommended range • Target design values • Tables and charts (e.g. psychrometric chart)

2.2 Classification, indexing and mapping

The performance domains are used as the backbone of the classification system adopted in this catalogue. However, since the domains appear also in the content section of this publication forming an index to help the user navigate the catalogue, the following more indicative grouping was adopted:

- Energy efficiency and hygro-thermal performance
- Thermal comfort
- Indoor air quality
- Visual environment
- Acoustic environment

In this grouping, the domain of hygro-thermal performance is divided into two domains, energy efficiency and hygro-thermal performance and thermal comfort. Still, these domains are not homogenous but instead comprise various sub-categories that express different requirements within a performance domain. For example, the domain of the indoor visual environment contains the following distinct performance requirements:

- Indoor lighting: assessment of the capacity of the indoor lighting system to provide suitable conditions to support specific tasks, promote acuity etc.
- Daylight performance: assessment of the potential for daylight lighting in indoor spaces
- Glare: prediction of occupant's acceptability to different levels of discomfort glare
- Colour (quality of light): assessment of the ability of light sources to render colour.

Similar sub-categories exist in other performance domains as well and are used to furthermore develop the classification system. However, in some cases, an additional grouping criterion is applied. Specifically, in the category of thermal comfort the indicators are additionally grouped in a way that reflects fundamentally different measurements approaches for thermal comfort (e.g. indices based on adaptive models or physiological models). This helps reveal important information on their application context, capacities and scientific basis.

The final classification system used in this catalogue is formed as following:

- Energy efficiency and hygro-thermal performance
- Thermal comfort: environmental indices
- Thermal comfort: heat balance indices
- Thermal comfort: adaptive model indices
- Thermal comfort: Local thermal discomfort indices
- Thermal comfort: long-term and overheating indices
- Indoor air quality (IAQ)
- Visual environment: Indoor lighting
- Visual environment: Daylight performance
- Visual environment: Glare
- Visual environment: Colour (quality of light)
- Acoustic environment: Room acoustics (perform. spaces)
- Acoustic environment: Speech perception
- Acoustic environment: Privacy and concentration (offices)
- Acoustic environment: Noise
- Acoustic environment: Building acoustics

Finally, an effort was made to harmonise the classification system (division of domains, terminology etc.) with established systems used in relevant literature in order to make the catalogue familiar and accessible to users in the professional and academic community.

2.3 Terms and definitions

The performance-based building sector uses a rich and varied vocabulary of terms, perhaps since it combines people and knowledge from different professional and scientific spheres. As a result, there is an alternative for almost any major term in the sector. This publication does not introduce new terms, however, the use of existing terms must be clarified.

The most prevalent example of alternative terminology is the term "performance indicator" itself. Terms like performance index, performance criterion, performance measure and performance metric can be found instead of performance indicator in literature. Alternative terms may express shared "naming habits" within specific professional or scientific communities or reveal information on the specificities of the tool. For example, in acoustics the term "acoustic measure (or quantity)" is dominant whilst in the visual environment domain, the term "daylight metric" is commonly used to referred to daylight performance indicators.

The term "index" is used typically when the object in question (the indicator) represents both the measurement and the evaluation system. Therefor the term is used for indicators that express performance as a percentage of optimum performance (e.g. the various speech perception indices) or on a rating scale, (e.g. the various PMV and PD indices). Additionally, the term "index" is used for benchmark indicators that rate the performance of products against the performance of other products, e.g. Energy Performance Index (EPIs) or Energy Cost Index (ECI) (see section 3.1.1). These values combine several performance metrics, require intricate calculating procedures and do not necessarily reveal much information on the inner workings of a system.

However, because this terminology is not unambiguously defined, the term "performance indicator" (or indicator) is used in this catalogue to refer to all objects. Exceptions are made when an object includes an alternative as part of its name (e.g. Speech Transmission Index) or is overwhelmingly referred to as i.e. index (e.g. PMV index).

The term "metric" may be defined as "a standard definition of a measurable quantity (Deru et al. 2005, p. 20)" whilst the term "performance metric" may be defined as "a metric of some performance characteristic (Deru et al. 2005, p. 20)". For example, the area [m^2] is a metric but not a performance metric. In the same context, a performance indicator is "a high-level performance metric that is used to simplify complex information and point to general state or trends of a phenomenon (Deru et al. 2005, p. 20)." In this publication the term metric is used to refer to measurable quantities and not the indicators themselves.

The term "performance requirement" may be defined as "a suitable level of performance which must be met by building materials, components, building as a whole in order for a building to meet the relevant functional statements and, in turn, the relevant objectives. The requirement can be assessed by an objective assessment method (Stesken et al. 2010, p.3)".

The term "performance criteria" is used in this catalogue to refer to the conditions under which the performance requirement is satisfied. This is typically represented by the context under which the results of the indicators are evaluated. For example, a minimum daylight factor over an area may be the performance criterion for “daylight performance”, a range of acceptability stated in terms of operative temperature may be the performance criterion for thermal comfort and the required ventilation rates may be the performance criterion for indoor air quality. The term “performance criterion” is sometimes difficult to distinguish from the term performance indicator, because as shown in the examples, the performance criteria are often stated as permissible or suggested values for performance indicators.

The performance domain described in Section 3 under the term “thermal comfort” is sometimes described in the relevant literature as “thermal environment” (e.g. ISO 7730:2005 Ergonomics of the thermal environment). The terms “heat balance indices” and “adaptive model indices”, included in this domain, where chosen to address text formatting issues. More appropriate terms would have been “indices based on physiological models of heat balance” and “indices based on adaptive model of thermal comfort”. Finally, the term “environmental indices” is one of the many terms used in the literature to describe and group these types of indices. Other terms used for that purpose are “temperature indices”, “Indices Based on Physiological Strain” etc.

3 Results

3.1 Energy efficiency and hygro-thermal performance

The domain of hygro-thermal performance deals with the movement of energy and mass (air and humidity) thought the building and the building elements (e.g. walls). It involves performance requirements such as energy efficiency, avoidance of condensation and thermal comfort. This chapter includes energy efficiency, air permeability (or air tightness of the building envelope), interstitial condensation and surface condensation. These requirements are regularly prescribed in building codes as well as other compliance and rating programs and are typically grouped together.

Condensation in building assemblies and moisture levels in general influence another important performance requirement, the indoor air quality (IAQ). The indicators referring to this subject are discussed in section 3.7.

3.1.1 **Energy Performance Indicators (EPI) [kWh.m^{-2}.a^{-1}] * & energy balance**

The fundamental energy performance indicator (EPI) used for energy performance rating and certification in performance-based schemes (EPBD energy performance certificates, NZEB etc.) is the annual energy demand/consumption typically normalised per area, and/or parts of it (e.g. the heating demand). This quantity can be directly measured using energy meters, or calculated using a computational model. A combination of the two is also common, using measured data such as the leakage rate of the envelope (see section 3.1.2) to inform the computational model.

The quantification may be performed for the building as a whole, using an overall performance indicator and for separate sub-systems (e.g. heating/cooling, hot water, lighting) using a partial energy performance indicator. Most energy efficiency schemes require an overall performance indicator. However, some schemes might set performance requirements for sub-systems as well. For example, the Passive House program sets requirements for maximum heating demand and cooling demand to be satisfied parallel with a requirement for the overall demand (see section 4.4).

The energy measured or calculated is often normalised per reference floor area (kWh.m^{-2}). The calculation period is typically a year, therefor the indicator units are expressed as kWh.m^{-2}.a^{-1}. Different normalisations are possible as well, such as kWh.m^{-2}.HDD^{-1} where the climate indicator Heating Degree Days (HDD) is used to normalise per local climate.

Energy Performance Indicators (EPI) are alternatively referred to as Energy Use Intensity (EUI), Building Performance Index (BPI), Energy Cost Index (ECI) etc. Additionally, the terms demand, load and consumption are used sometimes interchangeably (but do not mean the same).

Most Energy Performance Indicators (EPI) used in energy rating schemes are weighed versions of the annual energy demand (or part of it e.g. heating demand). The weighting factors used, express the priorities (e.g. environmental, financial and political) of the stakeholders requiring or performing the evaluation. Examples of weighted EPIs are (EN 15217 2007):

- primary energy (E_p)
- greenhouse gas emissions (E_{mCO2})
- energy costs

Furthermore, the Energy Performance Indicators (EPI) may express the energy balance. The energy balance is the delivered energy minus exported energy (on-site or nearby produced energy from renewable resources) and is particularly important for energy efficiency programs that go beyond code compliance such as the Nearly Zero Energy Buildings (NZEB) and the Plus Energy Buildings. Such programs typically require the implementation of Renewable Energy Sources (RES) (see section 4.4).

Equations 1 and 2 calculate the energy balance expressed using the commonly used EPIs primary energy (E_p) and greenhouse gas emissions (E_{mCO2}) (EN 15217 2007):

$$E_p = \sum \left(E_{del,i} * f_{P,del,i}\right) - \left(E_{exp,i} * f_{P,exp,i}\right) \qquad (1)$$

$$E_{mCO2} = \sum \left(E_{del,i} * K_{del,i}\right) - \left(E_{exp,i} * K_{exp,i}\right) \qquad (2)$$

where $E_{del,i}$ is the delivered energy for energy carrier i, $E_{exp,i}$ is the exported energy for energy carrier i, $f_{P,del,i}$ is the primary energy factor for the delivered energy carrier i, $f_{P,exp,i}$ is the primary energy factor for the exported energy carrier i, $K_{del,I}$ is the CO_2 emission coefficient for delivered energy carrier i, $K_{exp,I}$ is the CO_2 emission coefficient for the exported energy carrier *i.*

The various context in which EPIs are used in different energy efficiency rating and certification programs is discussed in section 4.4.

NOTE: Energy efficiency can be evaluated for separate building systems. For example, the Lighting Energy Numeric Indicator (LENI) is used to assess energy efficiency in regard to the energy consumption of the lighting system as it is affected (among other factors) by the daylight performance of the building (see section 3.9.11).

3.1.2 Air tightness/permeability (n_{pr}, q_{Epr} etc.) [ACH or h^{-1}] *

Low air tightness (or high air permeability/leakage) of the building envelope affects significantly the energy loads and comfort conditions of a building and is therefore commonly used as an indicator of hygro-thermal performance and energy efficiency alike. Leakage is due to the undeliberate and uncontrolled exchange of energy carrying mass (air and humidity) thought the building's envelope caused by difference in pressure on each side of the envelope. Usually the quantity is expressed in terms of Air Change per Hour [ACH]. ISO 9972 (2016) defines a procedure for determining air permeability of buildings using a fun pressurised method and the following indicators.

The air change rate is calculated at a reference pressure difference (n_{pr}), usually set to 50 Pa (written as n_{50}), using Equation 3:

$$n_{pr} = \frac{q_{pr}}{V} \qquad (3)$$

The specific leakage rate is calculated at a reference pressure difference, usually set to 50 Pa,

using Equation 4 for the envelope (q_{Epr}):

$$q_{Epr} = \frac{q_{pr}}{A_E} \qquad (4)$$

and Equation 5 for the floor (q_{Fpr}):

$$q_{Fpr} = \frac{q_{pr}}{A_F} \qquad (5)$$

The effective leakage area (ELA_{pr}) is calculated at a reference pressure difference (e.g. 10Pa) using equation 6:

$$ELA_{pr} = \frac{1}{3600} C_L \left(\frac{\rho_0}{2}\right)^{0,5} (\Delta p_r)^{n-0,5} \qquad (6)$$

The specific effective leakage rate is calculated at a reference pressure difference (e.g. 10Pa),

using Equation 7 for the envelope (ELA_{Epr}):

$$ELA_{Epr} = \frac{ELA_{pr}}{A_E} \qquad (7)$$

and Equation 8 for the floor (ELA_{Fpr}):

$$ELA_{Fpr} = \frac{ELA_{pr}}{A_F} \qquad (8)$$

where q_{pr} is the air leakage rate, A_E is the envelope area [m^2], A_F is the floor area [m^2], C_L is the air leakage coefficient and ρ_0 is the air density at standard conditions [$kg*m^{-3}$].

The Passive House program (sees section 4.4) for energy efficiency certification requires n_{50}< 0,6 ACH. The Austrian building codes (OIB Richtlinie_6 2015) require for new buildings $n_{50} \leq 3$ ACH for building without ventilation and $n_{50} \leq 1,5$ ACH for buildings with ventilation.

3.1.3 **Moisture protection: Surface condensation-Temperature factor (f_{Rsi}) ***

Avoiding condensation on the surface of a building element (e.g. walls, ceilings) facing the inside of a room is critical for discouraging mould growth, corrosion and other moisture related damages. The temperature factor (ISO 13788 2012) is used to calculate the likeliness of critical surface humidity using inside and outside air temperatures as well as and the temperature of the inside surface of the element as shown in Equation 9:

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad (9)$$

Where θ_{si} is the temperature of the internal surface, θ_i internal operative temperature and θ_e is the external air temperature.

Effective values of f_{Rsi} for any given building for plane elements can be derived using Equation. (0:

$$f_{Rsi} = 1 - f_{si} U \qquad (10)$$

Where U is the thermal conductance of the wall [W.m^{-1}.K^{-1}]. ISO 10211 gives information for calculation of multidimensional heat flow though using computation software.

3.1.4 **Moisture protection: Interstitial condensation ***

Avoiding interstitial condensation of humidity (condensation occurring in-between the inside and outside surfaces of a building element) is critical to ensure that the building's construction integrity is not compromised by factors such as the formation of ice or mould. Condensation occurs when humidity contained in air (water vapor) moving through the building element condensates due the differences in saturation vapor saturation pressure caused by the temperature gradient. ISO 13788 (2012) specifies a method to predict interstitial condensation due to vapor diffusion based on the calculation of the vapor pressure and the saturation vapour pressure.

The calculation method takes account of external conditions (monthly boundary conditions) and material properties (e.g. λ values) to assess the whole of the annual moisture balance within the element and the maximum amount of accumulated moisture.

First the temperature is calculated at the surface between the elements components. The calculation is performed under steady stage conditions using Equation 11:

$$\theta'_n = \theta_e + \frac{R'_n}{R'_T}(\theta_i - \theta_e) \tag{11}$$

Next the saturation vapour pressure is calculated based on the surface temperatures. Then the vapour pressure distribution is calculated according to the vapour flow rate using Equation 12:

$$g = \delta_0 \frac{p_i - p_e}{s'_{d,T}} \tag{12}$$

where θ_n is the surface temperature at interface n, R'_n is accumulated thermal resistance, R'_T is total thermal resistance, $s'_{d,n}$ is water vapor diffusion-equivalent air layer and $s'_{d,T}$ is the total water vapor diffusion-equivalent air layer

A graphical method where the two profiles (vapor pressure and saturation vapour pressure) are plotted against the cross section of the element can be used to indicate condensation. If the two lines cross condensation is to be expected.

ISO 13788 (2012) suggest that the results are reported in accordance to the time of condensation (which month), the amount of points of condensation (one or more interstitial layers) and the persistence of the phenomenon (evaporated or not).

3.2 Thermal comfort: Environmental indices

Environmental indices are single values that represent one or multiple environmental variables. Examples of fundamental environmental indices (and environmental variables) are the air temperature (dry bulb), the wet bulb temperature, the mean radiant temperature (MRT), the relative humidity and the air speed. Some of these variables can be directly measured using instruments like thermometers. However, the environmental indices most likely to be used for whole body thermal comfort combine various environmental variables into a single value that represents the temperature of an imaginary uniform enclosure in which the occupants are expected to exchange the same amount of heat as in the actual environment (or experience equal physiological strain). The single value is calculated using regression equations or physiological models of heat balance (that account for both environmental variables and personal variables but are still expressed in the form of an environmental index e.g. ET*, SET*). The calculated value (temperature) is typically evaluated in terms of acceptable range and design target values.

Furthermore, environmental indices are typically evaluated depending on a specific application context defined using sets of other parameters that are not accounted for by the index. For example, the operative temperature is often evaluated for assumed relative humidity, occupant's clothing and activity levels and wind speed. Selecting a suitable thermal comfort index may depend on the input variables and the application context as shown in Table 2.

Table 2 Thermal comfort indices may have different input variables and application context

Indices for whole body thermal comfort (except long-term)	Considered variables	Application remarks
Operative Temperature (TOP)	Environmental (air temperature, radiant temperature)	(Should be) evaluated differently depending on context (e.g. metabolism rate, relative humidity)
new Effective Temperature (ET*) (based on Pierce model)	Environmental (air temperature, radiant temperature, relative humidity)	(Should be) evaluated differently depending on various values of "clo" and "met"
Standard Effective Temperature (SET*) (based on Pierce model)	Environmental and personal	Assumes standard values for "clo" and "met"
Wet Bulb Globe Temperature Index (WBGT)	Environmental (but can be adjusted for personal)	Heat stress in hot conditions (e.g. industrial environments, athletic environments)
equivalent Temperature (T_{eq})	Environmental	Confined space with non-uniform climatic conditions
PMV-PPD index (based on Fanger model)	Environmental and personal	Uniform environment and calculation under steady state conditions
TSENS, DISC, PMVET, PMVSET (based on Pierce model)	Environmental and personal	Uniform environment and transient thermal conditions calculation
Thermal Sensation Vote (TSV) (based on KSU model)	Environmental and personal	Separate calculation for cold and hot thermal stress. Transient thermal conditions calculations.
Adaptive models (based on ASHRAE & ISO)	Environmental (outdoor mean temperature)	Naturally ventilated buildings (with operable windows).

3.2.1 **Operative temperature (TOP or t_o) [°C] * & elevated air speed (v) [m.s^{-1}]**

The Operative Temperature (Winslow et al. 1938) is a widely used and prescribed environmental index. ASHRAE standard 55 (2010) defines the TOP as 'the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment'. In other words, the TOP combines the effects of air temperature (t_a) and radiant temperature (t_r) into a single number. Equation 13 is listed in ASHRAE standard 55 (2010) as an acceptable approximation of Operative Temperature:

$$t_o = At_a + (1 - A)t_r \tag{13}$$

where t_a is the air temperature [°C], t_r is the mean radiant temperature [°C] and coefficient A is depended on the air velocity. ISO 7726 describes methods and techniques for the measurement of operative temperature.

The operative temperature is usually evaluated in terms of acceptable range (comfort zone), design target values and threshold values for overheating. In ISO 15251 (2017), the TOP is used to define thermal comfort categories for different types of buildings based on the occupant's clothing and activity levels. In the popular graphic comfort zone method (psychrometric chart), parameters such as the relative humidity are used to shift the acceptable range of TOP. In these chars (ASHRAE standard 55 2010), acceptability corresponds to 80% of the occupancy and to predefined values of air speed, metabolic rate, and clothing insulation.

In cases where the operative temperature cannot be kept consistency within limits, ISO 15251 (2007) suggests that increasing wind speed can offset the negative effects of an increased TOP by maintaining equal heat transfer.

3.2.2 **New Effective Temperature (ET*) [°C] * & humid operative temperature (T_{oh})**

The new Effective Temperature (Gagge et al. 1971) is a widely used environmental index of thermal comfort. It combines the effects of operative temperature (air temperature and radiant temperature, see 3.1.1) and water vapour pressure into a single value, defined in the ASHRAE Handbook as the "temperature at 50% RH that yields the same total heat loss from the skin as for the actual environment" (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009). The heat exchange that accounts for both sensible and evaporative heat transfer is calculated at the surface of the skin using the Pierce Two-Note heat balance model (Gagge et al. 1986).

The ET* offers a more comprehensive assessment of thermal comfort than the operative temperature (TOP) or the Wet Bulb Temperature (WBT) since it reflects better the thermal impact of humidity on the occupant's perception (Fobelets et al. 1988). The effective temperature is calculated using Equation 14:

$$ET^* = t_o + wi_m LR(p_a - 0.5p_{ET^*,S}) \tag{14}$$

where $p_{ET^*,S}$ is the saturated water vapor at ET* [psi], p_a is the water vapor partial pressure [Pa], w is the wettedness, w is the skin wettedness and i_m is the permeability index.

A similar indicator is the humid operative temperature (T_{oh}) (Nishi et al. 1971) shown in Equation 15. The ASHRAE Handbook defines the humid operative temperature as the "temperature which at 100%

RH yields the same total heat loss as for the actual environment" (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009).

$$t_{oh} = t_0 + wi_m LR(p_a - p_{oh,s}) \tag{15}$$

Where $p_{oh,s}$ is the saturated water vapor at t_{oh} [psi].

The first version of this indicator, called the effective temperature (ET), was proposed by Houghten and Yaglou (1923) and is calculated using Equation 16:

$$ET = DBT - 0.4(DBT - 10) \cdot (1 - \frac{RH}{100}) \tag{16}$$

where DBT is dry bulb temperature [°C] and RH is the relative humidity [%]. This indicator unlike the new Effective Temperature (ET*) is not calculated based on a heat balance model.

The ET* can be evaluated in terms of acceptable range (comfort zone) and equal sensation isotherms (equal heat loss) typically using graphical methods. Additionally, using a regression equation it can be used to predict a thermal sensation vote (PMVET*, see section 3.3.4). However, the ET* must be evaluated in the context of the different values of clothing and metabolism rate in every situation. In contrast, the Standard Effective Temperature (SET*) assumes standard values for these variables as discussed in section 3.2.3.

3.2.3 **Standard Effective Temperature (SET*) [°C] ***

This environmental index (Gagge et al. 1986) encompasses both environmental and personal variables. Similar to the ET* the heat exchange is calculated at the surface of the skin using the Pierce Two-Note heat balance model (Gagge et al. 1986) and accounts for both sensible and evaporative heat transfer. However, the SET* assumes standard values for clothing and metabolism, unlike the ET* that must be evaluated in the context of the different met and clo values in each situation.

The ASHRAE standard 55 (2010) defines SET* as "the temperature of an imaginary environment at 50% RH, <0,1 $m.s^{-1}$ air speed, and t_r=t_a (radiant temperature equal to air temperature), in which the total heat loss from the skin of an imaginary occupant with an activity level of 1,0 met and a clothing level of 0,6 clo is the same as that from a person in the actual environment, with equal clothing and activity level".

The SET model can be evaluated in terms of acceptable range (comfort zone) and is used to draw boundaries on psychrometric charts to facilitate graphic comfort zone methods. It is also evaluated using regression equations (PMVSET*) to predict thermal sensation vote (see section 3.3.4).

3.2.4 **Wet Bulb Globe Temperature index (WBGT) [°C] * for hot environments**

The WBGT (according to ISO 7243 2015) is an environmental index combining wet-bulb temperature and globe temperature used to predict the absence or presence of heat stress among those exposed to hot conditions in industrial environments, athletic environments and the military. The index is based on measurements and is designed to evaluate the effect of heat during periods representative of the whole of the possible exposure time (i.e. the working day) and is not suitable for very short exposures. The measurements should be carried out in hourly basis over period where heat stress is likely to occur (i.e. at summer period in middle of the day). Instrument setups, alternatives and specifications are stated in the relevant standard (ISO 7243 2015). The WBGT is calculated using Equation 17:

$$WBGT = 0{,}7t_{nwb} + 0{,}3t_g \tag{17}$$

In the case where the measuring devices are influenced by direct incident radiation the air temperature is also considered as shown in Equation 18:

$$WBGT = 0{,}7t_{nwb} + 0{,}2t_g + 0{,}1t_a \tag{18}$$

where t_{nwb} is the wet-bulb-temperature [°C] t_g is the black globe temperature [°C] and t_a is the air temperature [°C].

The WBGT can be adjusted for the effects of clothing (actual clothing rather that standard work clothing) as shown in Equation 19:

$$WBGT_{eff} = WBGT + CAT \tag{19}$$

ISO 7243 (2015) provides threshold values for heat stress using the WBGT and different metabolic rates.

3.2.5 **Total and local equivalent temp. (t_{eq}) [°C]* for asymmetric climatic conditions**

The equivalent temperature (according to ISO 14505-2 2006) is an environmental index developed to assess thermal conditions inside a vehicle compartment where the asymmetric climatic conditions are a usual cause of thermal discomfort. However, the indicator can be used to predict thermal stress in other confined space with asymmetric climatic conditions. However, according to ISO 14505 part 2 (2006) this assessment is intended for thermal conditions “when the deviations from thermal neutrality are relatively small”.

The equivalent temperature (t_{eq}) is defined as ‘temperature of a homogenous space, with mean radiant temperature equal to air temperature and zero air velocity, in which a person exchanges the same loss by convection and radiation as in actual conditions under assessment’ (ISO 14505 part 2 2006). The equivalent temperature can be calculated in four categories: for heat exchange between the enclosure and the whole body or body segments as well as between a flat surface (directional) or an ellipsoid (omnidirectional). The calculation method described in ISO 14505-2 (2006) involves experimental setups using thermal manikins as well as omnidirectional and flat, heated sensors. The measurements are weighed and aggregated accordingly in respect to the aforementioned categories. The equivalent temperature is calculated using Equation 20:

$$t_{eq} = t_s - \frac{Q}{h_{cal}} \tag{20}$$

where t_s is the surface temperature, $t_{eq}$is the temperature of the standard environment h_{cal} is the combined heat transfer coefficient, determined during calibration in a standard environment and Q (Equation 21) is the measure of convective and radiative heat loss during the actual conditions:

$$Q = R + C \quad (21)$$

$$R = h_r(t_{sk} - \bar{t}_r) \quad (22)$$

$$C = h_c(t_{sk} - t_a) \quad (23)$$

where R (Equation 22) is the heat exchange by radiation [w*m-2], t_{sk} is the skin temperature [°C], C (Equation 23) is the heat exchange by convection [w*m-2], $\bar{t}_r$ is the mean radiant temperature [°C], h_r is the radiation heat transfer coefficient [w*m-2], t_a is the ambient air temperature [°C], h_c is the convection heat transfer coefficient [w*m-2].

3.3 Thermal comfort: Heat Balance indices

The heat balance indices are used to assess whole body thermal comfort. They are indices based on physiological models of the heat balance of the human body that account for the balance between the gains (e.g. metabolism, energy from the environment) and losses (e.g. respiration) as they are affected by environmental and personals variables. The capacity of the body to maintain a steady deep body temperature is affected by the heat balance and therefore disturbances in the heat balance are experienced as disturbances in thermal comfort. Common environmental variables considered by the heat balance models are the air temperature, radiant temperature, relative humidity and wind speed. Common personal/behavioural variables considered by the heat balance models are the activity levels (metabolic rate) and clothing (clo value) of the occupants.

Results from this type of indices are typically expressed using a thermal sensation vote, calculated based on regression equations that connect disturbances in the heat balance to the opinion of occupants on their state of thermal comfort.

Different thermal comfort indices are calculated using different heat balance models. These models may represent the body as a single node such as in the Fanger (1970) and Givoni et al. (1971) models, two nodes such as in the Pierce (Gagge et al. 1986) and KSU (Azer et al.1977) models and multiple nodes such as in the Stolwijk (1971) and Fiala (Cropper et al. 2008) models. A single note model considers the exchange of heat between the body and the environment whilst a two-node model considers the exchange of heat between two body components, e.g. the skin and the core of the body. Furthermore, the various heat balance models may represent the environment as uniform or non-uniform and be calculated under steady state or transient thermal conditions. Cheng et al. (2012) discuss the characteristics and performance of such models in a comprehensive review.

The indices discussed in this section are calculated based on three of the most referenced models, the Fanger, the Pierce and the KSU. See Table 2 for basic distinctions between thermal comfort indices.

3.3.1 **Predicted Mean Vote (PMV) * Fanger model**

The PMV/PPD (Fanger 1970) is a comprehensive and widely used index used to evaluate thermal comfort, particularly in building where the indoor environment is regulated by a HVAC system. ISO 7730 (2005), perhaps the most referenced thermal comfort standard, defines the PMV as “an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment”. (See Table 3 shows the seven-point thermal sensation scale)

This index is calculated using the Fanger (one-note) thermal physiological model that predicts the heat exchange between the body and the environment depending on several variables (see section 3.3). The Fanger model represents the environment as uniform and is calculated only for steady-state condition. For transient conditions, indices based on other physiological models can be used instead (e.g. thermal sensation (TSENS), see 3.3.3). Some fluctuations (in the conditions) can be approached by time-weighted average of the fluctuating variable for a period of 1 hour (ISO 7730 2005). To account for asymmetric conditions in the environment (e.g. draught, hot and cold surfaces) local thermal discomfort indices can be used (see section 3.5).

The PMV is particularly accurate in predicting physiological response in buildings regulated by HVAC systems. In the case of naturally ventilated buildings (with operable windows) the adaptive models (see section 3.4) have been found to be more accurate (de Dear et al. 1998, McCartney et al. 2002).

Equation 24 expresses the heat balance according to the Fanger model:

$$M - W = H + E + C_{res} + E_{res} \tag{24}$$

Information on the calculation of this index (calculation using predefined input values, computer algorithm etc.) can be found in ISO 7730 (2005). The PMV is calculated using Equation 25:

$$\begin{aligned}
\mathrm{PMV} = {} & [0{,}303 \cdot \exp(-0{,}036 \cdot \mathrm{M}) + 0{,}028] \\
& \cdot \{(\mathrm{M}-\mathrm{W}) - 3,05.10^{-3} \cdot [5733 - 6{,}99 \cdot (\mathrm{M}-\mathrm{W}) - \mathrm{p_a}] \\
& - 0{,}42 \cdot [(\mathrm{M}-\mathrm{W}) - 58{,}15] - 1,7.10^{-5} \cdot \mathrm{M} \cdot (5867 - \mathrm{p_a}) \\
& - 0{,}0014 \cdot \mathrm{M} \cdot (34 - \mathrm{t_a}) - 3{,}96 \cdot 10^{-8} \cdot \mathrm{f_{cl}} \\
& \cdot [(\mathrm{t_{cl}} + 273)^4 - (\bar{\mathrm{t}}_\mathrm{r} + 273)^4] - \mathrm{f_{cl}} \cdot \mathrm{h_c} \cdot (\mathrm{t_{cl}} - \mathrm{t_a})\} \\
\mathrm{t_{cl}} = {} & 35{,}7 - 0{,}028 \cdot (\mathrm{M}-\mathrm{W}) - \mathrm{I_{cl}} \\
& \cdot \{3{,}96 \cdot 10^{-8} \cdot \mathrm{f_{cl}} \cdot [(\mathrm{t_{cl}} + 273)^4 - (\bar{\mathrm{t}}_\mathrm{r} + 273)^4] + \mathrm{f_{cl}} \cdot \mathrm{h_c} \\
& \cdot (\mathrm{t_{cl}} - \mathrm{t_a})\} \\
& \begin{cases} 2{,}38 \cdot |\mathrm{t_{cl}} - \mathrm{t_a}|^{0{,}25} & \text{for } 2{,}38 \cdot |\mathrm{t_{cl}} - \mathrm{t_a}|^{0{,}25} > 12{,}1 \cdot \sqrt{\mathrm{v_{ar}}} \\ 12{,}1 \cdot \sqrt{\mathrm{v_{ar}}} & \phantom{\text{for }} 2{,}38 \cdot |\mathrm{t_{cl}} - \mathrm{t_a}|^{0{,}25} < 12{,}1 \cdot \sqrt{\mathrm{v_{ar}}} \end{cases}
\end{aligned} \tag{25}$$

where M is the metabolic rate [W.m^{-2}], W is the effective mechanical power (heat loss due to work performed) [W.m^{-2}], I_{cl} is the clothing insulation [m^2*K.W^{-1}], f_{cl} is the clothing surface area factor, t_a air temperature [°C], $\bar{t}_r$ is the mean radiant temperature [°C], v_{ar} is the relative air velocity [m.s^{-1}], p_a is the water vapor partial pressure [Pa], h_c is the convective heat transfer coefficient [W.m^{-2}*.K^{-1}], t_{cl} is the clothing surface temperature [°C].

1 metabolic unit= 1 met= 58,2 W.m^{-2}

1 clothing unit= 1 clo= 0,155 m^2*°C.W^{-1}

Table 3 Seven-point thermal sensation scale (or ASHRAE thermal sensation scale)

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PMV is a thermal comfort index for the whole body. However, other factors of the environment, such as radiant asymmetry, warm/cold floors, draught and vertical air temperature difference can cause local thermal discomfort. For a comprehensive approach to thermal comfort, important standards such as ISO 7730 and ASHRAE 55 suggest the parallel use of local thermal discomfort indicators. For example, in ISO 7730 2005 the PMV/PPD and local thermal discomfort criteria are used to define a classification of the thermal environment into three categories.

Other uses of the PMV index include calculating the Predicted Percentage of Dissatisfied (PPD) (see section 3.3.2) and drawing boundaries on psychrometric charts to support a graphic comfort zone method of evaluating thermal comfort using the operative temperature and other environmental indices. Additionally, in buildings where systems of radiative heating/cooling are used, the PMV formula can be used by the thermostat to regulate surface temperatures whilst accounting for multiple factors (ISO 11855-1 2012).

3.3.2 **Predicted Percentage of Dissatisfied (PPD) [%] * function of PMV**

According to ISO 7730 (2005) 'the PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm'. The PPD is calculated as a function of the PMV index using Equation 26:

$$\mathrm{PPD} = 100 - 95 \cdot \exp(-0{,}03353 \cdot \mathrm{PMV}^4 - 0{,}2179 \cdot \mathrm{PMV}^2) \qquad (26)$$

ISO 15251 (2007) defines categories of the thermal environment using the indices PMV and PPD.

3.3.3 **Thermal sensation (TSENS) & thermal discomfort (DISC) Pierce model**

TSENS and DISC (Gagge, Fobelets et al. 1986) are commonly used comprehensive indices based on a physiological model of heat balance used to calculate thermal sensation vote (see 3.2). These indices are similar to the PMV, however, TSENS and DISC use the Pierce two-node model (Gagge et al. 1986) where the human body is represented by two concentric thermal compartments exchanging energy, the skin and the core of the body.

Similar to the Fanger model (PMV-PPD indices), the Pierce model (of the Pierce foundation) represents the thermal environment as uniform. However, unlike the PMV-PPD indices, the TSENS and DISC indices can be used to assess physiological response in transient thermal conditions.

Equation 27 expresses the heat balance according to the Pierce model:

$$M = E_{sk} + Q_{res} + Q_{dry} + Q_{crsk} + W \quad (27)$$

where M is the metabolic rate [W.m^{-2}], W is the effective mechanical power (heat loss due to work performed) [W.m^{-2}], E_{sk} is the total evaporative heat loss from skin [W.m^{-2}], Q_{res} is the rate of respiratory heat loss [W.m^{-2}], Q_{dry} is the sensible heat loss from skin [W.m^{-2}] and Q_{crsk} is the heat flow from the core to skin[W.m^{-2}] .

Information on the calculation of the TSENS and DISC indices can be found in the ASHRAE handbook: fundamentals (2009) and the Energy Plus engineering reference. Table 4 shows the thermal sensation scales corresponding to the two indices.

Additionally, the Pierce model is used to calculate the environmental indicators ET* and SET*.

Table 4 The scales used by TSENS and DISC to express physiological response (source: American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009)

	TSENS	DISC
+5	Intolerably hot	Intolerable
+4	Very hot	Limited tolerance
+3	Hot	Very uncomfortable
+2	Warm	Uncomfortable and unpleasant
+1	Slightly warm	Slightly uncomfortable but acceptable
0	Neutral	Comfortable
-1	Slightly cool	
-2	Cool	
-3	Cold	
-4	Very cold	
-5	Intolerably cold	

3.3.4 **Predicted Mean Vote (PMVET*, PMVSET*) function of ET* and SET***

The PMV index (see section 3.3.1) can be calculated also as a function of the ET* and SET*. These environmental indices are calculated using the Pierce two-node model (Gagge et al. 1986, see section 3.3.3) and can be used in the PMV calculation to account for dry heat loss.

Information on the calculation of the PMVET* and PMVSET* can be found in the Energy Plus engineering reference (U.S. Department of Energy 2017).

3.3.5 **Thermal Sensation Vote (TSV) KSU model**

The Thermal Sensation Vote is a comprehensive index based on a physiological model of heat balance used to calculate thermal sensation vote (see 3.3). The Kansas State University (KSU) model (Azer et al.1977) represents the body into two thermal compartments, similar to the Pierce two-node model, the core and the skin. However, the KSU model calculates differently the sweat rate and blood flow and predicts thermal sensation vote differently for cold and warm environments.

Information on the calculation of the TSV can be found in the Energy Plus engineering reference (U.S. Department of Energy 2017).

3.4 Thermal comfort: adaptive model indices

Indices based on adaptive models are used to assess whole body thermal comfort in (primarily) naturally ventilated buildings where predictive models like the PMV are not as accurate (de Dear et al. 1998). The adaptive method is based on the adaptive principle, according to which, people will react to changes in their environment that may bring discomfort and adapt in order to restore their comfort (Humphreys et al. 1998). The adaptation measures may be behavioural (e.g. window opening, clothes), technological (e.g. controlling equipment) etc.

Generally, the empirical field studies that helped ground the adaptive models show that in naturally ventilated buildings the temperature of perceived comfort runs along the external temperature. For example, ASHRAE defines the adaptive model as “a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological parameters” (ASHRAE Standard 55 2010, p. 3).

Beside evaluating thermal comfort, ASHRAE Handbook states that the “adaptive models are useful to guide design and energy decisions, and to specify building temperature set points throughout the year” (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009, p.9.19).

The two most widely used adaptive models are the de Dear and Brager’s model (based on worldwide measurements) that was commissioned and adopted by ASHRAE and the McCartney and Nicol’s model (based on measurements in Europe) that is adopted by EN ISO 15251.

See Table 2 for basic distinctions between thermal comfort indices.

3.4.1 **ASHRAE 55 (de Dear and Brager) [°C] ***

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) includes the de Dear and Brager’s adaptive model (de Dear et al. 1998) in the ASHRAE 55 standard and proposes that the model is used as an optional method for determining the acceptable indoor temperature range for thermal comfort in naturally ventilated buildings.

According to ASHRAE 55 (2010) this method is to be used when monthly mean outdoor temperature ranges between 10 °C and 33,5 °C in spaces where operable windows are the main means of regulating thermal conditions. Acceptable values for the indoor operative temperature must fall into a range defined by regression equations (typically illustrated on charts).

The equations were determined for different buildings (free-running buildings, slow-acting buildings, with or without indoor climate control mechanisms, etc.), based on the ASHRAE RP-884 project database of 21,000 measurements (mostly offices) from field studies of 160 buildings located on four continents in varied climatic zones since the mid-1980s.

3.4.2 **ISO 15251 (McCartney and Nicol) [°C] ***

ISO 15251 (2007) proposes an adaptive model to be used as an optional method for determining the acceptable indoor temperature range for thermal comfort in the summer period mostly in office buildings and similar buildings that operate without machine cooling. The occupants in these buildings must be able to adjust their clothing and should perform mostly sedentary activities. Furthermore, this method is to be used when monthly mean outdoor temperature ranges between 10 °C and 30 °C and buildings are naturally ventilated by operable windows.

The equations were determined based on the SCATs project database that was the result of field research in office buildings in Europe (McCartney et al. 2002). Equations 28, 29 and 30 are used to calculate acceptable range for operative temperature for 90%, 80% and 65% acceptability respectively.

90% acceptability: $$t_{oc} = 0{,}33 \cdot (T_O + 18{,}8) \mp 2 \tag{28}$$

80% acceptability: $$t_{oc} = 0{,}33 \cdot (T_O + 18{,}8) \mp 3 \tag{29}$$

65% acceptability: $$t_{oc} = 0{,}33 \cdot (T_O + 18{,}8) \mp 4 \tag{30}$$

3.5 Thermal comfort: Local thermal discomfort indices

For a comprehensive thermal comfort assessment, important standards (e.g. ISO, ASHRAE) suggest that local thermal discomfort factors are considered along with whole body thermal comfort assessment since the latter functions typically under the assumption of a uniform thermal environment. Local thermal discomfort is caused by asymmetrical conditions in the thermal environment such as draught (due to ventilation systems), radian asymmetry (different temperatures of internal surfaces), too cold or hot surfaces and vertical air temperature difference.

Local discomfort assessment is particularly relevant in spaces where occupants are dressed lightly and engage in sedentary activity (e.g. office) (ASHRAE 55 2010, ISO 7730 2005).

3.5.1 **Draught Rate (DR) [%] ***

This index (included in ISO 7730 2005) for local thermal discomfort predicts the percentage of occupants that experience discomfort due to draught. Like other local discomfort indices, the Draught rate is to be applied, according to ISO 7730 (2005) to people "at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral and for prediction for draught at the neck". At other body parts such as the arms and feet the prediction might be overestimated. The DR is calculated using Equation 31:

$$DR = \left(34 - t_{a,l}\right)\left(\bar{v}_{a,l} - 0{,}05\right)^{0{,}62}\left(0{,}37 \cdot \bar{v}_{a,l} \cdot Tu + 3{,}14\right) \tag{31}$$

and

$$Tu = \frac{SD}{v_a} \tag{32}$$

where $t_{a,l}$ is the local air temperature (20°C TO 26°C), $\bar{v}_{a,l}$ is the local mean air velocity [m*s^{-1}], Tu is the local turbulence intensity [%], SD is the standard derivation of air velocity and v_a is the local mean air velocity.

A similar index used to evaluate thermal discomfort due to draft caused by the performance of air terminal devices in mixing ventilation is discussed in section 3.7.9.

3.5.2 **Vertical air temperature difference (PD) [%] ***

This index (included in ISO 7730 2005) for local thermal discomfort predicts the percentage of occupants dissatisfied as a function of vertical temperature difference based on the observation that high differences in air temperature between head and angles may cause discomfort (ISO 7730 2005). It applies when the temperature increases upward and when the temperature difference is less than 8 °C. The PD is calculated using Equation 33:

$$PD = \frac{100}{1 + exp(5{,}76 - 0{,}856 \cdot \Delta t_{a,v})} \tag{33}$$

where $\Delta t_{a,v}$ is the vertical air temperature difference between head and feet [°C].

3.5.3 **Warm and cool floors (PD) [%] ***

This index (included in ISO 7730 2005) for local thermal discomfort predicts the percentage of occupants dissatisfied as a function of the floor temperature based on the observation that too warm and too cold floors may cause discomfort (ISO 7730 2005). The index applies to standing and/or sedentary activities. Similar values can be used for sitting on the floor or lying on the floor. The PD is calculated using Equation 34:

$$PD = 100 - 94 \cdot exp(-1{,}387 + 0{,}118 \cdot t_f - 0{,}0025 \cdot t_f{}^2) \tag{34}$$

Where t_f is the floor temperature [°C]

ISO/TS 13732-2 provide information on how to assess human response in the case of spaces that people occupy with bare feet

3.5.4 **Radiant asymmetry (PD) [%] ***

This index (included in ISO 7730 2005) for local thermal discomfort predicts the percentage of occupants dissatisfied as a function of radiant asymmetry based on the observation that radiation emitted by building elements can create conditions of radiant asymmetry that may cause discomfort (ISO 7730 2005). The PD is calculated using Equation 34:

$$PD = \frac{100}{1 + exp(a - b \cdot \Delta t_{pr})} - c \tag{35}$$

where Δt_{pr} is the radiant temperature asymmetry [°C].
Most potent in creating discomfort are warm ceilings and cool walls (and windows). ISO 7730 defines coefficients to weight the impact of the different building elements.

3.6 Thermal comfort: Long-term and overheating indices

Buildings that provide thermal comfort continuously (during all hours or all occupied hours) can be expensive and environmentally unsustainable (ISO 7730 2005). Small intervals outside the limits are considered acceptable. For this reason, scientific and professional literature such as the standards ISO 7730 (2005) and ISO 15251 (2007) suggest long term indices that allow the aggregation for results from PMV/PPD and TOP (or adaptive model for naturally ventilated buildings) over longer periods of time (e.g. annually). For example, a simple long-term index sums the hours outside of comfort conditions and can be used in optimization procedures. The more complicated indices account for factors such as the severity of the events and their impact on the occupancy and can predict overheating as well as compare the performance of different buildings (ranking).

Carlucci (2013) presents an analytical review on long term discomfort indices that may help the reader better understand the capacity of each tool and support better implementation of this kind of assessment. Among other, the review includes a comparison of the indices ranking capabilities and a gap analysis.

3.6.1 **Method A (ISO 7730): Percentage Outside the Range (POR) [%] ***

Method A "calculates the percentage of hours during which the building is occupied, the PMV or the operative temperature (TOP) is outside a specific range" (ISO 7730 2005) using Equation 36:

$$POR = \frac{\sum_{i=1}^{0h}(wf_i \cdot h_i)}{\sum_{i=1}^{0h} h_i} \cdot 100 \tag{36}$$

where wf_i equals 1 when the metric (PMV or TOP) falls within range (otherwise 0) and "h" the occupied hours.

3.6.2 **Method B (ISO 7730): Degree hour Criterion (DhC) [h] ***

Method B sums the hours when the operative temperature falls out of range. The considered hours are furthermore weighted using a factor that represents how much the range is exceeded. Due to this weighting criterion, this index accounts for the severity of exceedance events. The method B is calculated using Equation 37:

$$DhC = \sum_{i=1}^{0h}\left(w_{fi} \cdot h_i\right) \tag{37}$$

where

$$wf_i = 1 \quad for \quad t_{op} = t_{op,limit}$$

and

$$wf_i = 1 + \frac{|t_{op} - t_{op,limit}|}{|t_{op,optimal} - t_{op,limit}|} \quad for \quad \begin{matrix} t_{op} > t_{op,limit,warm\ period} \\ t_{op} < t_{op,limit,cold\ period} \end{matrix}$$

3.6.3 Method C (ISO 7730) [h] *

Method C sums the hours when the PMV falls out of range. The considered hours are furthermore weighted using a factor that is a function of PPD. Due to the weighting criterion, this index accounts for the severity of exceedance events. The method C is calculated using Equation 38:

$$Method\ C = \sum_{i=1}^{0h} \left(w_{fi} \cdot h_i\right) \tag{38}$$

Where:

$$wf_i = 1 \quad for \quad PMV = PMV_{limit}$$

and

$$wf_i = \frac{PPD_{actualPMV}}{PPD_{PMVlimit}} \quad for \quad \begin{matrix} PMV > PMV_{limit,warm\ period} \\ PMV < PMV_{limit,cold\ period} \end{matrix}$$

3.6.4 Method D (ISO 7730): Average PPD (<PPD>) *

Method D is a simple average of the PPD over the occupied hours. This index is suitable for comparisons and optimisation. When using this index for comparison, the same number of hours for every case must be used. The method D is calculated using Equation 39:

$$\langle PPD \rangle = \frac{\sum_{i=1}^{0h} (PPD_i \cdot h_i)}{\sum_{i=1}^{0h} h_i} \tag{39}$$

3.6.5 Method E (ISO 7730): Accumulated PPD (Sum_PPD) [%] *

Method E is a simple sum of the PPD over the occupied hours. This index is suitable for comparisons and optimisation. However, when using this index for comparison, the same number of hours for every case must be used. The method E is calculated using Equation 40:

$$sum_{PPD} = \sum_{i=1}^{0h} PPD_i \tag{40}$$

3.6.6 CIBSE overheating risk indices [%]

The Chartered Institution of Building Services Engineers (CIBSE) proposes an overheating index that calculates the percentage of hours the operative temperature (TOP) exceeds a threshold (similar to method A of ISO 7730). There are multiple variations of this index that account either for just the occupied hours or all hours and that use different threshold temperatures (25,26 and 28 C) overall or at different zones in the building (e.g. lower in the bedrooms).

The CIBSE overheating risk index is calculated using Equation 41:

$$CIBSE = \frac{\sum_{i=1}^{0h}(wf_i \cdot h_i)}{\sum_{i=1}^{0h} h_i} \cdot 100 \qquad (41)$$

where wf_i equals 1 when the operative temperature exceeds the threshold (otherwise 0).

3.6.7 Exceedance$_M$ [%]

This indicator (Borgeson et al. 2010) is an overheating index that measures the percentage of the occupancy affected by thermal discomfort during occupied hours based either on the PPD or the adaptive model and the occupancy rate. The Excceedance$_M$ is calculated using Equation 42:

$$Exceedance_M = \frac{\sum_{i=1}^{0h}(n_i \cdot Discomfort_i)}{\sum_{i=1}^{0h} n_i} \cdot 100 \qquad (42)$$

where discomfort is equal to 1 for discomfort experienced by more than 20% of occupants (otherwise 0) and “n” is the number of occupants at a given hour.

3.6.8 Overheating risk (NaOR)

This indicator (Nicol et al. 2008) calculates the likelihood of overheating based on the differences between the operative temperature and the adaptive comfort temperature, rather than a simple threshold exceedance (used by many overheating indices). The NaOR is calculated using Equation 43:

$$P(\Delta\theta) = \frac{exp(0{,}4734\Delta\theta - 2{,}607)}{1 + exp(0{,}4734\Delta\theta - 2{,}607)} \qquad (43)$$

Using a regression equation, the results are presented on the ASHRAE thermal sensation scale.

3.7 Indoor Air Quality (IAQ)

The Indoor Air Quality in buildings is compromised by airborne contaminants/pollutants emitted from the occupants (bio-effluents), indoor activities (e.g. cooking, smoking, chemicals from industrial applications), emissions from building materials (during construction and operation like TVOC and radon) and outdoor air pollution. The IAQ is a performance domain closely linked to the health performance of buildings (Hasselaar 2006).

The concentration of pollutants in indoor air is controlled thought ventilation strategies mainly by introducing fresh air and exhausting contaminated air. Therefor many indoor air indicators reflect on attributes of the performance of ventilation systems. These include the ability to ventilated (exchange air) and to effectively distributed heating energy (for energy efficiency and thermal comfort).

Commonly used indicators of IAQ dealing with concentration of pollutants and mould growth are not included in this catalogue because they do not quantify directly the performance of building systems.

A European Concerted Action (COST 613) on Indoor Air Quality & its Impact on Man published a series of reports discussing a wide spectrum of subjects relating to this performance requirement.

3.7.1 **Percentage of Dissatisfied (PD_{AQ}) [%] function of $C0_2$ levels**

Carbon Dioxide (CO_2) is a distinctive human bio-effluent and can be therefore used as an indicator for the whole of human bio-effluent emissions to help predict the nuisance of occupants. For the same reason CO_2 monitoring is being used to control ventilation rates in high occupancy spaces.

This indicator (Fanger 1987) calculates the percentage of occupants dissatisfied by air quality based on the CO_2 levels. The measurement is applicable in situations of sedentary occupancy (e.g. lecture halls) and various other pollutants (beside the CO_2) that are pertinent to perceived air quality and safety cannot be evaluated using this indicator. The PD_{AQ} is calculated using Equation 44:

$$\mathrm{PD_{AQ}} = 395 * \exp\left(-1{,}83 * \mathrm{C_{CO2}}^{0{,}25}\right) \tag{44}$$

where C_{CO2} is the indoor concentrations measured above outdoor level.

ISO 13779 (2008) provides values for ventilation rates per person for various categories of CO_2 concentration (measured by ppm above level of outdoor air concentration) for smoking and non-smoking areas.

3.7.2 **Percentage of Dissatisfied (PD_{AQ}) [%] function of [olf] & ventilation rate (q)**

This indicator (Fanger 1987) predicts the percentage of occupants dissatisfied by the indoor air quality (perception of a person walking into the room) as indicated by the unit “olf” and the ventilation rates. “Olf” represents the pollution (bio-effluents) generated by one standard person.

The dissatisfaction caused by a standard person (one olf) at different ventilation rates is calculated using Equation 45:

$$\mathrm{PD_{AQ}} = 395 * \exp(-1{,}83 * \mathrm{q}^{0{,}25}) \tag{45}$$

$$\mathrm{PD_{AQ}} = 100$$

Where q is the ventilation rate [l*s], for $q \geq 0{,}32$ l∗s-1∗olf-1 and for $q < 0{,}32$ l∗s-1∗olf-1.

More information on the PD_{AQ} indices can be found in the publications of the the European Concerted Action (COST 613) (1992).

3.7.3 **Perceived air quality (C_i) [decipol] function of PD_{AQ}**

The perceive air quality (Fanger 1987) is calculated as a function of the percentage of occupants dissatisfied by the indoor air quality (PD_{AQ}) using Equation 46:

$$\mathrm{C_i} = 112(\ln(\mathrm{PD}) - 5{,}98)^{-4} \tag{46}$$

Information on the calculation of the olf and decipol units can be found in the ASHRAE Handbook: Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009). Some publications (European Concerted Action (COST 61 3) 1992) define ventilation rates per standard person (olf) for three different categories of indoor air quality using the PD and decipol.

3.7.4 **Ventilation rate/air supply rate [per person, per area, per appliance, ACH] ***

The ventilation rates are the most prescribed indoor air quality criteria. Indoor Air Quality standards include ventilation rates appropriate to restrain the concentration levels of pollutants within permissible levels. The rates are set in respect to occupancy (e.g. number of people, time of occupation, sensitivity of occupation), emission from indoor activities (e.g. cooking, smoking), emissions from processes in non-residential buildings and emissions from building materials.

The control of humidity level is also considered when deciding on ventilation rate. Excess humidity may have serious consequence (especially in residential environments) in terms of the health of occupants and the integrity of the building elements.

Most codes and standards specify required design ventilation rates, in respect to the aforementioned criteria using the following indicators:

- Air Changes per Hour [ACH] or air change rate [h-1] is a common indicator that counts the times the air contained in a room (equal to the volume of the room) has changed within an hour.
- air supply rate per person (qp) is used in situations of typical human occupancy [l.s-1.person-1].
- air supply per area can be used for rooms that are not intended for human occupancy or have a clearly defined use [l.s-1.m-2].
- air supply per appliance is used to account for emission of specific appliances that may have a serious polluting effect.

Standards ISO 15251 (2007) and ISO 13779 (2008) provide ventilation rates and categorization principles for residential and not residential applications, for human emissions, building emission, CO_2 and humidity. ASHRAE standard 62 (2007) specifies requirements for minimum ventilation rates in breathing zones per people and area.

ISO 15251 (2007) provides ventilation criteria combining ventilation requirements for pollution due to people (q_p) and buildings (q_E). Total ventilation for both building emission and occupancy emission is calculated using Equation 47:

$$q_{tot} = n \cdot q_p + A \cdot q_E \tag{47}$$

where “n” is the number of persons in the room and A the room floor area [m^2].

3.7.5 **Minimum exhaust rate [per area] ***

The minimum exhaust rate or required exhaust rate is a type of ventilation rate indicator, similar to the air supply rates, but prescribed typically in spaces with high concentration of pollutants such as toilets and kitchens. ASHRAE standard 62.1 (2007) includes recommended values for different type of spaces (e.g. Arenas, Art classrooms, Auto repair rooms, Barber shop).

3.7.6 **Contaminant Removal Effectiveness (CRE or ε^c) * & local air quality index (ε^c_p)**

The Contaminant removal effectiveness (Yaglou et al. 1937) is a zone indicator that measures the performance of the ventilation system in respects to contaminants removal (or fresh air diffusion). This indicator can be used when the contamination source type and location is known (e.g. when the use of the room is known, otherwise see 3.7.7).

The CRE is calculated using Equation 48:

$$\mathrm{CRE} = \frac{\mathrm{C_e} - \mathrm{C_s}}{\langle C \rangle - \mathrm{C_s}} = \frac{\text{Concentration in the exhaust}}{\text{Mean concentration in the room}} \quad (48)$$

where <C> is the room (breathing zone) average contaminant concentration, C_s is the contaminant concentration at supply and C_e is the contaminant concentration at exhaust.

The Contaminant Removal Effectiveness is referenced in ISO literature (e.g. ISO 15242, ISO 13779) as ventilation effectiveness. The ventilation effectiveness can be used to predict the air diffusion with in a room (e.g. mixing ventilation, displacement ventilation). ISO 13779 2008 provides values for ventilation effectiveness for different air diffusion (Mixing horizontal jet, Mixing vertical jet, Displacement ventilation).

The Ventilation effectiveness (ε_v) is used to calculate the required ventilation rate to dilute pollutants using Equation 49:

$$Q_h = \frac{G_h}{C_{h,j} - C_{h,o}} \cdot \frac{1}{\varepsilon_v} \quad (49)$$

where Q_h is the ventilation rate required for dilution [$l.s^{-1}$], G_h is the pollution load of a pollutant [$\mu g.s^{-1}$], $C_{h,J}$ is the guideline value of a pollutant [$\mu g.m^{-3}$], $C_{h,o}$ is the supply concentration of pollutants at the air intake [$\mu g.m^{-3}$].

The local air quality index ($\varepsilon^c{}_p$) (Mundt et al. 2004) is similar to the CRE but is instead a local index that measures the performance of the ventilation system in respects to contaminants removal at a certain point (using a point sensor). The local quality index is calculated using Equation 50:

$$e_p^c = \frac{\mathrm{C_e} - \mathrm{C_s}}{C_i - \mathrm{C_s}} \quad (50)$$

where C_i is the concentration at the point of measurement.

Calculating these indicators may involve CFD simulation or field measurements.

3.7.7 **Air Change Efficiency (ACE or ε^α) & local air change index ($\varepsilon^a{}_p$)**

This air change efficiency/effectiveness (Etheridge et al. 1996) is a zone indicator that measures the performance of the ventilation system in respect to the ability of the system to renew the air in the room (introduce and distribute fresh air) based on the age of air. This indicator can be used when the contamination source type and location is unknown (e.g. when the use of the room is known, otherwise see 3.7.6). The air change efficiency is calculated using Equation 51:

$$\varepsilon_a = \frac{\tau_n}{\theta_{age}} = \frac{\text{mean age of air in the exhaust}}{\text{average age of air in the room}} \quad (51)$$

Where the nominal time constant (τ_n) is the ration of the volume of the room and the air flow rate and represents the mean age of air in the exhaust and θ_{age} is calculated through local values of the age of air and represents the average age of air in the room.

The Air change efficiency (ε^{α}) can be used to predict the air diffusion with in a room (e.g. mixing ventilation, displacement ventilation). For displacement ventilation, the air change efficiency is 1 and for complete mixing 0.5. values form 0-0,05 represent short circuit ventilation (e.g. supplied air is exhausted immediately) and must be avoided

The local air change index is similar to the air exchange efficiency but is instead a local index that uses a point sensor as an input instead on the mean concentration. The air change efficiency is calculated using Equation 52:

$$e_p^a = \frac{\tau_n}{\theta_{age,local}} \tag{52}$$

where the nominal time constant (τ_n) is the ration of the volume of the room and the air flow rate and represents the mean age of air in the exhaust and $\theta_{age,local}$ is measured using a point sensor.

Calculating these indicators may involve CFD simulation or field measurements.

3.7.8 Air Distribution Index (ADI and ADI$_{new}$)

This zone indicator (Karimipanah et al. 2008) is a comprehensive measurement that evaluates ventilation performance in terms of pollutants removal and distribution of thermal energy (relevant to thermal comfort). To evaluate these ventilation performance factors, the PPD index (see section 3.3.2) and PD_{aq} (see section 3.7.1 and 3.7.2) are used. The ADI is calculated using Equation 53:

$$ADI = \sqrt{N_t \cdot N_v} \tag{53}$$

And

$$N_t = \frac{\varepsilon_t}{PPD} \qquad N_c = \frac{\varepsilon_v}{PD_{aq}}$$

where ε_t is effectiveness for heat removal and ε_v is ventilation effectiveness.

ADI is not suitable for non-uniform thermal environments (e.g. thermal stratification) because it is based on the PVM/PPD model. In such cases, the use of a different air distribution index ADI_{new} is suggested (Almesri et al. 2013). The ADI_{new} is calculated using Equation 54:

$$ADI_{new} = \left(1 - \frac{|S|}{3}\right) \cdot \varepsilon_t + \left(\frac{\tau_n}{\bar{\tau}_p}\right) \cdot \varepsilon_v \tag{54}$$

where τ_p is the local mean temperature, τ_n is the room constant depended on air change rates and S is acquired thought a multi node thermal sensation model. The first set of terms in this equation represents thermal comfort parameter and the later the air quality parameter.

Awbi (2017) investigates the capacity and implementation of these indicators using CFD simulation.

3.7.9 **Air Diffusion Performance Index (ADPI) [%]**

This indicator (Miller et al. 1970) is used to evaluate the performance of air terminal devices (in mixing ventilation and in cooling mode) in terms of thermal comfort. The EDT is based on the effective draught temperature (θ_{ed} or EDT) and combines the effects air temperature and air velocity. The effective draught temperature is measured at several points on grid in room. The ADPI expresses the points that satisfy the threshold requirement as a percentage of the total points. However, this indicator is neither a complete air quality indicator nor a complete thermal comfort indicator.

$$\theta_{ed} = (T_x - T_c) - 0{,}07(V_x - 30) \tag{55}$$

where T_x is local airstream dry bulb temperature [°C], T_c is average room temperature [°C] and V_c local air stream velocity [m.s^{-1}].

The ASHRAE Handbook: Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers) proposes an ADPI greater than 80 for office environment in cooling mode and suggests that ADPI is not used for heating conditions. ADPI of 100 % indicates perfect conditions. Measurement methods are specified in ASHRAE Standard 113.

3.8 Visual environment: Indoor lighting

Indoor lighting indicators help evaluate the indoor lighting conditions created typically by electrical lighting systems in terms of adequate amount of light (per task), effective distribution over space and uniformity. The fundamental metric involved in this type of measurements is the illuminance level.

3.8.1 **Illuminance levels (E_v, $E_{av,m}$, E_{av}) [lx] ***

Illuminance target values are a commonly prescribed lighting criterion. The goal is to provide sufficient illuminance according to task characteristics and observer characteristics such as age and sight (DiLaura et al. 2011 (IES The Lighting Handbook 10TH)).

Illuminance is the amount of "light" (luminous flux) incident on a surface. The IES The Lighting Handbook defines Illuminance as the "incident luminous flux density located at a point and oriented in a particular direction" (DiLaura et al. 2011). Vertical plane illuminance (at a point) is calculated using Equation 56:

$$E_v = \frac{d\Phi_{on}}{dA} \tag{56}$$

The illuminance ate a point can be measured using an illuminance meter. Recommended values are usually stated either in terms of maintained average illuminance over the task area/work plane ($\overline{E_m}$ or $E_{av,m}$) which represent a value under which the illuminance levels are not to fall or in terms of average illuminance ($\overline{\mathrm{E}}$ or E_{av}) which represents the average of illuminance over a surface. Illuminance criteria are usually accompanied by uniformity ratio criteria.

In the various standards and codes illuminance recommendations are typically accompanied by other lighting design criteria such as uniformity criteria, glare criteria and colour rendition criteria (see sections 3.8.3, 0 and 3.11.1). ISO 12464-1, EN 12193 and EN 1838 provide such lighting criterial for indoor spaces, for sport buildings and for emergency spaces respectively.

Besides recommendation based on the type of buildings, illuminance targets can be given in respect to the type of task (e.g. cognitive task, physical task), the task characteristics (sport situation, social situation), the age of the observer etc. Such recommendations can be found in the IES The Lighting Handbook (DiLaura et al. 2011).

3.8.2 Criterion Rating (CR) & Coefficient of variation (C_v)

These area indicators proposed by the IES The Lighting Handbook 10TH (DiLaura et al. 2011) are used to calculate the sufficiency of illuminance levels over an area in the case where the task location is unknown. These measures (Equations 57 and 58) might be applied in spaces that require use and layout flexibility (e.g. educational spaces). Alternatively, the maintained average illuminance and the average illuminance may be used (see section 3.8.1).

- The Criterion Rating (CR)

$$CR = \frac{Number\ of\ calculation\ or\ measurement\ points\ at\ or\ above\ the\ criterion}{Number\ of\ calculation\ or\ measurement\ points} \quad (57)$$

Values for this measure should not fall under 70%

- The coefficient of variation (Cv)

$$C_V = \frac{Standard\ deviation\ (\sigma)}{Mean\ (\mu)} \quad (58)$$

3.8.3 Illuminance Uniformity (U_O) *

This visual comfort indicator assesses the distribution of light (illuminance levels) for artificially lit environments (daylight-lit environments typically have a non-uniform light distribution except in the case of spaces lit by skylights). Generally, the illuminance uniformity is prescribed along with other criteria such as luminance uniformities and surface reflectance to address visual discomfort, strain and glare (DiLaura et al. 2011). Equations 59 expresses uniformity as the ratio of the minimum to average illuminance (measured on a surface) and is prescribed in situations where illuminance that is considerably lower than average has to be avoided.

$$U_{O,average} = \frac{E_{min}}{E_{avg}} \quad (59)$$

Equation 60 expresses uniformity as the ratio of the minimum to maximum illuminance and is prescribed in situations where too much variation in illuminance levels has to be avoided

$$U_{O,average} = \frac{E_{min}}{E_{max}} \quad (60)$$

Equation 61 expresses uniformity as the ratio of the average to maximum illuminance and is prescribed in situations where over-lighting has to be avoided

$$U_{O,max} = \frac{E_{avg}}{E_{max}} \tag{61}$$

ISO 12464-1 (2011) provides recommended values for Illuminance Uniformity per type of use and space.

3.9 Visual environment: Daylight performance

Daylight performance indicators, often referred to as daylight metrics, are used to evaluate the effectiveness with which the building uses daylight to support the occupant's activities. The measurements involve different aggregation methods of illuminance levels, measured over space and time, designed to answer questions such as: how much of the area is effectively illuminated by daylight and how much of the target period is covered. Daylight performance indicators are used to design façade systems and assess the need for daylight control systems (e.g. shades) and artificial lighting systems (and therefor energy consumption). Additionally, they are used to predict negative aspects of daylight performance such as unwelcome solar gains and discomfort glare.

3.9.1 **Daylight Factor (DF)**

This daylight performance indicator (Walsh 1951) is a widely used historical metric that expresses the ratio of the illuminance measured at a point inside, to the illuminance produced by an overcast sky, measured at a point outside. In EN 12665 (2016) this definition is given as the "ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded". The DF is calculated using Equation 63:

$$DF = \frac{E_{int}}{E_{kh,oc}} \tag{62}$$

where E_{int} is the illuminance [lx] at a point measured inside and $E_{kh,oc}$ is the illuminance [lx] measured outside.

This indicator cannot effectively assess daylight performance under clear and other sky conditions (except overcast). It is therefore more suitable for locations which often have an overcast sky.

The DF can be evaluated for minimum or average values that are achieved over a minimum required area. For example, the BREEAM rating scheme assigns up to 2 credits for 2% average DF for 80% of the surface in educational buildings, living rooms and kitchens and 3% average DF for 80% of the surface in patient care spaces.

3.9.2 **Daylight Autonomy (DA) [%]**

This long-term daylight performance indicator (Association Suisse des Electriciens 1989; Reinhart et al. 2001) is a widely used metric that calculates the percentage of time the illuminance level exceeds a predefined threshold (set for sufficient illuminance). This metric can be evaluated for individual points on a grid as well as for the whole of the grid (see sections 3.9.4 and 3.9.5). The DA is calculated using Equation 64:

$$DA = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \tag{63}$$

where wf_i is equal to 1 when the illuminance threshold is equal or exceeded (otherwise 0) and t are the operating hours.

Besides daylight performance assessment, this metric is typically used to assess the need for artificial lighting (see also sections 3.9.3 and 3.9.11).

3.9.3 **Continuous Daylight Autonomy (DA_{CON} or cDA) [%]**

This long-term daylight performance indicator (Rogers 2006) calculates the percentage of time the daylight illuminance levels exceeds a predefined threshold. The DA_{CON} is a modified version of the Daylight Autonomy (DA) that instead of using a 1 or 0 weighting coefficient for when the threshold is exceeded or not, the coefficient will cover all the in-between values as well. For example, 0,5 is used if the illuminance levels reach half the threshold. It is therefore suitable to be used in conditions where daylight is being supplemented by electric lighting. The DA_{CON} is calculated using Equation 65:

$$DA_{CON} = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1] \tag{64}$$

where wf_i is equal to 1 when the illuminance threshold is equal or exceeded otherwise:

$$wf_i = \frac{E_{Daylight}}{E_{threshold}}$$

3.9.4 **Zonal Daylight Autonomy (zDA) [%]**

This long-term daylight performance indicator (included in the IES The Lighting Handbook 10TH, DiLaura et al. 2011) measures daylight sufficiency across a zone using a single value. Sufficiency in this case means that the illuminance levels exceed a predefined threshold (typically 300 lx). The measurement is carried out by sensors across the zone. The hours of exceedance in every sensor are summed and then the sum of all the sensors is divided by the number of sensors and the total hours of measurement as shown in Equation 66:

$$zDA = \frac{\sum_{k=1}^{n} (\sum_i wf_i \cdot t_i)_k}{n \cdot \sum_i t_i} \tag{65}$$

where wf_i is equal to 1 when the illuminance threshold is equal or exceeded (otherwise 0), “n” is the number of sensors and t are the operating hours.

3.9.5 **Spatial Daylight Autonomy (sDA) [%]**

This long-term daylight performance indicator, proposed by the Illuminating Engineering Society IES (2012), calculates the percentage of area where the illuminance levels exceeds a threshold (typically 300lx) for a minimum percentage of the analysis time (typically 50%). The indicator depending on the criteria is stated as such: e.g. $sDA_{300/50\%}$. The sDA is calculated using Equation 67:

$$sDA_{x/y\%} = \frac{\sum_i (wf_i \cdot DA)}{\sum_i p_i} \quad (66)$$

where DA is the Daylight Autonomy at a certain grid point, wf_i is equal to 1 when the DA threshold is equal or exceeded (otherwise 0) and p_i is a point on the grid.

The LEED certification system assigns 2 points for 55% and 3 for 75% for most spaces and 1 point for 75% and 2 for 90% for healthcare.

3.9.6 **Temporal Daylight Autonomy (tDA) [%]**

This long-term daylight performance indicator (included in the IES The Lighting Handbook 10^{TH}, DiLaura et al. 2011) calculates the fraction of time the illuminance levels measured at grid points over an area reach a set value (typically 300lx) for over 75% of that area.

3.9.7 **Annual Sun Exposure (ASE) [%]**

This long-term daylight performance metric (included in the IES The Lighting Handbook 10^{TH}, DiLaura et al. 2011) calculates the percentage of floor area that receives excessive direct sunlight (at least 1000 lx) that may cause visual discomfort or excessive solar gains. This indicator is usually expressed as $ASE_{1000/250}$ (for 1000lx over 250 occupied hours per year).

The LEED certification system assigns 1 point for 75% and 2 for 90%.

3.9.8 **Useful Daylight Illuminance (UDI) [%]**

This long-term daylight performance indicator (Nabil et al. 2006) calculates the percentage of operating hours when the illuminance levels fall within certain limits (categories). The categories are: $UDI_{overlit}$ for E_v>2000lx, UDI_{useful} for E_v=100lx-2000lx and $UDI_{underlit}$ for E_v<100lx. The UDI is calculated using Equation 68:

$$UDI = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \quad (67)$$

where wf_i is either 0 or 1 depending on if the measurement falls into the limits of a category and t the operating hours.

3.9.9 **Direct sunlight hours [h]**

This long-term daylight performance indicator, included in the IES The Lighting Handbook 10^{TH}, (DiLaura et al. 2011), sums the hours when a point receives direct sunlight. It can be used to design and evaluate shading strategies.

3.9.10 **Frequency of Visual Comfort (FVC) [%]**

This long-term daylight performance indicator (Sicurella et al. 2012) calculates the percentage of time when daylight alone offers sufficient illuminance. The FVC is calculated using Equation 69:

$$FVC = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1] \tag{68}$$

where wf_i is 1 if illuminance levels are within limit (otherwise 0).

3.9.11 **Lighting Energy Numeric Indicator (LENI) [kWh.m^{-2}.a^{-1}] ***

Daylight performance has serious implications on the overall energy efficiency of a building as it is affected by the energy consumption of the lighting system. For this reason, EN 15193-1 (2017) defines "methods for estimating or measuring the amount of energy required or used for lighting in buildings" expressed in the Lighting Energy Numeric Indicator (LENI). This measurement concerns buildings where the needs of rooms are serviced completely of partly by daylight. The LENI can be calculated for a building or for a zone ($LENI_{sub}$) and can be used to benchmark and assess the energy performance of existing and new buildings. Additionally, EN 12665 (2016) states that "the LENI can be used to make direct comparisons of the lighting energy used in buildings that have similar functions but are of different size and configuration".

3.10 Visual environment: Glare

Glare indicators predict the occupant's acceptability to different levels of discomfort (or disability) glare. EN 12665 (2016) defines glare as the "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts". As suggested by this definition the measurement depends mostly on the fundamental metric of luminance. However, besides the luminance levels and the luminance contrast, glare is influenced by the size of the glare sources and the position of the sources in the field of view, expressed in most indicators using the Guth position index (DiLaura et al. 2011). Different indicators are used to evaluate glare caused by electric lighting and daylight.

3.10.1 **Luminance levels (L) [cd.m^{-2}]**

The Luminance is a fundamental metric of the surface brightness used alone or as part of other indicators to predict discomfort glare. It is the density of luminous intensity per unit of area calculated using Equation 70:

$$L = \frac{dE}{d\omega} \cos\theta \tag{69}$$

where E is the illuminance produced by the surface at a distant point [lx], ω is the solid angle the surfaces subtends at the point.

Surfaces with too much luminance (two much brightness) will eventually cause discomfort glare or even disability glare. However, other factors affect the phenomenon as well, such as the difference between the luminance levels in the scene (e.g. between the light source and the background) and the position of the high luminance surfaces in the field of view (DiLaura et al. 2011).

3.10.2 **British Glare Index (BGI)**

This visual comfort indicator (Petherbridge et al. 1950) is used to assess discomfort glare and is applicable for small sources (therefore electric lighting rather than e.g. windows). The BGI is calculated using Equation 71:

$$BGI = 10log_{10}0{,}478\sum_{i=1}^{n}\frac{L_s^{1,6}\omega_s^{0,8}}{L_b P^{1,6}} \tag{70}$$

where L_b is luminance of the field of view (but not the luminaires) [$cd.m^{-2}$], L is the luminance of the glare source in the direction of the observer[$cd.m^{-2}$], P is the Guth position index, ω is the solid angle [sr] and "n" the number of glare sources.

A value of 30 indicates intolerable glare (Boyce et al. 2003).

3.10.3 **CIE's glare index (CGI)**

This visual comfort indicator (Einhorn 1979) is used to assess discomfort glare and is applicable for small sources (therefore electric lighting rather than e.g. windows). The CGI accounts for the illuminance levels in the field as well as the luminance levels used by other indices. The CGI is calculated using Equation 72:

$$CGI = 8log_{10}2\frac{[1+(E_d/500)]}{E_d+E_i}\sum_{i=1}^{n}\frac{L_s^2\omega_s}{P^2} \tag{71}$$

where L_s is the luminance of the glare source in the direction of the observer [$cd.m^{-2}$], E_d: is the direct vertical illuminance at the eye due to all sources [lx], E_d: is the direct vertical illuminance at the eye due to all sources [lx], E_i: is the indirect illuminance at the eye ($E_i = \pi L_b$) [lx], P is the Guth position index, ω is the solid angle [sr] and "n" the number of glare sources.

Table 5 defines tolerance level for various glare indices.

Table 5 Discomfort glare psychometric scale derived from psychophysical experiments for different indicators (source: Jakubiec et al. 2012)

	imperceptible	perceptible	disturbing	intolerable
DGI	<18	18-24	24-31	>31
UGR	<13	13-22	22-28	>28
CGI	<13	13-22	22-28	>28
VCP	80-100	60-80	40-60	<40
DGP	<0,3	0,3-0,35	0,35-0,4	>0,45

3.10.4 **CIE's Unified Glare Rating (UGR) ***

This visual comfort indicator, proposed by the International Commission Of Illumination CIE (1995), assesses discomfort glare for electric lighting systems. The UGR is a widely used indicator and is included in ISO literature (see **Error! Reference source not found.**). This indicator is calculated using Equation 73:

$$UGR = 8log_{10} \frac{0,25}{L_b} \sum_{i=1}^{n} \frac{L_i^2 \omega_i}{P^2} \tag{72}$$

where L_b is luminance of the field of view (but not the luminaires) [cd.m^{-2}], L is the luminance of the luminaire in the direction of the observer [cd.m^{-2}], P is the Guth position index and ω is the solid angle [sr].

Values range from 5 to 30. Table 5 defines tolerance level for various glare indices.

3.10.5 **Visual Comfort Probability (VCP)**

This visual comfort indicator (Guth 1963) assesses discomfort glare for small sources (therefore electric lighting rather than e.g. windows) and calculates the percentage of people that accepts the lighting environment as comfortable due to absence of glare.

A numerical approximation proposed by the Illuminating Engineering Society of North America (IESNA) is calculated using Equation 74:

$$VPC = 279 - 110(log_{10}DGR) + C \tag{73}$$

where DGR is Discomfort Glare Rating (see below) and c is 0 if DGR is between 55 and 200 or:

$$C = 350(log_{10}DGR - 2,08)^5$$

The Discomfort Glare Rating (DGR) is the Glare-sensation index (M) of every possible glare source calculated using Equation 75:

$$DGR = \left(\sum_{i=1}^{n} M_i\right)^{n^{-0,0914}} \tag{74}$$

and the Glare-sensation index (M) using Equation 76:

$$M = \frac{0,5L_{s,i}}{P \cdot L_{vf}^{0,44}} \left(20,4\omega_{s,i} + 1,52\omega_{s,i}^{0,2} + 0,075\right) \tag{75}$$

where ω is the solid angle [sr], P is the Guth position index and L_s is the luminance of the glare source [cd.m^{-2}].

To evaluate this index the borderline between comfort and discomfort (BCD) threshold criterion must be calculated using Equation 77 (Luckiesh et al., 1949):

$$BCD = 185{,}67 L_{s,i}^{0{,}44} (\omega_{s,i}^{-0{,}21} - 1{,}28) \qquad (76)$$

where ω is the solid angle [sr] and L_s is the luminance of the glare source [cd.m^{-2}].

Table 5 defines tolerance level for various glare indices.

3.10.6 **J-index**

This visual comfort indicator (Meyer et al. 1993) calculates the degree of visual acuity in non-optimal lighting conditions (insufficient or excessive illuminance levels) as a fraction of best possible acuity. In EN 12665 (2016) visual acuity is defined as the "capacity for seeing distinctly fine details that have very small angular separation". The acuity may be influenced negatively by the presence of glare or by very low lighting as indicated by the contrast's values in the scene. This indicator that is sometimes considered a glare index, can be used to evaluate conditions in working environments (e.g. computer rooms). The J-index is calculated using Equation 62:

$$J = \frac{(A_{max} - A)}{A_{max}} \qquad (77)$$

and

$$A = A_{max} \cdot r_1(C_1) \cdot r_2(C_2) \cdot r_3(E_p)$$

where A_{max} is the optimal possible visual acuity of the person and is derived through a visual test , A is the actual visual acuity, C_1 is the target/background contrast, C_2 is the back/round surrounding contrast, E_p is the pupil illuminance and r is the relative influence on the acuity. A value of one (J=1) represents best possible conditions.

3.10.7 **Daylight Glare Index (DGI and DGI$_N$) for daylight and large sources**

This visual comfort indicator (Chauvel 1982) assesses daylight discomfort glare for large sources such as windows (but is not suitable for evaluating direct sunlight as a glare source). The DGI is calculated using Equation 78:

$$DGI = 10 log_{10} 0{,}478 \sum_{i=1}^{n} \frac{L_{s,i}^{1{,}6} \omega_{s,i}^{0{,}8}}{L_b + 0{,}07 \omega^{0{,}5} \cdot L_{win} \cdot P_i^{1{,}6}} \qquad (78)$$

where L_b is luminance of the field of view (but not the luminaires) [cd.m^{-2}], L is the luminance of the luminaire in the direction of the observer [cd.m^{-2}], L_{win} is the window luminance [cd.m^{-2}], P is the Guth position index, ω is the solid angle [sr] and "n" is the number of light/glare sources.

The New Discomfort Glare Index (Nazzal 2005) tackles some of the limitation of the DGI (e.g. account for direct sunlight as a source of glare). The DGI$_N$ is calculated using Equation 66:

$$DGI_N = 8 log_{10} \left[0{,}25 \frac{\sum_{i=1}^{n} L_{exterior,i}^2 \cdot \Omega_{pN}}{L_{adaptation} + 0{,}07 \left[\sum_{i=1}^{n} \left(\omega_{N,i} \cdot L_{window,i}^2 \right) \right]^{0{,}5}} \right] \qquad (79)$$

where $L_{exterior}$ is the exterior illuminance (direct sunlight, diffused sky-light and ground reflected light), $L_{adaptation}$ is the adaptation luminance (soundings and internal surfaces), L_{window} is the window luminance (average for all window surfaces) and Ω_{pN} is a corrected solid angle [sr].

Table 5 defines tolerance level for various glare indices. In a review of daylight glare indices Belia et al. (2008) discusses issues around the applicability and capacity of the indices.

3.10.8 **Discomfort Glare Probability (DGP) for daylight and large sources**

This visual comfort indicator (Wienold et al. 2006) assesses daylight discomfort glare for large sources (such as windows) based on vertical illuminance at eye level produced by the source. The DGP is calculated using Equation 80:

$$DGP = 5{,}87 \cdot 10^{-5} E_v + 0{,}0918 \cdot log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1{,}87} \cdot P_i^2}\right)\right] + 0{,}16 \qquad (80)$$

where E_v is the vertical illuminance at eye level [lx], L is the luminance of the glare source [cd.m^{-2}], ω is the solid angle [sr] and "n" is the number of light/glare sources.

Because this index is computationally complicated, several simplified versions where developed such as the one in Equation 81 (Wienold 2007):

$$DGP = 6{,}22 \cdot 10^{-5} E_v + 0{,}185 \qquad (81)$$

where E_v is the vertical illuminance at eye level [lx].

Table 5 defines tolerance level for various glare indices. In a review of daylight glare indices Belia et al. (2008) discusses issues around the applicability and capacity of the indices.

3.10.9 **Predicted Glare Sensation Vote (PGSV) for daylight and large sources**

This short term visual comfort indicator (Iwata et al. 1992) assesses daylight discomfort glare for large sources such as windows and is used to calculate the Glare Sensation Vote (GSV). This index uses an average window luminance instead of sky and ground luminance levels. The PGSV is calculated using Equation 66:

$$PGSV = 3{,}2 log_{10} L_{wp-} 0{,}64 log_{10} \omega_s + (0{,}79 log_{10} \omega_s - 0{,}61) log_{10} L_b - 8{,}2 \qquad (82)$$

$$L_b = \left(\frac{\frac{E_v}{\pi} - L_{wp}\Phi_W}{1 - \Phi_W}\right) \qquad (83)$$

where L_b (Equation 83) is luminance of the field of view (but not the luminaires) [cd.m^{-2}], L_{wp} is the luminance of the window plane [cd.m^{-2}], Φ_W is a configuration factor of the window, Ev is the vertical illuminance in the eye level, ω is the solid angle [sr] and "n" is the number of light/glare sources.

In a review of daylight glare indices Belia et al. (2008) discusses issues around the applicability and capacity of the indices.

3.11 Visual environment: Colour (quality of light)

Colour indices evaluate the ability of artificial light sources to render colour, in terms of rendition faithfulness (benchmarked against a reference light), gamut rendered, occupant's preferences etc. Colour rendition (or "quality of light" as it is sometimes referred to) is especially relevant for some spaces such as printing shops and medical examining rooms and therefore criteria for this requirement are included in relevant standards grouped with other criteria on the visual environment to support activities per task or space (e.g. ISO 12464-1:2011, see **Error! Reference source not found.**).

3.11.1 **CIE Colour Rendering Index (CRI or R_a) ***

This colour rendition indicator (CIE 1965) assesses the capacity of a light source to render the colour of objects in terms of rendition faithfulness. This index is prescribed along with other Visual environment criteria in the popular lighting standard ISO 12464-1:2011. The calculation is based on a reference light source (test lamp) and 8 colour test samples (provided by the CIE). The samples are exposed to both the reference light and the evaluated light source. The CRI is the mean resultant colour shift between the two sources.

The Colour Quality Scale (CQS) presented in section 3.11.2 can be seen as an updated version of the CRI.

The CRI ranges from 0 to 100 (100 representing complete colour faithfulness). A value above 90 is considered excellent rendering capacity. In IES The Lighting Handbook 10TH various lamps are evaluated by different colour indices (DiLaura et al. 2011).

3.11.2 **Colour Quality Scale (CQS or NIST-CRI)**

This colour rendition indicator (Davis et al. 2005) assesses the capacity of a light source to render the colour of objects in terms of rendition faithfulness. The CQS is calculated similarly to the CRI, however, it is designed to reflect new knowledge on colour science (e.g. uses a set of test samples). However, the CQS and CRI correlate highly.

The CQS ranges from 0 to 100.

3.11.3 **Flattery index (R_f)**

This colour rendition indicator (Judd 1967) assesses the capacity of a light source to render the colour of objects in terms of human preferences. The calculation is based on the tested light source's "desirable" rendition of 14 test colours each weighted differently (e.g. the Caucasian skin complexion receives the heaviest weighting).

The Flattery Index ranges from 0 to 100 (complete colour faithfulness).

3.11.4 **Colour Preference Index (CPI)**

This colour rendition indicator (Thornton 1974) assesses the capacity of a light source to render colour in terms of human preferences. This index is similar to the Flattery Index (R_f), however, it uses 8 instead of 14 test colours.

The CPI ranges from 0 to 156. In **Error! Reference source not found.** various lamps are evaluated by different colour indices.

3.11.5 **Colour Discrimination Index (CDI)**

This colour rendition indicator (Thornton 1972) assesses the capacity of a light source to render the colour in terms of the width of the spectrum rendered (gamut) by the tested light. The results of the tested light are normalised using the performance of the CIE illuminant C (theoretical source).

The CDI ranges from 0 to 100.

3.11.6 **Cone Surface Area (CSA)**

This colour rendition indicator (Fotios 1997) assesses the capacity of a light source to render the colour in terms of the of the width of the spectrum rendered (gamut) by the tested light. The result is calculated based on a geometrical method using a cone, whose base represents the gamut (in respect to CIE issued colour diagram) and height the chromaticity (expressed by hue and saturation).

The area of the cone represents the colour rendition capacity of the light source.

3.11.7 **Colour Rendering Capacity (CRC)**

This colour rendition indicator (Xu 1993) assesses the capacity of a light source to render the colour in terms of the width of the spectrum rendered (gamut) by the tested light. The calculation is based on the number of colours a light source can theoretically render. Similar to the cone surface area (CSA) the CRC expresses the results using geometric method, where the volume of the colour solid produced by a CIELUV colour space represents the colour rendition capacity of the light source.

The index ranges from 0,0 to 1,0.

3.11.8 **Pointer's Index**

This colour rendition indicator (Pointer 1986) assesses the capacity of a light source to render the colour of objects benchmarked against the performance against a reference light (determined by the user). The calculation is based on a colour appearance model that characterises colour according to condition, perception and cognition using parameters like lightness, saturation, hue.

The Pointer's Index ranges from 0 to 100.

3.11.9 **Feeling of Contrast Index (FCI)**

This colour rendition indicator (Hashimoto et al. 2007) assesses the capacity of a light source to render saturated colour in terms of the range of the spectrum rendered (gamut) by the light tested. The results are compared to the performance of a reference light source over 4 saturated colours.

This index can be used in combination to the Colour Rendition Index (CRI).

3.12 Acoustic environment: Room acoustics (perform. spaces)

Room acoustics is a performance sub-domain concerned with ensuring suitable and effective sound propagation to support the activities of a space. Performance indicators in this sub-domain, often referred to as "acoustic measures" or "acoustic quantities", help connect the listener's subjective impression of the acoustic conditions in a given space to the objective properties of that space's sound field (see Table 6). Subsequently the properties of the sound field can be influenced in the desirable direction by adjusting the architectural features of the space.

The acoustic attributes of a space (how the space "sounds") are investigated through the room's "impulse response signal". In unoccupied rooms, a room's impulse response is typically measured (recorded) by introducing a short sound signal and then recording the sound energy as it decays due to being absorbed by the space boundaries and other elements in the space. The recording is curried out using non-directional and/or directional microphones placed typically at the receiver's position. The first part of this recording (typically from 0 to 10ms) is considered to be sound energy reaching the receiver directly from the sound source, whilst the latter parts are considered to be sound energy reaching the receiver after being reflected from elements in the space such as the walls, the ceiling and the floor. Therefore, the recorded impulse response signal may be divided into three components: the direct, early and late components of the room's impulse response (or alternatively direct sound, early reflections and late reflections).

The sound energy in each component is recorded as a function of the sound pressure level, the frequency (sound energy or decay rates averaged over frequency bands) and angle of incidence. Objective acoustic measures (room acoustic indicators) use this information to correlate the listener's subjective impression to the properties of the sound field as shown in Table 6.

The measurements are performed either directly in the field or using simulation programs. Field measurements the can be performed in occupied or unoccupied state (no audience), however, in the case of some indicators, such as the reverberation time (see section 0), measuring an occupied hall is more meaningful (Beranek 2003). This is because, the audience absorbs much of the sound energy, affecting thus the properties of the sound field and the measurement itself. ISO 3382-1 (2009) provides information on the measurement of some important room acoustic indicators, including information on experimental setups (appropriate source signals, microphone types and measurement positioning etc.).

In the case of music auditoriums and other performance spaces, deciding on the appropriate target values (performance criteria) for acoustic indicators is not a straight forward process. It may depend on multiple factors such as the music type and the hall characteristics as well as factors that are still not fully understood.

Beranek (2004), a scientist with significant contribution in the field, explored this question in his book Concert Halls and Opera Houses: Music, Acoustics, and Architecture, where he published a ranking of 100 concert halls and opera houses. The ranking is based on the opinions of music conductors and music critics and is accompanied by technical drawings and photographs of the halls as well as measurements of their acoustic attributes using some of the indicators discussed in this chapter. The ranking shows that not all of these indicators have the same capacity to predict the subjective response to the acoustic conditions. In a paper discussing this ranking, Beranek (2003) states that "the quantities that correlate best with the subjective rank orderings are BQI, EDT_{MID}, G_{125}, SDI and ITDG, in that order".

Table 6 Objective acoustic measures and the subjective acoustic attributes they measure

Indicator name (objective acoustic measure or acoustic quantity)	subjective listener's aspect (or acoustic attribute of the hall)
Reverberation Time (T)	Liveliness/Fullness/Clarity
Early Decay Time (EDT)	Perceived Reverberation
Brilliance (Br)	Increased Timbre (Sound colouration)
Bass-Ratio (BR) & Treble Ratio (TR)	warmth/Timbre
Timbre Ratio (TR1)	Timbre (Sound colouration)
Clarity measures (C_{50} and C_{80})	Definition/Clarity/Transparency/Speech intelligibility
Definition or Deutlichkeit (D50)	Definition/Clarity/Speech intelligibility
Center time (t_s)	Definition/Clarity/Speech intelligibility
Echo criterion (EK_{speech}, EK_{music})	Echoes/clarity
Sound Colouration Measures (KT, KH)	Change of Timbre (sound colouration)
Sound strength (G and G_{mid}, G_{low}, G_{125})	Subjective loudness/Bass loudness
Stage support ST (ST_{early}, ST_{late})	Performer support
Reverberance measure (H)	Reverberation/liveliness/Spatial impression
Initial Time Delay Gap (ITDG)	Intimacy with sound source
Direct sound measure (C7) [dB]	nearness and directive (to the sound source)
Early and Late lateral energy measures (J_{LF} , L_j)	Apparent Source With (ASW)/Listeners Envelopment (LEV)
Lateral hall gain (LG or GLL)	Listeners Envelopment (LEV)
Spatial Impression Measure (R)	Listeners Envelopment (LEV)
Inter-Aural Cross Correlation (IACC)	Apparent Source With (ASW)/Listeners Envelopment (LEV)
Binaural Quality Index (BQI)	Apparent Source With (ASW)
Listeners envelopment (LEV_{calc})	Listeners Envelopment (LEV)

3.12.1 **Reverberation time (T) [s] ***

The reverberation time (also known as RT) is perhaps the most prescribed room acoustics indicator used as an objective measure of the subjective listeners's aspects “liveness”, “fullness of sound” and “clarity”. The measure is relevant both in the case of speech and music. Generally, lower reverberation time is associated with “clarity” (and therefore more relevant to speech) and higher reverberation time is associated with “liveliness” (and therefore more relevant to music).

In ISO 3382-1 (2009) the Reverberation Time (T_{60} or RT_{60}) is defined as “the duration required for the space-average sound energy density in an enclosure to decrease by 60dB after the source emission has stopped”. Such a measurement is sometimes difficult to curry out therefore T_{30} and T_{20} are used instead. In this case, the time is measured over a decay of 30dB and 20dB respectively and then extrapolated to a 60dB decay.

ISO 3382-1 (2009, p. 5) states that “for reverberation time measurements, it is important that the measurement positions sample the entire space”. Depending on the space characteristics (materials of boundary surfaces, suspended elements, room geometry etc.) the Reverberation Time in different positions may vary significantly and therefor instead of evaluating an average reverberation time, the different reverberation times should be considered separately.

Wallace Clement Sabine (1922) introduced the first reverberation time equation (Equation 84):

$$T = 0{,}163 \frac{V}{A_{tot} + 4mV} \tag{84}$$

$$A_{tot} = \sum_{i=i}^{n} S_i \cdot a_i \tag{85}$$

where V is the room volume [m^3], A_{tot} is the total equivalent absorption area [m^2], S_i is the room surface area [m^2], a_i is the room surface absorption coefficient.

The term 4mV (m: coefficient that depends on the relative humidity, V: volume of air of are [m^3]) accounts for absorption due to air volume and can be ignored in the case of small rooms. The Sabine equation is most accurate in a room where the average absorption coefficient is less than 0.25. The Eyring-Norris equation (1930) (Equation 86) yields accurate results for rooms with average absorption coefficient less than 0.25 (i.e. recording rooms):

$$T = 0{,}161 \frac{V}{-S \cdot ln\left(1 - a_{average}\right) + 4mV} \tag{86}$$

$$a_{average} = \frac{\sum_{i=i}^{n} S_i \cdot a_i}{\sum_{i=i}^{n} S_i} \tag{87}$$

where V room volume [m^3], A_{tot} is the total equivalent absorption area [m^2], S is the room total surface area [m^2] and $a_{average}$ is the average absorption coefficient.

Recommended values for reverberation time are typically given in relation to the activities taking place in a rooms and the room's volume (*ÖNORM B8115-3 2006*). Additionally, considering that the reverberation time is frequency depended (different reverberation times in different frequencies), the tolerance for the reverberation time can also be evaluated as frequency depended (*ÖNORM B8115-3 2006*).

3.12.2 **Early Decay Time (EDT) [s] ***

This room acoustics indicator measures perceived reverberance and is used to evaluate the subjective listener's aspect "clarity" that refers to the degree of perception of detail in a signal. The EDT is defined as the time required for sound pressure level to decay 10dB after the signal is switched off (and then extrapolated to a 60dB decay, similar to T_{20} and T_{30}). The early decay time, called also early reverberation (due to early reflections), defines largely our impression of the whole reverberation. This is because, during running sound the latter parts of the reverberation energy are masked by freshly produced sound (Gade 2007). According to ISO 3382-1 (2009, p.15) "both the EDT and T should be calculated. EDT is subjectively more important and related to perceived reverberance, while T is related to the physical properties of the auditorium". In terms of speech perception, a shorter EDT means increased signal clarity.

Measurements should take account of the fact that EDT times defer in different position of a room (more than T_{60}). Similar to T_{60} and other acoustic indicators, recommended EDT are depended on the type of music. Furthermore, the EDT is less affected by occupancy that the T, making the measurement more feasible. Benarek (2003) found that the $EDT_{MID,UNOCCUPIED}$ correlates better than the $T_{OCCUPIED}$ with the subjective ranking of concert hall (except in the presence of highly upholstered seats). However, he notes that in the case of pauses in the music (e.g. stop chords) the reverberation time remains relevant.

ISO 3382-1 (2009) defines the measurement of this indicator as well as typical range (1,0s; 3,0s) and just noticeable differences (JND).

3.12.3 **Brilliance (Br)**

This room acoustics indicator (Beranek 1962) is an objective measure of the subjective listener's aspect "Brilliance" used to describe bright and clear sound. This aspect is connected to increased energy in the high frequency part of the spectrum during the first part of the reverberation event. Therefore, this indicator calculates the logarithmic ratio of high frequency EDT to mid frequency EDT (Reverberance ratio over frequency bands) using Equation 88:

$$Br = \frac{EDT_{2000}}{EDT_{Mid}} = \frac{EDT_{2000}}{EDT_{500} + EDT_{1000}} \tag{88}$$

Brilliance can be also calculated for EDT_{4000}.

3.12.4 **Bass-Ratio (BR) and Treble Ratio (TR)**

This acoustics indicator (Beranek 1962) is an objective measure of the subjective listener's aspect often described as 'warmth' that refers to a certain liveliness of the bass (low frequencies) and fullness in tone. Warmth is attributed to longer reverberation times at low frequencies. Therefore, this measure is calculated as the logarithmic ratio between the reverberation times of low frequency bands and middle frequency bands using Equation 89:

$$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}} \tag{89}$$

Likewise, the Treble Ratio (TR) is calculated using Equation 90:

$$TR = \frac{T_{2000} + T_{4000}}{T_{500} + T_{1000}} \quad (90)$$

An alternative measure for "warmth" is the Bass Strength (G_{125}) (see section 3.12.13) that is also found to correlate better to the subjective ranking of sound quality in concert halls (Beranek 2003).

3.12.5 **Timbre Ratio (TR1)**

This room acoustics indicator (Schmidt 1979) is an objective measure of the subjective listener's aspect often described as "timbre". Timbre is the acoustic attribute that makes the sound signal perceived as unique and distinguishable (e.g. sound from different musical instrument). This quality is also referred to as "sound colour". It is calculated as the ratio between the reverberation time averaged at mid frequencies to the reverberation time averaged at low frequencies using Equation 91:

$$TR1 = \frac{T_{2000} + T_{4000}}{T_{125} + T_{250}} \quad (91)$$

Similar to BR and TR if the equation yields a value greater than one, the room impulse response indicates higher reverberation time in the mid frequency bands rather than the low frequency bands and therefor "more timbre" is perceived.

3.12.6 **Initial Time Delay Gap (ITDG) [ms]**

This room acoustics indicator (Davis 1979) is an objective measure of the subjective listener's aspect often described as "intimacy". The sense of intimacy is influenced by the listener's perception of the size of the hall and the listener's sense of being close to the sound source. The indicator measures the delay between sound reaching the listener directly form the source (direct sound) and sound reaching the listener after being reflected. The ITDG can be derived using the architectural drawing to calculate the distance the signal travels. This indicator becomes relevant in larger rooms where intimacy is de facto more difficult to achieve.

In a subjective ranking of concert halls published by Benarek (2003) the ITDG was found to correlate well with the overall subjective acoustical quality of a hall, whilst the top ranked halls have an ITDG of about 20ms and the lowest rank halls have an ITDG of about 40ms.

3.12.7 **Direct sound measure (C_7) [dB]**

This room acoustics indicator (Ahnert et al. 1980) is an objective measure of the subjective listener's aspects of 'nearness' and 'directness' of the sound sources. The direct sound measure C7 should not fall below a range from -10 to -15 dB. The C7 is calculated using Equation 92:

$$C_7 = 10log\left(\frac{E_{0\ldots7ms}}{E_\infty - E_{0\ldots7ms}}\right) \quad (92)$$

Where E_7 is the sound energy (squared and integrated sound pressure) reaching the listener between 0 to 7ms (considered to be direct sound) [dB] and E_∞ is the total energy of the impulse response [dB].

3.12.8 **Clarity measures (C_{50}, C_{80}) [dB] ***

This acoustics indicator (Thiele 1953, Abdel Alim 1973, Ahnert 1980) is an objective measure of the subjective listener's aspect "clarity" that refers to the degree of perception of detail in a signal. It is defined in the logarithmic ratio between the sound energy (squared and integrated sound pressure) coming from early reflections to the sound energy of late reflections (also referred to as early and late component of the room's impulse response). More energy in the early reflections is associated to the perception of clarity. The boundary between early and late reflections is set at 50ms for speech and 80ms for music as shown in Equations 93 and 94.

Clarity Measure for speech:

$$C_{50} = 10log\left(\frac{E_{0\ldots50ms}}{E_{50ms\ldots\infty}}\right) \qquad (93)$$

Clarity Measure for music:

$$C_{80} = 10log\left(\frac{E_{0\ldots80ms}}{E_{80ms\ldots\infty}}\right) \qquad (94)$$

With exponential decay the Clarity measures can be also expressed as a function of T (reverberation time) as shown in Equation 95 (Gade 2007):

$$C_{exp} = 10log\left[exp\left(\frac{1{,}104}{T}\right) - 1\right] \qquad (95)$$

Higher values offer higher clarity. Clarity can also be evaluated per frequency bands. The mid frequencies bands are particularly relevant to the perception of speech.

ISO 3382-1 (2009) defines the measurement of this indicator as well as typical range (-5 dB; +5dB for C_{80}) and just noticeable differences (JND).

3.12.9 **Definition or Deutlichkeit (D_{50}) [%] ***

This room acoustics indicator (Thiele 1953) is an objective measure of "speech intelligibility" (or signal "clarity") similar to C_{50}. In contrast to the clarity measure (C_{50}) the D_{50} expresses the early to total sound energy (squared and integrated sound pressure) ratio of the room's impulse response, rather than the early to late sound energy ratio (C_{50}), as shown in Equation 96:

$$D_{50} = \frac{E_{0\ldots50ms}}{E_{0\ldots50ms} + E_{50ms\ldots\infty}} = \frac{E_{0\ldots50ms}}{E_{\infty}} \qquad (96)$$

The relation between C_{50} and D_{50} is shown in Equation 97:

$$C_{50} = 10log\left(\frac{D_{50}}{1 - D_{50}}\right) \qquad (97)$$

where $E_{0\ldots50ms}$ is the sound energy from 0 to 50ms [dB] and $E_{50ms\ldots\infty}$ is the energy after 50ms [dB].

ISO 3382-1 (2009) defines the measurement of this indicator as well as typical range (0,3; 0,7) and just noticeable differences (JND).

3.12.10 Centre time (T_s) [ms] *

This room acoustics indicator (Kürer 1971) is an objective measure for "speech intelligibility" and "music transparency" (the latter being a term used instead of "clarity" in the case of music) similar to other clarity measures like C_{50} and C_{80} (see section 3.12.8). It is calculated as the time of the centre of gravity of the squared impulse response as shown in Equation 98:

$$T_s = \frac{\int_0^\infty t \cdot p^2(t)dt}{\int_0^\infty p^2(t)dt} \tag{98}$$

An analytical correlation between C80 and t_s is shown in Equation 99 (Reichardt et al. 1975):

$$T_s = 114 - 10{,}53 \cdot C_{80} \tag{99}$$

Lower values of t_s are expected to yield good speech intelligibility (or high music transparency). ISO 3382-1 (2009) provides information on the measurement of this indicator as well as typical range (60 ms; 260 ms) and just noticeable differences (JND).

3.12.11 Echo criterion (EK_{speech}, EK_{music})

This room acoustics indicator (Dietsch et al. 1986) is used to predict distortions due to the perception of echo inside a room. First the build-up function of the centre time is calculated. Then the difference quotient must be calculated as $\Delta t_s / \Delta t$ (with different n, Δt and band width for music) and be compared with the critical difference quotient (that is also depended on whether the signal is music or speech). If a certain value is exceeded, then echoes are expected to be perceived. The Echo criterion is calculated using Equations 100:

$$EK_{speech/music} = \frac{\Delta t_s(\tau)}{\Delta t_E}\ , \quad t_s(\tau) = \frac{\int_0^\tau t \cdot |p(t)|^n dt}{\int_0^\infty |p(t)|^2 dt} \tag{100}$$

where "n" is 0,67 for speech and 1 for music and Δt_E is 9 [ms] for speech and 14 [ms] for music.

3.12.12 Sound colouration measures (KT, KH) [dB]

This room acoustics indicator (Schmidt 1979) is an objective measure of the subjective listener's aspect "spectral sound colouration". Colouration of sound means changes in the timbre and pitch of the signal (attributes that distinguish one signal from another) caused by the sound reflections in a room. This change is sometimes described as distortion of the signal. However, such distortion may be to some extent desirable. The indicators KT and KH evaluate colouration expressed in the logarithmic ratio of the sound energy (squared and integrated sound pressure) at either the low or high frequency components of the room's impulse response to the sound energy at the mid frequency component (set at the 500Hz octave) as shown in Equations 101 and 102:

$$K_T = 10log\left(\frac{E_{\infty,100Hz}}{E_{\infty,500Hz}}\right) \tag{101}$$

$$K_H = 10log\left(\frac{E_{\infty,3150Hz}}{E_{\infty,500Hz}}\right) \tag{102}$$

Favourable values for colouration for both indicators KT and KH may be -3dB=<$K_{T,H}$=<+3dB (Ahnertet al. 2008).

3.12.13 **Sound strength (G, G_{mid}, G_{low}, G_{125}) [dB] ***

This room acoustics indicator (Jamagushi 1972, Lehmann 1976) also referred to as the "strength factor" is an objective measure of the subjective listener's aspect "loudness" (of the sound signal at the listeners position). In other words, it indicates the subjective impression of the sound level as it is influenced by the room. This indicator is relevant to both speech and music. Instead on an overall averaging for the octave bands 500 to 100 (ISO 3382-1 2009) it can also be also averaged over other frequencies ranges (G_{mid}, G_{low}, G_{125}) to express gain in the mid, low and very low parts of the frequency spectrum. The G is calculated as the logarithmic ratio of the total sound energy of the room's impulse response to the sound energy measure 10m away from the sound source in a free field (meaning no reflections and therefor direct sound) as shown in Equation 103:

$$G = 10log\frac{E_{tot}}{E_{tot10}} \qquad (103)$$

where E_{tot} is the sound energy (squared and integrated sound pressure) of the impulse response at listeners position [dB] and E_{tot10} the sound energy (squared and integrated sound pressure) of the impulse response measured 10m away from the sound source in a free field [dB].

Preferable values for G range from+1dB to 10dB (for speech and music).

Bass Strength (G_{125}) can be used to measure satisfactory bass levels as an alternative to Bass Ratio (BR) and it has been found to related better to overall subjective acoustical quality, except in the presence of very lightly upholstered seats (Bradley et al. 1997, Beranek 2003).

G_{low} expresses gain averaged over the 250Hz and 150Hz bands and G_{mid} expresses gain averaged over the 500Hz and 1000Hz octave bands. These quantities can be also calculated as a function of the volume of the space and the reverberation (T_{60}) according to the diffused field theory as shown in Equation 104:

$$G = 10log\left(\frac{T}{V}\right) + 45 \qquad (104)$$

where G_{Mid} is the gain averaged at 500 and 1000 Hz [dB], T_{Mid} is the reverberation time averaged at [s], EDT_{Mid} is the early decay time averaged at 500 and 1000 Hz [s] and V is the volume [m^3].

ISO 3382-1 (2009) provide information on of this indicator as well as typical range (2 dB; +10dB for G_{mid}) and just noticeable differences (JND).

3.12.14 Early and late stage support (ST_{early}, ST_{late}) [dB] *

These room acoustics indicators (Gade 1989) are "stage measures" (ISO 3382-1 2009) designed to address issues that may affect the performance of the musicians. Early support addresses the so called "ease of assemble", meaning the effectiveness with which musicians hear and play with each other. This parameter may affect attributes of the assemble such as the rhythm and intonation. Early support is calculated as a logarithmic ration of the sound energy (squared and integrated sound pressure) in the early reflections to the sound energy of the direct sound (under 10ms) as shown in Equation 105:

$$ST_{early} = 10log\left(\frac{E_{20\ldots100ms}}{E_{10ms}}\right) \quad (105)$$

"Late support" addresses the so called "support", that is the way the room supports the effort of the musician to create their tone and make himself/herself audible without excessive effort (Gade 2007). This is calculated by ST_{late} as the logarithmic ration of the sound energy in the later reflections to sound energy of the direct sound as shown in Equation 106:

$$ST_{late} = 10log\left(\frac{E_{100\ldots1000ms}}{E_{10ms}}\right) \quad (106)$$

Measurement for ST_{early} and ST_{late} must be curried at 1m from the source, typically at the 150Hz, 500Hz, 1000Hz, 2000Hz frequency bands. ISO 3382-1 (2009) provide information on of the measurement of this indicator.

3.12.15 Reverberance measure (H) [dB]

This room acoustics indicator (Beranek et al. 1965) is an objective measure of the subjective listener's aspect "liveliness" that relates to reverberance and spatial impression. It is calculated at the octave band 1000Hz as the logarithmic ration of the sound energy (squared and integrated sound pressure) of the late component of the room's impulse response to the sound energy of the direct and early component (or late reflections to early reflections plus direct sound) in Equation 107:

$$H = 10log\left(\frac{E_{\infty} - E_{0\ldots50ms}}{E_{0\ldots50ms}}\right) \quad (107)$$

Preferable values for concert halls range from 0dB to 4dB, and for musical theatres from 2dB to 4dB (Ahnert et al. 2008).

3.12.16 Early and late lateral energy measures (J_{LF} , L_j) [%] *

These room acoustics indicators (Barron 1974), also written as LF_E and LF_L, are objective measures of the subjective listener's aspect "spatial impression" in terms of Apparent Source Width (ASW, the perception of the listener that the sound source is broadening) and listener's envelopment (LEV) in orchestra halls and other similar performance spaces. These aspects are found to correlated well with the overall subjective acoustical quality as shown by subjective rankings of performance spaces (Beranek 2003). The J_{LF} and L_j express the ratio of the sound energy coming from early or late lateral sound reflections (sound that is reflected by building element at the sides of the hall) to the early or total sound energy of the room's impulse response. The angle of incidence of the lateral reflections is measured using a figure-of-eight pattern microphone.

The J_{LF} calculates ASW (using the early lateral reflections) using Equation 108:

$$J_{LF} = LF = \frac{E_{5\ldots80ms(lateral)}}{E_{0\ldots80ms}} \tag{108}$$

The L_j calculates LEV (using the late lateral reflections) using Equation 109:

$$L_J = \frac{E_{80\ldots\infty ms(lateral)}}{E_{0\ldots\infty ms}} \tag{109}$$

ISO 3382-1 (2009) provides information on the measurement of this indicator as well as typical range (0,05; 0,35 for J_{LF} and -14 dB; +1dB for L_J) and just noticeable differences (JND).

3.12.17 **Lateral hall gain (LG or GLL) [dB] ***

This room acoustics indicator (Bradley et al. 1995) also referred to as late lateral energy level (G_{LL}) is an objective measure of the subjective listener's aspect "spatial impression" in terms of Listeners Envelopment (LEV). The calculation takes under account the lateral sound energy coming from the late part of the impulse response (late reflections) that is considered responsible for the listeners perception of being "enveloped" by the sound as shown in Equation 110:

$$LG_{80}^{\infty} = \frac{E_{80\ldots\infty(lateral)}}{E_{tot,10m}} \tag{110}$$

where $E_{80\ldots\infty(lateral)}$ is the lateral sound energy (squared and integrated sound pressure) coming from the late components of the impulse response [dB] and $E_{80\ldots\infty(lateral)}$ is the total sound energy measured 10m away from the source in a free field [dB].

3.12.18 **Spatial impression measure (R) [dB]**

This room acoustics indicator (Lehmann n.d.) is an objective measure of the subjective listener's aspect "spatial impression" in terms of listeners envelopment (LEV). The R is calculated as the logarithmic ratio of the late reflections (and some early lateral reflections) to the sound energy within the first 25ms (and some early reflections from the source) as shown in Equation 111. A directional microphone (e.g. figure-of-eight microphone) is used to measure the sound energy of the impulse response component that lies within the first 25ms and 80ms and is coming from the source.

$$R = 10log\left[\frac{(E_{\infty} - E_{25}) - (E_{80R} - E_{25R})}{E_{25} + (E_{80R} - E_{25R})}\right] \tag{111}$$

where E_{25R} is the measured with a directional microphone aimed at the sound source.

Favourable values range from -5Db to 1dB. Rooms with values lower that -5dB appear not "spacious" enough and above 1dB as too "spacious" (Ahnert et al. 2008).

3.12.19 **Inter-Aural Cross Correlation (IACC) ***

This room acoustics indicator (Takayuki et al. 1992) is a "binaural auditorium measure" (ISO 3382-1 2009) used to measure the subjective listener's aspect "spatial impression". The IACC measures spatial impression using a binaural device (e.g. dummy head) as a function of the difference in sound levels perceived between left and right ear. IACC can be calculated for early reflections ($IACC_E$) to express spatial impression in terms of Apparent Source Width (ASW, the perception of the listener that the sound source is broadening) and for late reflections ($IACC_L$) to express spatial impression in terms of listeners envelopment (LEV). The less the signals at the left and right ears correlate (the smaller the maximum yield by Equation 113) the more "spaciousness" is perceived. The IACF and IACC are calculated using Equations 122 and 113:

$$IACF = \frac{\int_{t1}^{t2} p_{L(t)} \cdot p_{R(1+\tau)dt \cdot}}{\sqrt{\int_{t_1}^{t_2} p_L^2(t)dt \cdot \int_{t_1}^{t_2} p_R^2(t)dt}} \tag{112}$$

$$IACC = max\left|IACC_{t_1,t_2}(\tau)\right| \tag{113}$$

where p_L is the pressure level at left ear [dB] and p_R is the pressure level at left ear [dB]. ISO 3382-1 (2009) provides information on the measurement of this indicator.

3.12.20 Binaural Quality Index (BQI) function of $IACC_E$

This room acoustics indicator was proposed by Benarek (2003) as a binaural auditorium measure of the subjective listener's aspect "spatial impression" in terms of Apparent Source Width (ASW, the perception of the listener that the sound source is broadening). The BQI is also found to correlate highly with the subjective perception of the "overall subjective acoustical quality" and curries the further advantage that the measurement is almost the same for occupied and unoccupied halls (Beranek 2003). The BQI is calculated as a function of $IACC_E$ using Equation 114:

$$BQI = 1 - IACC_E \tag{114}$$

where $IACC_E$ is the Inter-Aural Cross Correlation calculated for the early part of the impulse response (0-80ms).

3.12.21 Listeners envelopment (LEV_{calc}) function of LF, G and BQI

This room acoustics indicator (Bradley et al. 1995) is an objective measure of the subjective listener's aspect "spatial impression" in terms of listeners envelopment (LEV) that correlates highly with subjective judgement and is calculated based on the G and LF acoustic measures using Equation 115.

$$LEV_{calc} = 0{,}5G_{Late,mid} + 10logLF_{Late,mid} \tag{115}$$

The measure was revised by Benarek (n.d.) to be calculated using the BQI and G acoustic measures and considering the late reflections using Equations 116, 117 and 118:

$$LEV_{calc} = 0{,}5G_{Late,mid} + 10logBQI_{Late,mid} \tag{116}$$

where

$$BQI_{Late,mid} = 1 - IACC_{Late,mid} \tag{117}$$

and

$$G_{Late,mid} = g - 10log(1 + log^{-1}C_{80}/10) \tag{118}$$

3.13 Acoustic environment: Speech perception

Speech perception in a room can be measured partly and sometimes sufficiently using typical room acoustics indicators such as the Reverberation Time or the Clarity/Definition measures. However, due to the importance of this task a set of specific indicators has been developed for more effective and comprehensive measurements. The indicators in this field use one or many of the following metrics and mechanisms:

- Signal-to-noise difference/ratio: the difference or ratio between the sound pressure levels of the signal and the background noise is used as a simple metric to investigate if the noise is masking the speech signal. This metric is used alone as a simple speech perception indicator or as part of more complex indicators and is suitable only in specific circumstances.
- Reverberance: similar to the noise, the reverberance has a masking effect on the signal.
- Signal modulation: some of the most comprehensive indicators (e.g. STI) predict intelligibility by calculating the modulation of the signal (using modulation transfer functions) as its affected by factors such as reverberance, noise and frequency.
- Perceptual dynamic range: some indicators weight heavier certain frequency bands that are important to speech intelligibility (e.g. SII).
- Metrics based on the room's impulse response: see section 3.12 (e.g. U_{50}, U_{80}).

3.13.1 **Signal-to-Noise Ratio (S/N or SNR)**

This speech perception indicator measures the extend that a signal differentiates from background noise. It is a fundamental indicator used in speech intelligibility measurements and different versions of it are part of various other composite indices, such as the Speech Transmission Index (see 3.13.7) and the Speech Audibility Index (see 3.13.6). Various versions of this indicator are used. For example, some measure signal and noise leves over frequency bands and weight according to band-importance and other take account of the detrimental effects of reverberation (late reflections) on the signal.

3.13.2 **Articulation Index (AI)***

The Articulation Index (French et al. 1947, Fletcher et al. 1950) is an objective method of predicting speech perception. The calculation uses weighting factors in five octave bands (or one-third bands) that account for hearing sensibility in different frequencies band and the signal to noise ratio in each frequency band. Bands that are particularly important for speech perception are weighted more heavily. Theses quantities are multiplied and summed for all bands evaluated as shown in Equation 119. The signal to noise measure is used in other indicators as well such as the Speech Transmission

Index (see 3.13.7), however, calculating the AI is less complicated. The AI is an earlier version of Speech Intelligibility Index (see 3.13.3) which uses a Modulation Transfer Function (like the STI) for a more comprehensive prediction of the distortion on the signal. However, both the AI and the SII in contrast to the STI do not consider the negative effects of the late reverberation on speech intelligibility.

$$AI = \sum_{t=1}^{i=15} W_i R_i \tag{119}$$

Where W_i is the weighting factor for band i and R_i is the signal to noise ratio for band i. The AI ranges from 0 to 1. The higher the value the better the intelligibility.

3.13.3 **Speech Intelligibility Index (SII)* updated AI**

The Speech Intelligibility Index is an objective measure used to predict speech perception. It is an updated version of the AI but unlike its predecessor it is intended for acoustic environments and not for electronic communication equipment. Methods for calculating of SII are included in ANSI S3.5-1997. The calculation is depended on the Band Importance Value (BIF), which is used to weight the importance of different frequencies in terms of intelligibility and the band audibility function. The SII in contrast to other indicators (e.g. STI, Al_{cons}) does not consider the negative effect of the late reverberation on speech intelligibility. The SII is calculated using Equation 120:

$$SII = \sum_{i=1}^{n} I_i \cdot A_i \tag{120}$$

where I is the band importance function (BIF) with values from 1 (100% important) to 0 [-], A is the band audibility function [-] and i is the frequency band.

According to ISO 1921 (2004) values over 0,75 are deemed from good to excellent and values under 0,45 are deemed from poor to bad.

3.13.4 **Articulation loss of consonants (Al_{cons}) [%]**

The percentage articulation loss of consonants (Peutz 1971, Klein 1971) is a simple objective measure used widely to evaluated speech perception. It is based on the assertion that the articulation loss of consonants is particularly important for speech intelligibility in rooms and is calculated according to basic acoustic attributes of the space (see Table 7 for assessment values) using Equations 121 and 122.

$$Al_{cons} \approx 0{,}65 \left(\frac{s}{r_H}\right)^2 T \tag{121}$$

$$r_H = 0{,}057 \sqrt{\frac{V}{T}} \qquad [m] \tag{122}$$

Al_{cons} can also be measured from the room impulse response using Equation 123:

$$Alcons \approx 0.652 \left(\frac{E_\infty - E_{35}}{E_{35}}\right) T_{60} \tag{123}$$

where “s” is the distance between sound source and listener [m], r_H is the half room diffuse distance [m], T is the reverberation time [s] and E_{35} is the energy up to 35ms.

Table 7 Intelligibility rating for AI (source: Everest et al. 2009)

Subjective Intelligibility	%Alcons [%]
Ideal	=<3
Good	3-8
Satisfactory	8-11
Poor	>11
Worthless	>20

3.13.5 **Useful-to-detrimental index (U_{50}, U_{80}) function of D_{50} / C_{80}**

This indicator suggested by (Bradley 1986) is used to measure speech intelligibility and could be used as a simpler alternative to the STI since both indicators account for the negative effects (on intelligibility) of the late reflections and the signal to noise ratio (the detrimental parts of the signal). The Useful-to-Detrimental index can be also calculated as U_{80} by using the term $10^{C80/10}$ (based on the measure C_{80}) to replace the term D shown in Equation 124:

$$U_{50} = 10log\left[\frac{D}{1 - D + n/s}\right] \qquad (124)$$

where D is the sound energy from the early reflections (same as D_{50}) [dB] and s/n is the signal to noise ratio.

3.13.6 **Speech Audibility Index (SAI) [%]**

The Speech Audibility Index (Boothroyd et al. 2004) is a measure used to predict speech perception. It could be described as the proportion of useful signal that is above the effective noise (the actual noise and the reverberation). In that effect, it is similar to the STI measure, however, the later examines how noise and reverberation affect the variation on amplitude on the envelope of the signal and requires measurements at multiple location in the room.

The SAI for one frequency band (every frequency band might have different s/n) is calculated using Equation 125:

$$\mathrm{SAI} = \left(\frac{ESN + 15}{30}\right) \cdot 100 \qquad (125)$$

where Effective Signal to Noise ratio(ESN) calculated using Equation 126:

$$ESN = 10\log\left(10^{(\mathrm{d}/10)} + 10^{(\mathrm{e}/10)}\right) - 10log\left(10^{(\mathrm{n}/10)} + 10^{(\mathrm{l}/10)}\right) \qquad (126)$$

and “d” is the speech signal level [dB], “e” is the level of early reverberation [dB], “n” is the level of the actual noise [dB] and l is the effective noise created by late reverberation [dB].

Normally the measure is to be implemented in various bands and then weighted and integrated according to the importance of each band to speech perception (similarly to STI). However, it can be also applied to a single band (2000Hz) where much of the speech information is carried.

3.13.7 **Speech Transmission Indices (STI, STIPA, STITEL) [dB] ***

The Speech Transmission Index (Houtgast et al. 1985) is an objective measure used for the prediction and measurement of speech intelligibility. The measurement uses the Modulation Transfer Function (MTF) to calculate the changes in the aptitude of the signal envelope over time (the modulation of the signal), between the signal's source and the listener's position. The changes are depended on the reverberation time and the noise to signal ratio. The version of the Modulation Transfer Function (MTF) used by this indicator is the modulation reduction factor function (show in Equation 129). The STI indication will defer in different positions in the room, therefor the measurement must be carried out in all positions of interest. The final STI is obtained after the modulation transfer indices (MTI) shown in Equation 127 are weighted according to frequency in 7 bands (see Table 8 for assessment values). Equation 128 calculates the effective signal to noise ratio:

$$MTI = \frac{\overline{x_i} + 15dB}{30dB} \quad (127)$$

$$\overline{x_i} = 10log\left(\frac{m_i}{1 - m_i}\right) \quad (128)$$

$$m(F) = \frac{1}{\sqrt{1 + (2\pi F \cdot T/13{,}8)^2}} \cdot \frac{1}{1 + 10^{-\frac{S/N}{10dB}}} \quad (129)$$

where MTI is the modulation transfer indices, m(F) is the modulation reduction factor, m_i is the modulation reduction factors, X is the (apparent) effective signal-noise ratio, F is the modulation frequency [Hz], T is the reverberation time [s] and S/N is the signal/noise ration [dB].

Table 8 Intelligibility rating for STI (source: EN ISO 9921 2003)

Subjective intelligibility	STI
Unsatisfactory	0,00-0,30
Poor	0,30-0,45
Satisfactory	0,45-0,60
Good	0,60-0,75
Excellent	0,75-1,00

The IEC 60268-16 (2011) provides information on the commonly used intelligibility measures STI, STIPA (Speech Transmission Index for Public Address systems) and STITEL (Speech Transmission Index for Telecommunications systems). STI and STIPA can be used to rate speech transmission with or without sound systems. Information on the STI are also included in ISO 9921 (2003).

3.13.8 **Room Acoustical Speech Transmission Index (RASTI)**

The Room Acoustical Speech Transmission Index is an objective measure for the prediction and measurement of speech intelligibility that could be described as an abbreviated (and quicker) version of the STI. The RASTI uses a modulation transfer function (as STI does) but only for the frequencies bands 500Hz and 2000Hz. This method is referred to by several sources as obsolete.

3.13.9 **Speech Interference Level (SIL) [dB] * for noisy environments**

The Speech Interference Level (Beranek 1947) provides a simple method for predicting and measuring speech perception in cases of noisy environments (e.g. inside aircraft cabins). It considers an average of the noise spectrum, the speech level (vocal effort) and the distance between the speaker and the listener. According to ISO 9921 (2003) this method may be applied only when no other method is applicable (see Table 9 for assessment values). The SIL is calculated using Equations 130 and 131:

$$SIL = L_{S,A,L} - L_{SIL} \quad (130)$$

$$L_{SIL} = \frac{1}{4}\sum L_{N,oct,i} \quad (131)$$

where $L_{S,A,L}$ is the speech level [dB], L_{SIL} is the speech interference level of noise [dB] and $L_{N,oct,I}$ is the sound pressure level of ambient noise in four octave bands (500Hz, 1000Hz, 2000Hz, 4000Hz) [dB].

Table 9 Intelligibility rating for SIL (source: EN ISO 9921 2003)

Subjective intelligibility	SIL [dB]
Unsatisfactory	<3
Poor	3 to 10
Satisfactory	10 to 15
Good	15 to 21
Excellent	21

3.14 Acoustic environment: Privacy and concentration (offices)

Privacy and avoidance of distraction are performance requirements pertinent to work environments. Privacy is a measure of the ability to ensure the privacy of conversations and is especially relevant to open or partially open plan offices. Concentration (in this case lack of distraction) is also relevant to offices environments. The indicators in this field use some of the following metrics and mechanisms:

- Speech intelligibility: Regarding privacy, stopping the propagation of intelligible speech protects private information Regarding concentration, the propagation of intelligible speech is a distraction factor and may lead to drop of productivity (Hongisto 2005). (e.g. r_D)
- Level attenuation: the drop in sound pressure levels between specific points in space (e.g. different zones) is used (sometimes with frequency weighting) to predict distraction and privacy (e.g. $D_{2,S}$, AC).
- Masking form background noise: the signal of intelligible speech that may compromise privacy is masked by the background noise (e.g. SPC)

3.14.1 **ISO 3382-3 indicators for open plan offices ($D_{2,S}$, $L_{p,A,S,4m}$, r_D) ***

ISO 3382-3 (2012) deals with the acoustical conditions in open plan offices where the main consideration is how the acoustic environment disturbs productivity in terms of distraction and privacy. Whilst the acoustic environment in an office may include a variety of sound sources, the most disrupting is speech. Speech is particularly disrupting when it is intelligible (Hongisto 2005).

ISO 3382-3 (2012) provides ways of assessing the effect that sound pressure levels and speech intelligibility may have on privacy and distraction using the following three quantities:

- A-weighted sound pressure level of speech a 4m ($L_{p,A,S,4m}$): "the nominal A-weighted sound pressure level of normal speech at a distance of 4m from the sound source". This indicator is measured in dB.
- Distraction Distance (r_D) [m] : "'the distance from speaker where the Speech Transmission Index (STI) falls below 0,50". This indicator is measured in meters.
- Spatial decay rate of A-weighted sound pressure level of speech ($D_{2,S}$): the "rate of spatial decay of A-weighted sound pressure level of speech per distance doubling". This indicator is measured in dB and calculated using Equation 132:

$$D_{2,S} = -\log(2)\frac{N\sum_{n=1}^{N}\left[L_{p,A,S,n}log\left(\frac{r_n}{r_0}\right)\right] - \sum_{n=1}^{N}L_{p,A,S,n}\sum_{n=1}^{N}log\left(\frac{r_n}{r_0}\right)}{\sum_{n=1}^{N}\left[log\left(\frac{r_n}{r_0}\right)\right]^2 - \left[\sum_{n=1}^{N}log\left(\frac{r_n}{r_0}\right)\right]^2} \quad (132)$$

where $L_{p,A,S,n}$ is the A-weighted speech level in position "n" [dBA], "n" is the index number of the single measurement position, "N" is the total number of measurement positions, r_n is the distance [m] to measurement position "n" and r_0 is the reference distance (1m).

As is it stated in ISO 3382-3 (2012) an open office plan with poor and insufficient conditions would have typically $D_{2,S}$<5dB, $L_{p,A,S,4m}$>50dB and r_D>10m whilst an open office plan with good acoustic conditions would have $D_{2,S}$=>7dB, $L_{p,A,S,4m}$=<48dB and r_D=<5m.

3.14.2 **Privacy Index (PI) [%] * function of AI**

The Privacy Index (included in ASTM E1130) is the inverse of the Articulation Index (see 3.13.2) as shown in Equation 133. A value of 1 represents perfect speech privacy in the sense that the listener cannot perceive any information in speech (speech is not intelligible) (see Table 10 for assessment values). This measure is particularly relevant to open plan office environments.

$$PI = (1 - AI) \cdot 100 \quad (133)$$

Table 10 Speech privacy rating for PI (source: ASTM E1130)

Speech privacy	PI [%]
Normal speech privacy	80
Confidential speech privacy	95

3.14.3 **Speech Privacy Class (SPC) ***

The Speech Privacy Class Is a measure of speech privacy provided by a closed room. This indicator predicts privacy depending on the wall's capacity for sound insulation (level attenuation between zones) and the ambient noise levels (L_b) that may mask the speech signal. Similar to the Privacy Index (PI) the privacy increases when these two quantities increase and renter speech unintelligible or inaudible (see Table 11 for the performance scale). The SPC is calculated Equation 134:

$$SPC = LD(avg) + L_b(avg) \tag{134}$$

where LD(avg) is the arithmetical average of level difference between source and receiver at one third octave band level and L_b(avg) is the arithmetical average of background noise at one third octave band level.

Table 11 Speech privacy rating for SPC (source: ASTM E2638-10)

Speech privacy	SPC
minimal speech privacy	SPC 70
standard speech privacy	SPC 75
standard speech security	SPC 80
high speech security	SPC 85
very high speech security	SPC 90

3.14.4 **Articulation Class (AC) ***

The Articulation Class (included in ASTM E 1110-06) is a single number indicator used to rate/compare the performance of building elements (e.g. suspended ceilings, office screens, wall panel etc.) in terms of speech privacy. In this case speech privacy is depended on the loss of speech intelligibility (similar to the PI and SPC indices) between zones in open plan offices as it is predicted based on level attenuation and frequency weighting. A rating below 150 indicates poor speech privacy performance and a rating above 180 indicates good performance. The AC is calculated using Equation 135:

$$AC = \sum_{f_i} A(f_i) \cdot W(f_i) \tag{135}$$

where f_i is the centre frequency in the one-third bands between 200 to 5000 Hz, $A(f_i)$ is the measured sound pressure level attenuation in frequency band f_i and $W(f_i)$ is the weighting coefficient of the frequency band.

3.15 Acoustic environment: Noise

These indicators measure noise from sources located in the building (e.g. ventilators, pumps, water in pipes) and out of the building (e.g. traffic) to estimate the effects of background noise in terms of perceived loudness, occupant's annoyance, activity interference etc. and to help design noise control strategies (e.g. in relation to building elements and HVAC systems). These indicators follow two types:

- Loudness perception and equivalent energy: a single value that represent perceived noise level depending on frequency and/or equivalent energy aggregated over time and space.
- Loudness and frequency balance: frequency imbalance in the noise signal (e.g. hissy noise) has been found to have disruptive influence. These indicators combine loudness information as well as information on the frequency content of sound.

3.15.1 **A-weighted and Equivalent SPL (e.g. L_A, $L_{Aeq,T}$, L_{dn}, L_{den}) [dBA] ***

This noise measures are based on frequency weighting networks for equal loudness (e.g. A-weighted sound pressure level) and are used to evaluated environmental noise in terms of perceived loudness, occupant's annoyance, activity interference and hearing loss prediction. In contrast to other noise criteria such as the noise weighting curves (NC, RC etc.) they do not evaluate the frequency content of noise. These measures are usually used to set design goals and are important in developing noise control strategies or informing statistical research (e.g. noise mapping, hearing loss risk). Some deal with noise sources within the buildings (e.g. ventilators, pumps, water in pipes) and other with noise from outside (traffic, construction noise, nightlife etc.). Standards and regulations dealing with building performance will typically use the indicators $L_{p,A}$ and $L_{Aeq,T}$ and other similar indicators.

- A-weighted sound pressure level (Lp,A) [dB(A)]

The A-weighed sound pressure level dB(A) is a frequently prescribed measure of environmental noise from sources most often located inside the building (toilets, elevators, ventilation systems etc.). Weighting the sound pressure levels allows to correlate the actual "loudness" of the signal with the human perception of loudness that is depended on frequency. This procedure makes it possible to predict more accurately the effects of noise on occupancy (in terms of annoyance, disruption of activities, speech intelligibility etc.).

A-weighting is the most common among several other weighting curves (aka weighting networks, such as A,B,C,D,Z etc.). The C-weighting network (also frequently used) predicts the sensitivity of human hearing at very high noise levels and is usually described as "flatter" (in respect to the weighting coefficients). The indicator $L_{p,C,peak}$ is typically used to measure peak sound pressure levels.

The weighting is usually implemented automatically using sound level meters through the application of filters. The A-weighted sound pressure level ($L_{p,A}$) over a frequency spectrum is summed into a single number using Equation 136:

$$\mathrm{Lp(dBA)} = 10\lg\left(\sum_{16\,Hz}^{8000\,Hz} 10^{0,1\cdot Lp}\right) \quad [dB(A)] \tag{136}$$

This measurement is usually evaluated in terms of design values for outside noise levels or noise from sources located in the building such as service systems such as toilets, elevators, ventilation systems.

ISO 15251:2007 and ISO 13779 2008 recommend design values for noise per type of place and building using the A-weighted sound pressure level (dB(A)).

- A-weighted equivalent continuous sound pressure level ($L_{Aeq,T}$ or L_{AT}) *

The A weighted equivalent continuous noise level ($L_{Aeq,T}$ or L_{AT}) is a common measure used typically to evaluate outside environmental noise (e.g. rail road, traffic, industry, wind turbines, construction sites). This type of noise is sometimes described as community noise and is usually used to predict the disturbance of the intended activity. Therefore, it serves as an important tool when developing noise control strategies (e.g. designing the building's envelope etc.). This measure is also used to assess the effects of the exposure of workers to noise (ISO 9612 2009).

Since the sound pressure level of outside environmental noise is not constant but varies over time, this indicator is used to obtain a single sound pressure level that, when constant, provides equivalent total energy over the same period of time as the original fluctuating sound pressure levels that it represents. Over a period of T [h] the $L_{Aeq,T}$ can be calculated using Equation 137:

$$L_{Aeq,T} = 10log\left(\frac{\frac{1}{T}\int_0^T p_A^2(t)dt}{p_0^2}\right) \quad [dB] \tag{137}$$

To evaluate occupational noise levels an A-weighted noise exposure level normalized over 8 hours is used as shown in Equation 138 (ISO 9612 2009):

$$L_{EX,8h} = L_{A,eqTe} + 10log\left[\frac{T_e}{T_0}\right] \quad [dB] \tag{138}$$

Where $L_{p,A,eq,Te}$ is the A-weighted equivalent continuous sound pressure level for T_e [dBA], T_e is the effective duration of the working day [h] and T_0 is the reference duration [8h]. The exposure over a number of days is calculated using Equation 139 (ISO 9612 2009):

$$\bar{L}_{EX,8h} = 10log\left[\frac{1}{X}\sum_{x=1}^{X} 10^{0,1 \cdot L_{EX,8h,x}}\right] \quad [dB] \tag{139}$$

where X is the number of days. The Day-Night Sound Level (L_{dn} or DNL) is another common community noise indicator. In this case the night time sound pressure levels are weighted (multiplied by 10) to account for increased annoyance by noise at night as shown in Equation 140 (1996-1 2016):

$$L_{dn} = 10log\left[\frac{1}{24}\left(t_{day} \cdot 10^{0,1L_{day,15}} + t_{night} \cdot 10^{0,1L_{day,9+10dB}}\right)\right] \quad [dB] \tag{140}$$

where the default values for t_{day} and d_{night} are 15h and 9h. Similarly, the day-evening-night sound level (L_{den} or Community noise equivalent level (CNEL)) is calculated using Equation 141 (1996-1 2016). The L_{den} measure is used additionally to indicate noise levels for the purpose of noise mapping. Notice that each period is weighted differently (night being the most important):

$$L_{den} = 10log\left[\frac{1}{24}\left(t_{day} \cdot 10^{0,1L_{day,12}} + t_{evening} \cdot 10^{0,1L_{day,9+5dB}} + t_{night} \cdot 10^{0,1L_{day,9+10dB}}\right)\right] \quad [dB] \tag{141}$$

The World Health Organisation's (WHO) guidelines on community noise state the minimum values for L_{Aeq} that can produce an adverse health effect in relation to different environments. The guidelines take account of the period in the day when the exposure occurs and are accompanied by the time base of the measurement. Maximum values of noise fluctuation are also included using the L_{Amax}.

Table 12 includes recommended values for community noise issued by the World Health Organisation (WHO).

Table 12 Example of guideline values for community noise in specific environments (WHO Guidelines for community noise, Berglung et al. 1999)

Specific environment	Critical health effect(s)	L_{Aeq}[dB(A)]	Time base [Hours]	L_{Amax} fast [dB]
Outdoor living area	Serious annoyance, daytime and evening	55	16	
	Moderate annoyance daytime and evening	50	16	
Dwelling indoors	Speech intelligibility & moderate annoyance, daytime and evening	35	16	45
Inside bedrooms	Sleep disturbance night-time	30	8	
School class rooms & pre-schools indoors	Speech intelligibility, disturbance of information extraction, message communication	55	During class	45
Hospitals treatment rooms, indoors	Interference with rest and recovery	As low as possible		
Industrial, commercial shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110

3.15.2 **Noise rating curves (NC, NCB, RC, RC Mark II)**

Noise weighting curves are noise criteria used to rate background noise levels from HVAC equipment (or other noise related to mechanical equipment) as well as noise from adjacent rooms in indoor environments to avoid the occupant's annoyance and noise related activity interference.

In contrast to simpler noise criteria based mostly on equal loudness weighting (see section 3.15.1) these indicators will rate not only the sound level of the noise signal but also, its frequency content. This is because, an unbalanced distribution of noise levels over the frequency spectrum is also detrimental (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009).

Because these indicators provide information in both the sound level of the noise signal and its frequency content they are often prescribed in regulations and standards that refer to spaces with demanding acoustical criterial (e.g. music venues, conference venues, recording rooms).

Information on the noise rating curves and their calculation can be found in the ASHRAE Handbook: Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009). Presented following are some of these measures that were adopted from standardisation organisations.

- Noise Criterion (NC) (ANSI S12.2)

This criterion (Beranek 1957) is widely used by engineers and manufactures. According to the ASHRAE Handbook (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009), the CN is sensitive to relative loudness and speech interference on a given spectrum, however, it does not consider loudness over the frequency spectrum and therefore sounds that may be equally rated on loudness are perceived to have different subjective qualities. Furthermore, this criterion cannot be used to evaluate noise at very low frequencies.

The rating is done using a “tangency procedure” where the curve of measured noise is compared to a series of reference curves (that are usually given as the goal/design value). The curve that falls closest and entirely above the measured data curve is used to rate the noise (e.g. NC 45). If necessary interpolation is applied.

- Balanced Noise Criterion (NCB) curves (ANSI S12.2)

The Balanced Noise Criterion method (Beranek 1989) evaluates background noise in rooms, part of which may also come from occupant activity. In contrast to the NC method, the NCB comments on the existence of low frequency rumbly and high frequency hissy noise, they include two more frequency bands on the lower side and they can deal with very low frequency sound. The rating follows a similar “tangency procedure” to the NC method using additionally a curve related procedure to account for rumble and hissy noises

- Room criterion (RC) and RC Mark II methods (ANSI S12.2)

The Room Criterion (Blazier 1981) is used primarily as a diagnostic tool for HVAC related sound (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009). The curves represent perceived neutral background noise rather than equal loudness measured by other indicators (NC or NCB). The spectrum balance of the noise is characterised as neutral (N), hissy (H) and rumbly (R) but this method will also indicate the existence of vibrations.

The results of this rating are stated as such: e.g. RC 35(N). The letter (N,R OR H) indicates the frequency spectrum balance and RV for sound-induced vibration.

A revised method of the RC criterion, the RC Mark II method (Blazier 1997) added in the procedure the Quality Assessment Index (QAI) to help estimate occupant satisfaction for measured curves that have a different shape than the RC curve. The QAI [dB] measures the deviation of the measured curve from the criterion neutral curve and is then used to evaluate the frequency spectrum balance (e.g. for QAI=<5dB, frequency spectrum balance is neutral (N)).

The results of the RC Mark II method is stated similarly to the RC but with a wider variety of frequency spectrum: (N) for neutral, (LF) for low-frequency rumble, (MF) for mid-frequency roar, and (HF) for high-frequency hiss. (LF_B), moderate but perceptible sound-induced ceiling/wall vibration, and (LF_A), noticeable sound-induced vibration.

3.16 Acoustic environment: Building acoustics

Building acoustics is a performance domain concerned with the elimination of sound propagation thought building elements and zones that may disrupt the activities of the occupants. Building acoustic indicators measure the transmittance of either airborne or impact sound thought either building elements or building zones.

3.16.1 **Airborne sound insulation per ISO (R_w, R'_w, $R'_{tr,s,w}$, $D_{nT,w}$, $D_{n,e,w}$, etc.) [dB] ***

The insulating performance of an element in terms of airborne sound insulation is described using the following two indicators: the sound reduction index (R or transmission loss (TL)) that quantifies sound transmission loss between the sound energy incident on the surface of a building element and the sound energy radiated by that element to other adjustment rooms, and the level difference (D) that quantifies the level difference between source and receiving room .

There are many versions of these indicators for different sources of noise (e.g. traffic noise, loud speaker), different types of the transmission (e.g. direct transmission, flanking transmission), different evaluated elements (e.g. partition walls, façade elements), different measurement conditions (e.g. laboratory or field measurement) etc.

To evaluate the performance of insulating elements (e.g. partitions) insulation indices must apply standardised to account for the effect of different room. The effect of the room is represented thought equivalent the absorption area or the reverberation time.

As an alternative to performing a laboratory or field measurement, it is possible to estimate the element's capacity for sound insulation based on the sound reduction index of the composing parts using the procedures described in ISO 12354 (2016) (also includes are tables with transmission loss values for standard parts e.g. window panes, homogenous structures). For completely homogenous, single layer structures the sound reduction index can be calculated according to mass of the element and the frequency of the sound using Equation 142:

$$R_0 = 20log(f \cdot m) - 48 \tag{142}$$

Because the sound insulation performance of the is a frequency depended phenomenon, transmission loss is derived for one-third octave band and/or octave bands. To obtain a single value that would allow comparison between different elements a weighting procedure described in ISO 717-1 (2013) can be applied. These single value indicators are the weighted reduction index R_w and the weighted normalised level difference $D_{n,w}$ as well as various variations of them.

Additional use of the so-called noise spectrum adaptation terms (C, C_{tr}) allows for the consideration of a wider frequency range noise. These values are added by the various authorities to the transmission loss requirements to set appropriate design target values.

The weighting procedure includes weighting the measurements using a reference curve and a measurement curve. The reference curve is shifted gradually (in steps of 1 dB) towards the measurement curve until the sum of unfavourable deviation is as large as possible but no more than 32 dB. Unfavourable deviation occurs where the measurement is less than the reference value at a given frequency (after the two curves cross). Then the value of the reference curve at 500 Hz gives the single values R_w and $D_{n,w}$.

The following unweighted indices are measured either on field or laboratory for one third-octave frequency bands or octave frequency bands:

- Sound reduction index (R) [dB]

Used to evaluate transmission loss in between rooms. Accounts for total power transmitted in the receiving room. Derived from one-third octave band values and calculated according to ISO 10140-2:2010 Formula 2 (Equation 143):

$$R = L_1 - L_2 + 10lg\frac{S}{A} \tag{143}$$

- Apparent sound reduction index R' $[dB]$

Accounts additionally for sound transmitted by flanking elements. Derived from one-third octave band and one octave band values and calculated according to ISO 140-4:1998 Formula 5 (Equation 144 included also in EN I2354-1) based on field measurements:

$$R' = L_1 - L_2 + 10lg\frac{S}{A} \tag{144}$$

- Apparent sound reduction index $R'_{45°}$ $[dB]$

Used to evaluate facade elements and facades. Applies when the sound source is a loud speaker and the angle of incidence is 45°. Derived from one-third octave band and one octave band values and calculated according to ISO 140-5:1998 Formula 3 (Equation 145 included also in EN I2354-3)

$$R'_{45°} = L_{1,s} - L_2 + 10lg\frac{S}{A} - 1{,}5 \tag{145}$$

- Apparent sound reduction index $R'_{tr,s}$ $[dB]$

Used to evaluate facade elements and facades. Applies when the sound source is traffic noise. Derived from one-third octave band and one octave band values and calculated according to ISO 140-5:1998 Formula 4 (Equation 146 included also in EN I2354-3) based on field measurement:

$$R'_{tr,s} = L_{eq,1,s} - L_{eq,2} + 10lg\frac{S}{A} - 3 \tag{146}$$

- Normalised level difference D_n $[dB]$

The difference in space and time average in between two rooms when sound is emitted through one or more sound sources in one of the rooms. Normalised by the absorbing surface of receiving room. Derived from one-third octave band and one octave band values and calculated according to ISO 140-4:1998 Formula 3 (Equation 147 also included in EN I2354-1):

$$D_n = L_1 - L_2 + 10lg\frac{A}{A_0} \tag{147}$$

- Standardised level difference D_{nT} $[dB]$

The difference in space and time average in between two rooms when sound is emitted through one or more sound sources in one of the rooms. Normalised by the reverberation time of receiving room. Derived from one-third octave band and one octave band values and calculated according to ISO 140-4:1998 Formula 4 (Equation 148 included in EN I2354-1) based on field measurements:

$$D_{nT} = L_1 - L_2 + 10lg\frac{T}{T_0} \tag{148}$$

- Element-normalized level difference ($D_{n,e,}$) $[dB]$

Applied where sound transmission occurs only due to a small technical element (e.g. electrical cable ducts, transfer air devices, transit ceiling systems). Derived from one-third-octave band values and calculation according to ISO 10140-2:2010 Formula 5 (Equation 153 included in EN I2354-1) based on laboratory measurements:

$$D_{n,e} = L_1 - L_2 + 10lg\frac{nA_0}{A} \tag{149}$$

- Normalized flanking level difference $D_{n,f}$ $[dB]$

Accounts for transition that occurs only through a specified flanking path (other than separating partition i.e. suspended ceilings, pipework, ducting, façade, access floor). Flanking transmission exists in most situations. Derived from one-third octave band values and calculated according to ISO 10848-2:2006 Formula 1 (Equation 150 included in EN I2354-1):

$$D_{n,f} = L_1 - L_2 - 10lg\frac{A}{A_0} \tag{150}$$

- Standardised level difference $D_{tr,2m,nT}$ $D_{ls,2m,nT}$ $[dB]$

Used to evaluate facade elements and facades. Applies when the sound source is a loud speaker or traffic noise. Indicates the difference between the sound pressure level at 2m meters in front of the façade and inside the receiving room. Derived from one-third octave band and one octave band values and calculated according to ISO 140-5:1998 Formula 7 (Equation 151 included in EN I2354-3):

$$D_{2m,nT} = L_{1,2m} - L_2 - 10lg\frac{A}{A_0} \tag{151}$$

where L_1 is the energy average sound pressure level in the source room [dB] $L_{1,s}$ is the average sound pressure level on the outside element of a building element including the reflecting effects of the façade [dB], L_2 is the energy average sound pressure level in the receiving room [dB], $L_{eq,1,s}$ is the average equivalent sound pressure level on the outside element of a building element including the reflecting effects of the façade [dB], $L_{eq,2}$ is the average equivalent sound pressure level in the receiving room [dB], $L_{1,2m}$ is the sound pressure level at 2m in front of the façade [dB], T is the reverberation time in the receiving room [s], T_0=0,5s (for dwellings) is the reference reverberation time [s], S is the area of separating element (or test element) [m^2], A is the equivalent absorption area in the receiving room [m^2], A_0=10 m^2 is the reference absorption area [m^2] and “n” is the numbers of installed elements.

In the various standards and regulations, the requirement may be stated as such (source: ISO 717-1 2013):

$Rw(C;C_{tr})$=41(0;-5) dB (calculation values)

Rw=40,9dB ± 0,8dB (stated with uncertainties)

R'_w+C_{tr}=>45dB (minimum values)

The Austrian standard ÖNORM B 8115-2 (2006) gives sound weighted reduction index (R_w, $R'_{res,w}$, R_w+C_{tr} etc.) minimum values for different categories of background noise level, different categories of building use (e.g. hospitals, offices) and different groups of building elements (e.g. normal façade elements, transparent elements such as window, roofs etc.). Values range from R_w+C_{tr} =23dB (for windows and external doors in quite areas) to R_w=60dB (for roofs and walls against car passages and garages). Minimum values for weighted standardised level difference ($D_{nT,w}$) are given between different categories of spaces (e.g. between living quarters and staircases $D_{nT,w}$=55 dB, between adjustment rooms of different house units $D_{nT,w}$=50 dB) and different categories of building use (e.g. hospitals, offices). Different values are given if the spaces are connected with a door/window or not. Values range from 38dB (e.g. between rooms and staircases/corridors that are connected with a door in a hotel) and 60dB (e.g. between living quarters in adjacent buildings).

3.16.2 **Airborne sound insulation per ASTM (STC, NIC, OITC, CAC etc.) ***

The ASTM standards define single value indices for the evaluation of building elements in terms of airborne sound insulation, using procedures similar to those described in the ISO literature. E.g.:

- Sound Transmission Class (STC) is used to evaluate an element/partition in terms of sound transmission loss in laboratory conditions (ASTM E413–16).
- Noise Isolation Class (NIC) use to evaluate sound attenuation between rooms in field measurement (ASTM E336).
- Outdoor indoor transmission class (OITC) is used to evaluate outdoor to indoor attenuation (ASTM E1332).
- The Ceiling Attenuation Class (CAC) is used to evaluate flanking transmission through the ceiling (ASTM E1414)

3.16.3 **Impact sound insulation per ISO ($L_{n,w}$, $L'_{n,w}$, $L'_{nT,w}$, $L_{n,eq,0,w}$) [dB] ***

The insulating performance of an element in terms of impact sound insulation is described using the following indicators: the impact sound pressure level (L_n)

There are three versions of this indicator that take account different types of sound transmission (e.g. direct transmission, flanking transmission), and different normalization metrics (reverberation time and equivalent absorption area).

To evaluate the performance of insulating elements (e.g. partitions), insulation indices must be standardised to account for the effect of different rooms. The effect of the room on the measurement is represented thought the absorption area and the reverberation time.

Because the sound insulation performance of the elements is a frequency depended phenomenon, transmission loss is derived for one-third octave bands and/or octave bands. To obtain a single value that would allow comparison between different elements a weighting procedure described in ISO 717-

2 (2013) in applied. These single value indicators are Normalised impact sound pressure level (L_n and L'_n) and Standardized impact sound pressure level (L'_{nT}).

The weighting procedure includes weighting the measurements using a reference curve and measurement curve. The reference curve is shifted gradually (in steps of 1 dB) towards the measurement curve until the sum of unfavourable deviation is as large as possible but no more than 32 dB. Unfavourable deviation occurs where the measurement is less than the reference value at a given frequency (after the two curves cross). Then the value of the reference curve at 500 Hz gives the single values $L_{n,w}$, $L'_{n,w}$, $L_{nT,w}$.

Furthermore ISO 717-2 (2013) defines procedures to evaluate weighted reduction in impact sound due to floor coverings and floating floors.

The following unweighted indices are measured either on field or laboratory for one third-octave frequency bands or octave frequency bands:

- Normalised impact sound pressure level (L_n) [dB]

Derived from one-third octave band values and calculated according to ISO 10140-3:2010 Formula 1 (Equation 152) based on laboratory measurement:

$$L_n = L_i + 10log\frac{A}{A_0} \tag{152}$$

- Normalised impact sound pressure level (L'_n) [dB]

Accounts for the additional effect of the sound transmitted by flanking elements. Derived from one-third octave band and one octave band values and calculated according to ISO 140-7:1998 Formula 2 (Equation 153) based on field measurement:

$$L_n = L_i + 10log\frac{A}{A_0} \tag{153}$$

- Standardized impact sound pressure level (L'_{nT}) [dB]

Accounts for the reservation time on the receiving room. Derived from one-third octave band and one octave band values and calculated according to ISO 140-7:1998 Formula 2 (Equation 154) based on field measurements:

$$L_{nT} = L_i - 10log\frac{T}{0{,}5} \tag{154}$$

For homogeneous floor constructions and partially homogeneous floor constructions ISO 12354-2 includes a procedure to estimate a normalized impact sound that is already weighted.

- Equivalent weighted normalized impact sound pressure level $L_{n,eq,0,w}$ of homogeneous floor constructions calculated according to ISO 12354-2:2016 Formula B.5 (Equation 155):

$$L_{n,eq,0,w} = 164 - 35log\frac{m'}{[1kg/m^2]} \tag{155}$$

- Equivalent weighted normalized impact sound pressure level $L_{n,eq,0,w}$ of floor constructions with clay hollow-pots and upper light screed layer (partially homogeneous), calculated according to ISO 12354-2:2016 Formula B.6 (Equation 156):

$$L_{n,eq,0,w} = 160 - 35log\frac{m'}{[1kg/m^2]} \tag{156}$$

where L_i is the impact sound pressure level (measured in the receiving room as the energy average of one-third octave), A is the measured equivalent absorption area [m^2], A_0=10 m^2 is the reference equivalent absorption area [m^2], T is the reverberation time in the receiving room [s], m' (for homogeneous) is the mass per unit area in the range from 100 kg.m^{-2} to 600 kg.m^{-2} and m' (for partially homogeneous) is the mass per unit area in the range from 270 kg.m^{-2} to 360 kg.m^{-2}.

In the various standards and regulations, the requirement maybe stated as such (source: ISO 717-1:2013):

Rw(C;C_{tr})=41(0;-5) dB (calculation values)

Rw=40,9dB ± 0,8dB (stated with uncertainties)

R'_w+C_{tr}=>45dB (minimum values)

The Austrian standard ÖNORM B 8115-2:2006 gives weighted standardized impact sound pressure level ($L'_{nT,w}$) maximum permitted values depending on if the building hosts business functions or not and on the neighbouring uses. Values range from $L'_{nT,w}$=33dB (between quarters in sales and storage facilities that function between 2200 to 0600) to $L'_{nT,w}$=46dB (between quarters of different units) and $L'_{nT,w}$=60 (between common spaces in business premises and similar spaces).

3.16.4 **Impact sound insulation per ASTM (IIC, FIIC) ***

The ASTM standards define single value indices for the evaluation of building elements in terms of impact sound insulation using procedures similar to those described in the ISO literature (see section 3.16.3). E.g.:

- Impact Insulation Class (IIC) (ASTM E989 - 06)
- field impact insulation class (FIIC) (ASTM E989 - 06)

4 Discussion

4.1 PIs in international standards

Building codes as well as other voluntary and compulsory compliance programs reference building performance standards issued by major organisations such as CEN, ISO, ANSI and ASTM as a reference source for PI information and performance criteria. These standards inform on the performance indicators in terms of application context, calculation method and recommended values.

Certain performance requirements are covered simultaneously in several documents issued by major standardisation organisations. For example, noise insulation indices are included both in ASTM and ISO standards. The indicators have different names but similar structure and calculation methods (e.g. STC and R_w).

Following are some of the most commonly referenced standards per domain:

- Multidomain: EN 15251:2007 and CEN/CR 1752 (1998) are widely used multidomain sources for performance criteria.
- Energy efficiency: EN 15603:2008 and EN 15217:2007 provide calculation methods and rating strategies for Energy Performance Indicator (EPI).
- Hygro-thermal performance: ISO 13788:2012 and ISO 9972:2015 provide calculation methods for condensation and air permeability.
- Thermal comfort: ISO 7730:2005 and ANSI/ASHRAE Standard 55-2013 provide calculation methods for various PIs and performance criteria.
- Visual environment: ISO 12464-1:2011 provides performance criteria in respect to different types of spaces.
- Indoor air quality: ANSI/ASHRAE Standard 62.1-2007 and BS EN 13779:2008 provide calculation methods for various PIs and performance criteria.
- Acoustic environment: ISO 3382-2:2008 provides calculation methods for room acoustics PIs, ISO 717-1 and ISO 717-2 provide calculation methods for building acoustics PIs (sound insulation) and standards ISO 9921:2003 and IEC 60268-16:2011 provide calculation methods and performance criteria for speech intelligibility PIs.

Table 13, Table 14, Table 15, Table 16 and Table 17 list the most important international standards per domain and the PIs included in each standard.

Table 13 Energy efficiency and hygro-thermal performance standards

No.	Title	Indicators
EN 15217:2007	Energy performance of buildings – Methods for expressing energy performance and for energy certification of buildings.	Primary energy (Ep)
		CO_2 emissions (mCO_2)
		Energy cost
EN 15603:2008	Energy performance of buildings – Overall energy use and definition of energy ratings	Annual Energy Demand
ANSI/ASHRAE 90.1-2007	Energy Standard for Buildings Except Low-Rise Residential Buildings	Energy Cost Budget (ECB)
		Performance Cost Index (PCI)
ANSI/RESNET 301-2014	Standard for the Calculation and Labelling of the Energy Performance of Low-Rise Residential Buildings using the HERS Index	Energy Rating Index (ERI)
ISO 9972:2015	Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method.	leakage rate (e.g. n_{pr}, q_{Epr})
		leakage area (e.g. E_{LApr}, E_{LAEpr})
ISO 13788:2012	Hygro-thermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods.	Temperature factor (f_{Rsi})
		Interstitial condensation

Table 14 Thermal comfort standards

No.	Title	Indicators
EN 15251:2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics	PMV/PPD
		Operative Temperature (TOP)
		Adaptive model
		elevated air speed
ISO 7730:2005	Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.	PMV/PPD
		long term indices
		local discomfort (PD): Draught risk, vertical temperature diff., cold surfaces, radiant asymmetry
ANSI/ASHRAE Standard 55-2013	Thermal Environmental Conditions for Human Occupancy	PMV/PPD
		Operative Temperature (TOP)
		effective Temperature (ET)
		Standard Effective Temperature (SET)
		Local discomfort (PD)
		Adaptive model
ISO 14505-2:2006	Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles – Part 2: Determination of equivalent temperature	Total and local equivalent temperature (t_{eq})
ISO/DIS 7243:2015	Ergonomics of the thermal environment – Assessment of heat stress using the WBGT (wet bulb globe temperature) index.	Wet Bulb Globe Temperature Index (WBGT)

Table 15 Indoor Air Quality (IAQ) standards

No.	Title	Indicators
EN 15251:2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics	ventilation rates per person and area (q_p, q_B)
		Exhaust Rates
		air change per hour (ACH)
EN 13779:2008	Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning system	Ventilation Effectiveness (ε_v)
		CO_2 (as an indicator of IAQ)
CEN/CR 1752	Ventilation for Buildings - Design Criteria For The Indoor Environment	Various indoor environment indicators
ANSI/ASHRAE 62.1-2007	Ventilation for Acceptable Indoor Air Quality	ventilation rates per person and area (R_p, R_a)
		Exhaust Rates
		Ventilation Effectiveness (ε_v)
ANSI/ASHRAE 62.2-2007	Ventilation and Acceptable Indoor Air Quality in Low-Rise	ventilation rates per person and area (R_p, R_a)
		Exhaust Rates
		Ventilation Effectiveness (ε_v)

Table 16 Visual environment standards

No.	Title	Indicators
EN 15251:2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics	Illuminance levels (E_v)
		Unified Glare Rating (UGR)
		Colour Rendering Index (R_a)
ISO 12464-1:2011	Light and lighting – Lighting of work places – Part 1: Indoor work places.	Illuminance levels (E_v)
		Illuminance Uniformity (U_o)
		Unified Glare Rating (UGR)
		Colour Rendering Index (R_a)

Table 17 Acoustic environment standards

No.	Title	Indicators
EN 15251:2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics	A-weighted Sound Pressure Level (dB(A))
ISO 717-1:2013	Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation.	weighted Sound reduction Indices (e.g. R'_w)
		weighted Level Differences (e.g. D_w)
ISO 717-2:2013	Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation.	(weighted) Impact Sound Pressure Levels (e.g. $_{Ln,w}$)
ISO 12354-1:2016	Building acoustics – Estimation of acoustic performance of buildings from the performance of elements. Airborne sound insulation between rooms	(weighted) Level Differences (e.g. $D_{m,w}$)
		(weighted) Sound Reduction Indices (e.g. R'_w)
ISO 12354-2:2009	Building acoustics – Estimation of acoustic performance of buildings from the performance of elements. Impact sound insulation between rooms	(weighted) Impact Sound Pressure Levels (e.g. Ln,w)
ISO 3382-2:2008	Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms.	Reverberation Time (e.g. T_{20}, T_{30})
		Early Decay Time (EDT)
		Sound Strength (G)
		Clarity (C_{50}, C_{80})
		Early lateral energy fraction (J_{LF}, J_{LFC})
		Late Lateral sound level (L_J)
		Inter-Aural Corss Correlation (IACC)
		Early and Late Stage support (ST_{early}, ST_{late})
ISO 3382-3:2012	Acoustics – Measurement of room acoustic parameters – Part 3: Open plan offices.	A-weighted sound pressure level of speech a 4m ($L_{p,A,S,4m}$)
		Distraction Distance (r_D)
		Spatial decay rate of A-weighted sound pressure level of speech ($D_{2,S}$)
ISO 9921:2003	Ergonomics - Assessment of speech communication	Speech Transmission Index (STI)
		Speech Interference Level (SIL)
IEC 60268-16:2011	Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index	Speech Transmission Index (STI)
ANSI S3.5-1997 (R2017)	Methods For Calculation Of The Speech Intelligibility Index	Speech intelligibility index (SII)
ASTM E1130 - 16	Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index	Articulation Index (AI)

ASTM E 1110-06	Standard Classification for Determination of Articulation Class	Articulation Class (AC)
ASTM E2638-10	Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room	Speech Privacy Class (SPC)
ASTM E413–16	Classification for Rating Sound Insulation	Sound Transmission Class (STC)
		Noise Isolation Class (NIC)
		Normalized Noise Isolation Class (NNIC)
ASTM E1332	Standard Classification for Rating Outdoor-Indoor Sound Attenuation	Outdoor Indoor Transmission Class (OITC)
ASTM E1414 / E1414M - 16	Standard Test Method for Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum	Ceiling Attenuation Class (CAC)
ASTM E989 – 06 (2012)	Standard Classification for Determination of Impact Insulation Class (IIC)	Impact Insulation Class (IIC)

4.2 PIs in the Austrian building codes and standards

State authorities and buildings stakeholders intergrade increasingly performance-based assessment methods into their legislative frameworks. As a result, building performance indicators are now part of the everyday practice of building professionals. As part of the necessary deliverables for building permits, many countries require a performance-based building assessment, which typically include energy efficiency certification, energy auditing and minimum prerequisites for heat and noise protection.

The Austrian framework for building regulation is not uniform over the country. The different federal states may use their own regulations or adjusted version of general regulations. The Austrian Institute of Construction Engineering (OIB) whose members are all the federal states, issues a set of directives (OIB Richtlinien) “in order to enable federal states to harmonise the technical requirements in the building regulations” (OIB 2017). The directives presented in this section, the “OIB Richtlinie 5” and the “OIB Richtlinie 6” address building performance issues pertinent to those discussed in this catalogue. These directives define measurements methods, often referring to dedicated Austrian standards of the ÖNORM framework and provide performance criteria.

The “OIB Richtlinie 6” addresses energy efficiency, hygro-thermal performance and thermal comfort issues and defines the framework for the Austrian Energy Performance Certificate (EPC). Table 18 lists examples of performance criteria prescribed in the directive. Table 19 lists U-values requirements for new buildings. Table 27 shows efficiency categories using the above three EPIs and the energy efficiency factor (f_{GEE}) as they are used in the Austrian Energy Performance Certificate (EPC).

In this same category, the national standards ÖNORM B 8110-2:2006 02 01 and ÖNORM B 8110-3:2012 03 15 address issues of moisture diffusion, condensation and summer overheating.

The "OIB Richtlinie 5" addresses room and building acoustic (noise protection) performance issues. The performance criteria of this directive cover (among other) airborne sound insulation (see Table 20, Table 21 and Table 22), impact sound insulation (see Table 23) and maximum permissible noise levels from mechanical equipment (see Table 24) as well as sound clarity and noise reduction (see Table 25).

The national standards ÖNORM B 8115-2:2006 12 01 and ÖNORM B8115-3 2006 address issues of noise protection and room acoustics respectively.

Table 18 Austrian prerequisites for energy efficiency and thermal protections in new buildings and renovations. Part of Austrian regulation "OIB Richtlinie 6" (sources: OIB Richtlinie_6 2015)

Energy efficiency and hygro-thermal performance requirements	Indicators	Performance criteria
Energy efficiency indicators	EPIs (Heating Demand, Primary Energy, CO_2 emissions and energy efficiency factor) See Table 27	47,6 $kWh.m^{-2}.a^{-1}$ (maximum heating demand for living units)
		47,6 $kWh.m^{-2}.a^{-1}$ (maximum heating demand for other type of units)
	Thermal transmittance (maximum U-values for building elements)	See Table 19
Envelope air tightness	Leakage rate (n50)	e.g. for new buildings $\leq 3\ h^{-1}$ (without ventilation) $\leq 1{,}5\ h^{-1}$ (with ventilation)
Protection against interstitial and surface condensation	Calculation: ÖNORM B 8110-2 (similar to ISO 13788:2012)	
Protection against summer overheating	Operative Temperature (t_{op}) calculation: ÖNORM B 8110-3	$t_{op} \leq 27$ °C $t_{op} \leq 25$ °C (Night-time in bedrooms)

Table 19 Examples of requirements thermal transmittance values (U-values) for building elements in new buildings according to Austrian regulation "OIB Richtlinie 6" (source: OIB Richtlinie 6 2015)

	Building Element	Maximum U-value[1] $[W.m^{-2}.k^{-1}]$
1	Wall against outside air	0,35
2	Wall in contact with earth	0,40
3	Partition wall in between living or business units or conditioned staircases	0,90
4	Inside wall in living or business units	-
5	Window, window-door, glass-door in living units against outside air	1,40
6	Other vertical transparent elements against outside air	1,70
7	Doors (without glass) against outside air	1,70
8	Doors (without glass) against unheated building areas	2,5

Table 20 Example of minimum required noise insulation for facade elements (exposed to different levels of outside noise) in living units, hotels, schools, kindergartens, hospitals etc using the weighted sound reduction index (R_w) (See section 3.16.1) (source: OIB Richtlinie 5 2015)

For outside noise level [dB]		Façade elements (all together) [dB]	Façade elements (opaque) [dB]	Windows and doors [dB]		Ceilings and walls against undeveloped roof spaces [dB]	Ceilings and walls against passages and garages [dB]	Partition walls between buildings [dB]
Day	Night	$R'_{res,w}$	R_w	R_w	R_{w+Ctr}	R'_w	R'_w	R_w
≤ 45	≤ 35	33	43	28	23	42	60	52
46 - 50	36 - 40	33	43	28	23	42	60	52
51 - 60	41 - 50	38	43	33	28	42	60	52
61	51	38,5	43,5	33,5	28,5	47	60	52
62	52	39	44	34	29	47	60	52
63	53	39,5	44,5	34,5	29,5	47	60	52
64	54	40	45	35	30	47	60	52
65	55	40,5	45,5	35,5	30,5	47	60	52
66	56	41	46	36	31	47	60	52
67	57	41,5	46,5	36,5	31, 5	47	60	52
68	58	42	47	37	32	47	60	52
69	59	42,5	47,5	37,5	32,5	47	60	52
70	60	43	48	38	33	47	60	52
71	61	44	49	39	34	47	60	52
72	62	45	50	40	35	47	60	52
73	63	46	51	41	36	47	60	52
74	64	47	52	42	37	47	60	52
75	65	48	53	43	38	47	60	52
76	66	49	54	44	39	47	60	52
77	67	50	55	45	40	47	60	52
78	68	51	56	46	41	47	60	52
79	69	52	57	47	42	47	60	52
≥ 80	≥ 70	53	58	48	43	47	60	52
The OIB Richtlinie 5 prescribes required values additionally for business and office buildings.								

Table 21 Minimum values for sound level difference between spaces using the weighted standardised level difference ($D_{nT,w}$) (See section 3.16.1). Part of the Austrian regulation "OIB Richtlinie 5" (source: OIB Richtlinie 5 2015).

To		From	$D_{nT,w}$ [dB] with and without connection thought doors, windows or other openings
1	Living spaces	Living spaces of other units	55/50
		General access areas (e.g. staircases, corridors, basements, communal spaces)	55 / 50
		Adjoining rooms of other units	55 / 50
2	Hotel rooms, classrooms, hospital rooms, rooms in kindergarten as well as living rooms in communal homes	Rooms of the same category	55 / 50
		General access areas (e.g. staircases, corridors, basements, communal spaces)	55 / 38
		Adjoining rooms	50 / 35
3	Adjoining rooms	Living spaces of other units	50 / 35
		General access areas (e.g. staircases, corridors, basements, communal spaces	50 / 35
		Adjoining rooms of other units	50 / 35
Minimum values of sound level difference for walls in between terrace houses is $D_{nT,w}$= 60 [dB]			

Table 22 Minimum values for sound insulation of doors using the weighted sound reduction index (R_w) (See section 3.16.1) (source: OIB Richtlinie 5 2015).

In between		And	R_w [dB]
1	General access areas (e.g. staircases, corridors)	Spaces in living units without acoustic isolated vestibules or halls	42
		Spaces in living units without acoustic isolated vestibules or halls	33
2	Living spaces	Living spaces of other units	42
		Adjoining rooms of other units	33
3	Hotel rooms, hospital rooms and living rooms in communal homes	Rooms of the same category	42
		General access areas (e.g. staircases, corridors)	33
4	classrooms and rooms in kindergarten	Rooms of the same category	42
		General access areas (e.g. staircases, corridors)	28

Table 23 Maximum values for impact sound insulation using the weighted Standardized impact sound pressure level ($L'_{nT,w}$) (see section 3.16.3) (source: OIB Richtlinie 5 2015).

in		from	$L'_{nT,w}$ [dB]
1	Living spaces	Rooms of other units (living units, schools, kindergartens, hospitals, hotels, communal homes, businesses and offices buildings and similar uses)	48
		General access terraces, raingardens, balconies, loggias and roofs	48
		General access areas (e.g. staircases, pergolas)	50
		Open to use (living units, schools, kindergartens, hospitals, hotels, communal homes, businesses and offices buildings and similar uses)	53
2	Adjoining rooms	Rooms of other units (living units, schools, kindergartens, hospitals, hotels, communal homes, businesses and offices buildings and similar uses)	53
		General access terraces, raingardens, balconies, loggias and roofs	53
		General access areas (e.g. staircases, pergolas)	55
		Open to use (living units, schools, kindergartens, hospitals, hotels, communal homes, businesses and offices buildings and similar uses)	58
Minimum values of sound level difference for walls in between terrace houses is $L'_{nT,w}$= 43 [dB]			

Table 24 Permissible noise levels from mechanic equipment using A-weighted and Equivalent sound pressure levels (see section 3.15.1) (source: OIB Richtlinie 5 2015).

Maximum permissible noise levels		$L_{AFmax,nT}$ [dBA]
from mechanic equipment of other units	Continuous and intermittent noise	25
	Short terms noise	30
Maximum permissible noise levels		$L_{Aeq,nT}$ [dBA]
from ventilation equipment for within the unit	Units that support sleep (e.g. spaces in living units except kitchens)	25
	Units that support concentration (e.g. classrooms)	30

Table 25 Room acoustic measures for the protection of sound clarity using the reverberation time (see section 0) (source: OIB Richtlinie 5 2015)

Space use	T [s] (for the 250 Hz - 2.000 Hz octave bands)
Speech rooms (e.g. lecture rooms) with 30 m³ and 10.000 m³ volume	T = (0,37 × lg V) - 0,14
Communication rooms (e.g. classrooms, meeting rooms, media rooms) with 30 m³ and 10.000 m³ volume	T = (0,32 × lg V) - 0,17
As part of the room acoustic measures the OIB Richtlinie 5 prescribes additionally minimum values of sound absorbance for the reduction of noise in spaces such as sports halls, school corridors, kindergarten classrooms etc.	

The Austrian federal states encourage developers to pursue high building performance thought the allocation of financial subsidies. The subsidies concern (among other) energy efficiency, air tightness as well as ecological issues and the prerequisites include the fulfilment of minimum required values for EPIs and other similar indicators (Amt der Tiroler Landesregierung 2017, Amt der NÖ Landesregierung 2017, Amt der Vorarlberger Landesregierung 2017). The values are typically set lower in respect to those set by the OIB Richtlinie 6.

4.3 PIs in Green Building rating and certification

Green building certification is a developing trend in the performance-based building sector. Green building schemes certify the "environmental performance" of a building depending on performance criteria in multiple performance domains such as resource consumption (e.g. embodied energy, operation energy, land), environmental loading (e.g. airborne emissions, liquid waste), indoor environment (e.g. thermal comfort, IAQ), longevity (adaptability, maintenance of performance), process (Design and construction, building operation) and contextual factors (e.g. loads on immediate surrounding) (Crawley et al. 1999). Credits are allocated for fulfilled criteria and each category sum is weighted accordingly to provide an overall score.

The performance criteria are typically set both in prescriptive and performance steps. For example, in BREEAM program's "visual comfort" category the requirements are sets using prescriptive measures such as the provision of internal and external shading elements to address glare but also using performance measures such as the Daylight Factor (DF) and the Uniformity ratio (U_o) to address daylight performance (BRE Global, 2016). Different requirements may be set for different kinds of buildings (e.g. residential, non-residential). Table 26 contains some of the most prevalent indicators used by the two most prevalent Green building schemes, the BREEAM & LEED programs

.

Table 26 Examples of performance indicators involved in the two of the most popular Green Building programs, BREEAM & LEED. (source: USGBC 2017, BRE Global 2016)

		BREEAM[1]	LEED[2]
Energy efficiency and hygro-thermal performance		• EPIs (primary energy, CO_2 emissions)[3] • Air tightness (e.g. n_{50})	• EPI (Cost Performance Index) according to ASHRAE 90.1 • Air tightness (e.g. n_{50})
Thermal comfort		• PMV/PPD (for HVAC operated building) • winter TOP and adaptive comfort (evaluated by CIBSE (for free-running buildings))	• PMV/PPD • PD (local) • TOP • SET • Adaptive ASHRAE 55 or ISO 7730/EN 15251
Indoor Air Quality (IAQ)		• Ventilation rates	• Ventilation rates Minimum exhaust rates • Ventilation effectiveness (ε_v)
Visual environment	Indoor lighting	• Illuminance levels (Ev) CIBSE SLL Code for Lighting 2012	• Illuminance levels (E_v) • Colour Rendering Index (CRI)
	Daylight performance	• Daylight Factor (DF) • illuminance ratio (Uo) • average and minimum illuminance levels over operating time	• spatial Daylight Autonomy (sDA) • Annual Sun Exposure (ASE)
	Glare	• requires glare control in prescriptive terms (e.g. blinds)	• Luminance levels (of luminaires for glare)
Acoustic environment	Noise	• A-weighted equivalent sound pressure level (LAeg,T)	• A-weighted sound pressure level (dBA) • RC Curves
	Building acoustics	• Weighted standardised level difference ($D_{nT,w}$) • Weighted impact sound pressure level ($L'_{nT,w}$)	• Sound transmission class (STC)
	Room acoustics	• Reverberation Time (T) • Speech Transmission index (STI)	• Reverberation Time (T60)

[1] BRE Environmental Assessment Method (BREEAM). [2] Leadership in Energy and Environmental Design (LEED®)

4.4 PIs in Energy Efficiency rating and certification

Energy performance certification has become a prerequisite for receiving a building permit in many parts of the world. Such certification may be carried either in prescriptive terms, where minimum values for the performance of separate building systems and elements are prescribed (e.g. U-values) or in performance terms, where the performance of the building is evaluated using an overall performance indicator. Various other hybrid methods used such as the "trade of", "model building" and "energy frame" methods lie in between these two approaches (IEA 2008).

The annual energy demand (see section 3.1.1) is the fundamental overall performance indicator used in performance-based energy rating schemes. The calculation of energy demand must follow an agreed upon procedure described usually in a dedicated standard (see Table 28). The parameters defined in such standards include:

- definition load calculation equations (losses and gains, recovery of energy losses)
- definition of the calculation period (typically a year, but interpolations are also possible)
- definition of the system's boundaries (typically includes HVAC systems, hot water systems, lighting and plug loads)
- definition of on-site energy production (RES) integration.

Moreover, standards and regulations define a set of minimum indoor environmental quality (and other performance related) conditions that a building must provide. These may include:

- Thermal Comfort
- Indoor Air Quality
- Air permeability
- Thermal bridges
- Shading devices

Some standards and some regulations set minimum U-value requirements (and other prescriptive measures) to be fulfilled alongside the performance-based requirements. Local authorities typically adjust these requirements to better represent the specificities of each area. In example, the European Union countries have their own implementation of the Energy Performance Certificate (EPC).

Whilst the annual energy demand is the fundamental indicator, most EPIs used are weighted versions of this indicator. Common weighted EPIs are:

- primary energy (E_p)
- greenhouse gas emissions (E_{mCO2});
- energy costs;

Table 27 shows efficiency categories using the above three EPIs and the energy efficiency factor (f_{GEE}) as they are used for the Austrian Energy Performance Certificate (EPC).

Table 27 Scale of efficiency categories used on the Austrian EPC (see sections 3.1.1) (sources: OIB Richtlinie_6 2015)

class	$HWB_{Ref,SK}$ [kWh.m⁻².a⁻¹]	PEB_{SK} [kWh.m⁻².a⁻¹]	$CO_{2\,SK}$ [kg.m⁻².a⁻¹]	f_{GEE} [-]
A++	10	60	8	0,55
A+	15	70	10	0,70
A	25	80	15	0,85
B	50	160	30	1,00
C	100	220	40	1,75
D	150	280	50	2,50
E	200	340	60	3,25
F	250	400	70	4,00
G	> 250	> 400	> 70	> 4,00
$HWB_{Ref,SK}$ (reference-Heating demand for local climate), PEB_{SK} (Primary energy for local climate), CO_{2SK} (CO_2 emmisions for local climate), f_{GEE} (energy efficiency factor: heating demand of the building divided to a reference heating demand)				

The EPIs may also express the energy balance. The energy balance is the delivered energy minus the energy exported and is particularly important in the case of energy efficiency programs such as the nearly Zero Energy Building (NZEB) or the Plus Energy Building where the implementation of renewable energy resources (on site or nearby) is part of the requirements.

For instance, EN 15217 suggests that the Equations 158 and 159 are be used to express the energy balance, using the primary energy (E_p) and greenhouse gas emissions (E_{mCO2}) respectively:

$$E_p = \sum (E_{del,i} * f_{P,del,i}) - (E_{exp,i} * f_{P,exp,i}) \quad (157)$$

$$E_{mCO2} = \sum (E_{del,i} * K_{del,i}) - (E_{exp,i} * K_{exp,i}) \quad (158)$$

where $E_{del,i}$ is the delivered energy for energy carrier i, $E_{exp,i}$ is the exported energy for energy carrier i, $f_{P,del,i}$ is the primary energy factor for the delivered energy carrier i, $f_{P,exp,i}$ is the primary energy factor for the exported energy carrier i, $K_{del,I}$ is the CO_2 emission coefficient for delivered energy carrier i, $K_{exp,I}$ is the CO_2 emission coefficient for the exported energy carrier *i.*

Producing an Energy Performance Certificate (EPC) typically requires some type of energy benchmarking using the EPI. This rating procedure is typically performed according to the following methods:

- comparison against a fixed value: e.g. the EPI is compare to an energy performance requirement set typically as a predefined value (e.g. Austrian energy performance certificate).
- benchmarked against a reference building: the EPI of the evaluated building is compare to the EPI of a reference building that is simulated using the same conditions (e.g. boundary condition) and a set of predefined values for the performance of building systems and elements (e.g. U-vales). This approach is the most common among the European EPCs.
- benchmarked against a stock of buildings: the EPI of the evaluated building is compare to the performance of a general building stock to indicate the performance of that building in respect to other buildings.

Table 28 lists weighted and unweighted EPIs and performance criteria used for Energy Performance Certificates other energy benchmarking programs such as the NZEB.

Table 28 Energy performance indicators for different categories of energy performance assessment.

<table>
<tr><th>Evaluation scope</th><th>Energy Performance Indicator (EPI)[1]</th><th>Performance criteria</th></tr>
<tr><td rowspan="2">Energy Performance Certificates (EPC)

e.g. EPBD (EU), Energy star (US), MOHURD (China)</td><td rowspan="2">Un-weighted EPIs
• Annual energy demand [kWh.m^{-2}.a^{-1}]
• Heating/Cooling demand [kWh.m^{-2}.a^{-1}]

Weighted EPIs
• Primary energy [kWh.m^{-2}.a^{-1}]
• CO_2 emissions [kg.m^{-2}.a-1]
• Energy cost [euro.m^{-2}.a^{-1}]</td><td>meet performance requirements in one or multiple EPIs</td></tr>
<tr><td>additional prescriptive measures may be required (e.g. U-values, Air permeability)</td></tr>
<tr><td rowspan="3">Energy performance beyond the codes

e.g. NZEB, Passivhaus</td><td rowspan="3">Weighted EPIs
• Primary energy [kWh.m^{-2}.a^{-1}]
• CO_2 emissions [kg_{CO2}.m^{-2}.a^{-1}]</td><td>meet performance requirements in one or multiple EPIs</td></tr>
<tr><td>Energy balance[2] requirements (Implementation of RES[3])</td></tr>
<tr><td>additional prescriptive measures may be required (e.g. Air permeability)</td></tr>
<tr><td colspan="3">[1] EPIs are also referred to as Energy Use Intensity (EUI). [2] Energy imported minus the on-site or nearby produced renewable energy. [3] Renewable Energy Sources (RES)</td></tr>
</table>

Besides the EPC, a new ambitious energy benchmarking system that goes beyond the requirements of building codes has been developed to help address future environmental challenges. This type of energy rating is designed to promote buildings that strive to equalise the energy balance (e.g. Nearly Zero Energy Buildings) or produce a negative sum (e.g. Plus Energy Buildings). The energy balance is typically expressed using EPIs such as the primary energy (kWh.m^{-2}.a^{-1}) and the CO_2 emissions (kg_{CO2}.m^{-2}.a^{-1}).

Various versions of these rating systems exist as different national or international organisations develop their own versions of energy efficiency programmes. According to an ECOFYS report (Hermelink et al. 2013) these programmes can be classified in the following categories (according to the energy balance and the EPI used):

- efficient buildings
- nearly zero-energy buildings
- zero energy buildings
- plus energy buildings
- nearly zero emission buildings
- zero carbon emission buildings
- zero heating demand buildings

One such pioneering program is the popular "Passivhaus" (Passive house) standard developed by Professors Bo Adamson and Wolfgang Feist. This standard defines the energy performance of the building using a set of indicators and criteria as shown in Table 29.

Table 29 Passive House criteria. "The categories Passive House Classic, Plus or Premium can be achieved depending on the renewable primary energy (PER) demand and generation of renewable energy" (source: Passive House Institute 2016)

			Criteria[1]			Alternative Criteria[2]
Heating demand	[$kWh.m^{-2}a^{-1}$]	≤	15			-
Heating load[3]	[$W.m^{-2}$]	≤	--			10
Cooling + dehumidification demand	[$kWh.m^{-2}a^{-1}$]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[$W.m^{-2}$]	≤	-			10
Pressurization test result n_{50}	h^{-1}	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[$kWh.m^{-2}a^{-1}$]	≤	60	45	30	±15 $kWh.m^{-2}.a^{-1}$ deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[$kWh.m^{-2}a^{-1}$]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

[1] The criteria and alternative criteria apply for all climates worldwide. The reference area for all limit values is the treated floor area (TFA) calculated according to the latest version of the PHPP Manual (exceptions: generation of renewable energy with reference to projected building footprint and airtightness with reference to the net air volume). [2] Two alternative criteria which are enclosed by a double line together may replace both of the adjacent criteria on the left which are also enclosed by a double line. [3] The steady-state heating load calculated in the PHPP is applicable. Loads for heating up after temperature setbacks are not taken into account. [4] Variable limit value for the dehumidification fraction subject to climate data, necessary air change rate and internal moisture loads (calculation in the PHPP). [5] Variable limit value for cooling and dehumidification demand subject to climate data, necessary air change rate and internal heat and moisture loads (calculation in the PHPP). [6] The steady-state cooling load calculated in the PHPP is applicable. In the case of internal heat gains greater than 2.1 W/m² the limit value will increase by the difference between the actual internal heat gains and 2.1 W/m². [7] The requirements for the PER demand and generation of renewable energy were first introduced in 2015. As an alternative to these two criteria, evidence for the Passive House Classic Standard can continue to be provided in a transitional phase by proving compliance with the previous requirement for the non-renewable primary energy demand (PE) of QP ≤ 120 kWh/(m²a). PHI may specify other national values based on national primary energy factors. The desired verification method can be selected in the PHPP worksheet "Verification". The primary energy factor profile 1 in the PHPP should be used. [8] Energy for heating, cooling, dehumidification, DHW, lighting, auxiliary electricity and electrical appliances is included. The limit value applies for residential buildings and typical educational and administrative buildings. In case of uses deviating from these, if an extremely high electricity demand occurs then the limit value can also be exceeded after consultation with the Passive House Institute. Evidence of efficient use of electrical energy for all significant devices and systems is necessary for this with the exception of existing devices which have already been owned by the user previously and for which an improvement of the electrical efficiency by means of upgrading or renewal would prove uneconomical over the lifecycle. [9] Renewable energy generation plants which are not spatially connected to the building may also be taken into account (except for biomass use, waste-to-energy plants, and geothermal energy): only new systems may be included (i.e. systems which did not start operation before the beginning of construction of the building) which are owned by the building owner or the (long-term) users (first-time acquisition).

However, perhaps the most popular category at the moment, are the Nearly Zero Energy Buildings (NZEB). The NZEB rating is adopted by the European Performance of Buildings Directive (EPBD) as part of the future energy efficiency targets. According to the directive the "'nearly zero-energy building' means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (DIRECTIVE 2010/31/EU, p. 18).

In the European Union, every state member adopted its own definition. The various definitions state minimum performance requirements for overall primary energy or primary energy requirements for individual building systems (heating, cooling, ventilation, hot water etc.). Balaras et al. (2014) published an overview of the various definitions (part of it shown in Table 30).

Table 30 Representative NZEB Definitions in European Countries (source: Balaras et al. 2014)

Country	EPI ($kWh.m^{-2}$)	Energy basis for comparison	End-uses[1]						Use of RES
	Residential		SH	SC	MV	DHW	SL	AP	
	Non-residential								
Belgium (Brussels)	45	Primary	▪			▪		▪	
	95-(2.5 volume/area envelope)	Primary	▪	▪		▪	▪	▪	
			▪	▪		▪		▪	
	40								
Cyprus	180	Primary	▪	▪		▪	▪		25%
	210								
Denmark	20	Primary	▪	▪	▪	▪			51-56%
	25		▪	▪	▪	▪	▪		
Estonia	50 (SFH), 100 (MFH)	Primary	▪	▪	▪	▪	▪		
	90 (S), 100 (O), 120 (PB), 130 (H), 270 (HC)								
France	50	Primary	▪	▪	▪	▪	▪		
	70 (O no AC), 110 (O with AC)								
	34 (S), 60 (O)		▪	▪	▪	▪	▪		

[1] SH: Space Heating, SC: Space Cooling, MV: Mechanical Ventilation, DHW: Domestic Hot Water, SL: Space Lighting, AP: Appliances

However, many energy efficiency assessment programs (voluntary and compulsory) are not restricted to performance-based assessment methods that use overall performance indicators but may require additional prescriptive measures. Some prescriptive measures are low level indicators such as the energy frame indicators, such as heat loss ($W.m^{-2}$) used to assess the performance of the building enclosure or basic performance metrics such as U-values, g-values, Solar Heat Gain Coefficient (SHGC) values, Visible Light Transmittance (VLT) values, Shading Coefficient (SC) values and even material property indicators (e.g. λ, μ, c). Some programs may include an alternative route of compliance using exclusively a prescriptive approach (e.g. ASHRAE Standard 90.1.) whilst other programmes might require the fulfilment of requirements using both performance and prescriptive methods.

5 Conclusion

5.1 The role of PIs in the educational process

The PIs are typically considered the end-product of a scientific process and, as such, they are commonly introduced in the latter parts of a typical educational process, following an extensive explanation of the phenomena involved. However, a direct exposure to a comprehensive record of these tools, such as the one presented in this thesis, may help students and professionals alike to explore the field of building science, quickly, effectively and in a structured manner. This catalogue reveals information on the following subjects:

- The spectrum of the building performance sector: what can be measured; what is meaningful to measure; what are the priorities of the various stakeholders; where do the scientific and professional practice intersect; are there any gabs in the current assessment possibilities; what is the prevalent terminology used in each domain.
- The nature of the performance requirements: which metrics are involved; in what ways and how much do they influence the overall outcome; which building systems are involved; what are the nuances between similar performance requirements; what are the prevalent measurement approaches.

For example, the variety and nature of the PIs in each domain may help the reader apprehend the spectrum of the performance requirements in that domain:

The performance indicators belonging to the domain of Energy efficiency and hygro-thermal performance reflect on the following performance requirements:

- Expected services and conditions provided through effective use of energy (consideration of indoor environmental quality factors).
- Mitigation of the negative effects of energy use on the environment (weighted EPIs).
- Energy autonomy of buildings (energy balance and implementation of RES).
- Structural integrity of building elements and systems (humidity condensation and air leakage).

The performance indicators belonging to the domain of thermal comfort reflect on the following performance requirements:

- Whole body thermal comfort (calculated for transient and steady-state conditions).
- Avoidance of thermal risks (strain from extreme environments, local thermal discomfort, summer overheating etc.).
- Thermal comfort provided in a cost effective and environmentally sustainable way (long-term indices and adaptive models).
- Compensation for unfavourable conditions (increased air speed, dehumidification etc.).

The performance indicators belonging to the domain of Indoor air quality (IAQ) reflect on the following performance requirements:

- Introduction of adequate clean air, based on pollution load or occupant perception.
- Effective distribution of clean air (and removal of contaminants) through the building and its zones.
- Effective distribution of heating and cooling energy for thermal comfort and energy efficiency.

The performance indicators belonging to the domain of the Visual environment reflect on the following performance requirements:

- Adequate amount of light to support activities and visual tasks.
- Uniformity of light distribution to avoid visual discomfort and strain.
- Adequate and effective utilisation of daylight.
- Avoidance of discomfort (or disability) glare form natural and artificial light sources.
- The ability of artificial light sources to render colours.

The performance indicators belonging to the domain of Acoustical performance reflect on the following performance requirements:

- Support for preferable subjective listener aspects (e.g. clarity, warmth, intimacy).
- Adequate speech perception.
- Privacy (and elimination of distraction) in open plan offices.
- Mitigation of noise (coming from within or out of the building).

5.2 Trends in the use of performance indicators

Observing the trends in the field of building performance as they are expressed through voluntary and compulsory compliance programs (e.g. building codes, rating schemes) the following may be deducted:

- Performance-based assessment methods using overall performance indicators are gaining ground, but prescriptive measures are not completely abandoned.
- The simpler indicators are more often represented in building performance rating and certification programs, especially in programs of compulsory compliance.

The first trend is observed in the increasing use of performance-based assessment methods by building codes (e.g. energy performance certification), as prescribed by new major legislative frameworks such as the Energy Performance of Buildings Directive (EPBD), and in the increasing popularity of building performance rating schemes such as the Green Buildings programmes. However, many compliance programs suggest additional assessment (or alternative assessment routes) thought the prescription of “low end” performance metrics. This practice is especially common in the domain of energy efficiency where metrics such as U-values, g-values, Solar Heat Gain Coefficients (SHGC) and leakage rates are regularly prescribed in the relevant standards and regulations.

The second trend is observed especially in the case of compulsory programs. For example, in the Austrian directive OIB Richtlinie 6 (2015), that deals with issues of hygro-thermal performance, the requirement for thermal comfort is set as a threshold for operative temperature (TOP) to predict summer overheating. Considering the possibilities of thermal comfort evaluation, this approach is perhaps the simplest. In another example, Green Building programmes such as BREEAM and LEED, do not use glare indicators to assess glare but rather reward the provision for glare control measures such as operable blinds or prescribe values using basic metrics such as luminance values for light sources within the field of view.

5.3 Future research for further development of this catalogue

In order to advance and maintain the credibility, usability and relevance of this catalogue, future research for further development is expected to address the following aspects:

- Integration of additional performance requirements, such as fire protection and ecological performance (e.g. Life Cycle Analysis indicators).
- Integration of future standards, directives and regulations.
- Integration of further comparative literature (e.g. reviews, rankings, gap analyses).
- Integration of further data to support the use of PIs (applicability context, measurement methods, PIs in the various software environments, PIs in building monitoring).
- Integration of an ontological analysis to assist better understanding and comparison between the various similar PIs.

6 Index

6.1 List of tables

6.2 List of equations

(38)Equation for the calculation of long-term comfort (method C), ISO 7730, 2005
(39)Equation for the calculation of long-term comfort (method D), ISO 7730, 2005
(40)Equation for the calculation of long-term comfort (method E), ISO 7730, 2005
(41)Equation for the calculation of overheating risk, CIBSE
(42)Equation for the calculation of $Exceedance_M$, Borgeson et al., 2010
(43)Equation for the calculation of Overheating risk (NaOR), Nicol et al., 2008
(44)Equation for the calculation of PD (air quality by CO_2), Fanger, 1987
(45)Equation for the calculation of PD (air quality by ventilation rate per person), Fanger, 1987
(46)Equation for the calculation of the perceive air quality, Fanger, 1987
(47)Equation for the calculation of total ventilation, ISO 15251, 2007
(48)Equation for the calculation of ventilation effectiveness, Mundt et al., 2004
(49)Equation for the calculation of the required ventilation
(50)Equation for the calculation of local air quality index, Mundt et al., 2004
(51)Equation for the calculation of Air change efficiency, Etheridge et al., 1996
(52)Equation for the calculation of local air change index, Mundt et al., 2004
(53)Equation for the calculation of Air Distribution Index, Karimipanah et al., 2008
(54)Equation for the calculation of Air Distribution Index (new), Almesri et al., 2013
(55)Equation for the calculation of effective draft temperature, ASHRAE handbook, 2009
(56)Equation for the calculation of illuminance at a point, IES Lighting Handbook, 2011
(57)Equation for the calculation of the Criterion Rating, IES Lighting Handbook, 2011
(58)Equation for the calculation of the Coefficient of variation, IES Lighting Handbook, 2011
(59)Equation for the calculation of Illum. Uniformity (min/avg), IES Lighting Handbook, 2011
(60)Equation for the calculation of Illum. Uniformity (min/max), IES Lighting Handbook, 2011
(61)Equation for the calculation of Illum. Uniformity (avg/max), IES Lighting Handbook, 2011
(62)Equation for the calculation of the J-index, Meyer et al., 1993
(63)Equation for the calculation of the Daylight Factor, Walsh, 1951
(64)Equation for the calculation of the Daylight Autonomy, Assoc. Suisse des Electriciens, 1989
(65)Equation for the calculation of the Continuous Daylight Autonomy, Rogers, 2006
(66)Equation for the calculation of the Zonal daylight autonomy, IES Lighting handbook, 2011
(67)Equation for the calculation of the Spatial Daylight Autonomy, IES, 2012
(68)Equation for the calculation of the Useful Daylight Illuminance, Nabil et al., 2006
(69)Equation for the calculation of the Frequency of Visual Comfort, Sicurella et al., 2012
(70)Equation for the calculation of luminance, IES Lighting Handbook, 2011
(71)Equation for the calculation of the British Glare Index, Petherbridge et al., 1950
(72)Equation for the calculation of the CIE's glare index, Einhorn, 1979
(73)Equation for the calculation of CIE's Unified Glare Rating, CIE, 1995
(74)Equation for the calculation of Visual Comfort Probability, Guth, 1963
(75)Equation for the calculation of the Discomfort Glare Rating
(76)Equation for the calculation of the Glare-sensation index
(77)Equation for the calculation of the BCD, Luckiesh et al., 1949
(78)Equation for the calculation of the Daylight Glare Index, Chauvel, 1982
(79)Equation for the calculation of the new Discomfort/Daylight Glare Index, Nazzal, 2005
(80)Equation for the calculation of the Discomfort Glare Probability, Wienold et al., 2006
(81)Equation for the calculation of the Discomfort Glare Probability (simplified), Wienold, 2007
(82)Equation for the calculation of the Predicted Glare Sensation Vote, Iwata et al., 1992
(83)Equation for the calculation of luminance of the field of view
(84)Equation for the calculation of Reverberation Time, Sabine, 1922
(85)Equation for the calculation of total equivalent absorption area

6.3 List of abbreviations

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating And Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BREEAM	Building Research Establishment Environmental Assessment Method
CEN	European Committee for Standardization
CIBSE	Chartered Institution of Building Services Engineers
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
ECA	European Collaborative Action
ECI	Energy Cost Index
EPC	Energy Performance Certificate
EPBD	European Performance of Buildings Directive
EPI	Energy Performance Indicator
EUI	Energy Use Intensity
HVAC	Heating, Ventilation, And Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environment Quality
IES	Illuminating Engineering Society (Of North America)
ISO	International Organization for Standardization
KSU	Kansas State University
LEED	Leadership in Energy and Environmental Design
NZEB	Nearly Zero Energy Buildings
PI	Performance Indicator
OIB	Österreichisches Institut für Bautechnik (Austrian Institute of Construction Engineering)
RES	Renewable Energy Resource
RIBA	Royal Institute of British Architects
SPL	Sound Pressure Level
WHO	World Health Organisation

7 Literature

This section contains the literature referenced in this master thesis. The literature has been classified per domain and alphabetically to help the reader located sources faster. Furthermore, literature that discusses multiple domains or aspects of the performance-based building sector is classified under "multi-domain" and standards are classified under "standards".

7.1 Standards

ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy.

ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality.

ANSI/ASHRAE Standard 62.2-2007, Ventilation and Acceptable Indoor Air Quality in Low-Rise.

ANSI/ASHRAE Standard 90.1-2007, Energy Standard for Buildings Except Low-Rise Residential Buildings

ANSI/RESNET Standard 301-2014. Standard for the Calculation and Labelling of the Energy Performance of Low-Rise Residential Buildings using the HERS Index

ANSI S3.5-1997 (R2017), Methods for calculation of the speech intelligibility index. Acoustical Society of America.

ASTM E1130-16, Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index, ASTM International, West Conshohocken, PA, 2016, www.astm.org.

ASTM E1110-06(2011), Standard Classification for Determination of Articulation Class, ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM E413-16, Classification for Rating Sound Insulation, ASTM International, West Conshohocken, PA, 2016, www.astm.org.

ASTM E1332-16, Standard Classification for Rating Outdoor-Indoor Sound Attenuation, ASTM International, West Conshohocken, PA, 2016, www.astm.org.

ASTM E1414-06, Standard Test Method for Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum, ASTM International, West Conshohocken, PA, 2006, www.astm.org.

ASTM E989-06(2012), Standard Classification for Determination of Impact Insulation Class (IIC), ASTM International, West Conshohocken, PA, 2012, www.astm.org.

ASTM E2638-10, Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room, ASTM International, West Conshohocken, PA, 2010, www.astm.org

BS EN 15217:2007, Energy performance of buildings – Methods for expressing energy performance and for energy certification of buildings.

BS EN 15251:2007, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics

BS EN 13779:2008, Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning system.

CEN/CR 1752, 1998. Ventilation for buildings - Design criteria for the indoor environment.

EN 12665:2016, Light and lighting – Basic terms and criteria for specifying lighting requirements

IEC 60268-16:2011, Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index. International Electrotechnical Commission

ISO 11855-1:2012, Building environment design-Design, dimensioning, installation and control of embedded radiant heating and cooling systems-Part 1: Definition, symbols and comfort criteria.

ISO 12354-1:2016, Building acoustics – Estimation of acoustic performance of buildings from the performance of elements. Airborne sound insulation between rooms

ISO 12464-1:2011, Light and lighting – Lighting of work places – Part 1: Indoor work places.

ISO 12354-2:2009, Building acoustics – Estimation of acoustic performance of buildings from the performance of elements. Impact sound insulation between rooms.

ISO 13788:2012, Hygro-thermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods.

ISO 14505-2:2006, Ergonomics of the thermal environment – Evaluation of thermal environments in vehicles – Part 2: Determination of equivalent temperature

ISO 3382-2:2008, Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms.

ISO 3382-3:2012, Acoustics – Measurement of room acoustic parameters – Part 3: Open plan offices.

ISO 717-1:2013, Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation.

ISO 717-2:2013, Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation.

ISO 7243:2017, Ergonomics of the thermal environment – Assessment of heat stress using the WBGT (wet bulb globe temperature) index.

ISO 7730:2005, Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

ISO 9921:2003, Ergonomics - Assessment of speech communication.

ISO 9972:2015, Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method.

7.2 Multi-domain

American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009. 2009 ASHRAE Handbook: Fundamentals. Inch-pound ed. Atlanta, Ga.: ASHRAE.

Augenbroe, G., 2011. The role of simulation in performance based building. In: Hensen, J.L.M. and Roberto, L. (Eds.). Building Performance Simulation for Design. London and New York: Spon Press, pp. 15-35.

Bluyssen, P.M., 2009. The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable. London and Sterling, VA: Earthscan.

BRE Global, 2016. BREEAM UK New Construction non-domestic buildings technical manual 2014. https://www.breeam.com/BREEAMUK2014SchemeDocument/#_frontmatter/cover_nd_all.htm%3FTocPath%3D_____1. Accessed 31.10.2017

Crawley, D.B. and Aho, I., 1999. Building environmental assessment methods: Applications and development trends. Building Research and Information 27. pp. 300-308 DOI:10.1080/096132199369417

Deru, M. and Torcellini, P., 2005. Performance Metrics Research Project. National Renewable Energy Laboratory, Golden, Colorado, USA.

DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union L 153, 18th July, pp. 13-35.

Fisk, W.J., 2000. Health and productivity gains from better indoor environment and their relationship with building energy efficiency. Annual Review of the Energy and the Environment 25, pp 537-566.

Hasselaar, E., 2006. Health performance of housing: Indicators and tools. Amsterdam: IOS Press BV.

Hensen, J.L.M. and Lamberts, R. (Eds.), 2011. The role of simulation in performance based building. In:. Building Performance Simulation for Design. London and New York: Spon Press

Jasuja, M. (ed.), 2005. PeBBu 2nd International State of the Art Report: PBS state of the art. Rotterdam: PeBBu.

OIB, 2017. https://www.oib.or.at/en/about-us. Accessed 31.05.2017

Passive House Institute, 2016. Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard.

Steskens, P. and Loomans, M., 2010. Perfection Performance Indicators for Health, Comfort and Safety of the Indoor Environment FP7 Grant Number 212998 - T1.3 A Review of Performance Indicators for Health and Comfort. Eindhoven: Eindhoven University of Technology.

Seppänen, O., Fisk, W. and Mendell, M.J., 2002. Ventilation rates and health. ASHRAE Journal 44(8), pp. 56-58

U.S. Department of Energy, 2017. EnergyPlus™ Version 8.8.0 Documentation Engineering Reference. https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.8.0/EngineeringReference.pdf. Accessed 06.12.2017

USGBC, 2017. LEED v4 for building design and construction. https://www.usgbc.org/sites/default/files/LEED%20v4%20BDC_07.8.17_current.pdf. Accessed 31.05.2017

Amt der Tiroler Landesregierung, 2017. Wohnbauförderungsrichtlinie. https://www.tirol.gv.at/fileadmin/themen/bauen-wohnen/wohnbaufoerderung/downloads/wbf-richtlinie_1-10-2017.pdf. Accessed 06.12.2017.

Amt der NÖ Landesregierung, 2017. wohnbauförderung eigenheim. http://www.noe.gv.at/noe/Wohnen-Leben/EH-broschuere2017final.pdf. Accessed 06.12.2017.

Amt der Vorarlberger Landesregierung, 2017. Neubauförderungsrichtlinie 2016/2017 für den privaten Wohnbau. http://www.vorarlberg.at/pdf/neubaufoerderungsrichtlin.pdf. Accessed 06.12.2017.

7.3 Energy efficiency and hygro-thermal performance

Balaras, C., Daskalaki, E.G., Droutsa, K.G., Kontoyiannidis, S., Guruz, R. and Gudnason, G., 2014.Energy and other key performance indicators for buildings-Example of Hellenic buildings. Global journal of energy technology research updates 1, pp. 71-89.

Hermelink, A., Schimschar, S., Boermans, T., Pagliano, L., Zangheri, P., Armani, R., Voss, K. and Musall, E., 2013. Towards nearly zero-energy buildings: Definition of common principles under the EPBD Final report. Ecofys

IEA, 2008. Energy efficiency requirements in building codes, energy efficiency policies for new buildings. Paris: OECD/International Energy Agency (IEA).

IEA, 2010.Energy Performance Certification of Buildings: A policy tool to improve energy efficiency Paris: OECD/International Energy Agency (IEA).

7.4 Thermal comfort

Azer, N.Z. and Hsu, S., 1977. The prediction of Thermal Sensation from Simple model of Human Physiological Regulatory Response. ASHRAE Trans 83.

Borgeson, S. and Brager, G.S., 2010. Comfort standards and variations in exceedance for mixed-mode buildings. Build. Res. Inf. 39(2), pp. 118–133.

Carlucci, S., 2013. Thermal Comfort Assessment of Buildings. Milan: Springer.

Cheng, Y., Niu, J. and Gao N., 2012. Thermal comfort models: A review and numerical investigation. Building and Environment 47, pp. 13-22.

Cropper, P.C., Yang, T., Malcolm, J.C., Fiala, D. and Rehan, Y., 2008. Exchange of simulation data between CFD programs and a multi-segmented human thermal comfort model. Proceedings of conference: air conditioning and the low carbon cooling challenge Cumberland lodge. 27-29 July. London, UK.

de Dear, R.J. and Brager, G.S, 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104 (1a), pp. 145-167.

Epstein, Y. and Moran, D.S., 2006. Thermal comfort and the heat stress indices. Industrial health 44, pp. 388-398.

Fanger, P.O., 1970. Thermal comfort. Copenhagen: Danish technical press

Fobelets, A.P.R. and Gagge, A.P., 1988. Rationalization of the effective temperature, ET*, as a measure of the enthalpy of the human indoor environment. ASHRAE Transactions 94(1), pp.12–31.

Gagge, A.P., Fobelets, A.P. and Berglund, L., 1986. A standard predictive index of human response to the thermal environment. ASHRAE Transactions 92(2), pp. 709-731.

Gagge, A.P., Stolwijk, J.A.J. and Nishi, Y., 1971. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Transactions 77(1), pp. 247-262.

Gauthier, S., 2013. The role of environmental and personal variables in influencing thermal comfort indices used in building simulation. In: Conference of International Building Performance Simulation Association, 26-28 August, Chambéry, France.

Givoni, B and Goldman, R., 1971. Predicting metabolic energy cost. Journal of Applied Physiology 30:429-433.

Houghten, F.C. and Yaglou, C.P., 1923. ASHVE Research Report 673. ASHVE Transactions 29, pp. 361.

Humphreys, M.A. and Nicol, J.F., 1998. Understanding the adaptive approach to thermal comfort. ASHRAE Transactions 104 (1b), pp. 991-1004.

McCartney, K.J and Nicol, J.F., 2002. Developing an Adaptive Control Algorithm for Europe: Results of the SCATs Project. Energy and Buildings 34(6), pp. 623-663.

Nicol, J.F., Hacker, J., Spires, B. and Davies, H., 2008. Suggestion for new approach to overheating diagnostic. In: Proceedings of Conference: Air Conditioning and the Low Carbon Cooling Challenge, 27-29 July, London, UK.

Nishi, Y. and Gagge, A.P., 1971. Humid operative temperature, a biophysical Index of thermal sensation and discomfort. J. Physiol. (Paris) 63, pp. 365-368.

Psomas, T., Heiselberg, P., Duer, K. and Bjørn, E., 2015. Analysis and comparison of overheating indices in energy renovated houses. In: 14th Conference of International Building Performance Simulation Association, 7-9 Dec., Hyderabad, India.

Stolwijk, J.A.J., 1971. A mathematical model of physiological temperature regulation in man, NASA Contractor Report, NASA CR-1855. Washington, DC: National Aeronautics and Space Administration..

Taleghani, M., Tenpierik, M., Kurvers, S. and van den Dobbelsteen, A., 2013. A review into thermal comfort in buildings. Renewable and sustainable energy reviews 26, pp. 201-215.

Winslow, C.E.A., Herrington, L.P. and Gagge, A.P., 1938. Physiological reaction and sensations of pleasantness under varying atmospheric conditions. Trans ASHVE 44, pp. 179-196.

7.5 Indoor Air Quality

Almesri, I., Awbi, H.B., Foda, E. and Siren, K., 2013. Air distribution index for assessing the thermal comfort and air quality in uniform and nonuniformthermal environments. Indoor and Built Environment 22, pp. 618-639.

Awbi, B., 2017. Ventilation for good indoor air quality and energy efficiency. Energy Procedia 112, pp. 277 – 28

Etheridge, D. and Sandberg, M., 1996. Building ventilation: theory and measurement. England: John Wiley & Sons.

European Concerted Action (COST 61 3), 1991. Report No. 10: Effects of indoor air pollution on human health. Commission of the European Communities, Luxembourg.

European Concerted Action (COST 61 3), 1992. Report No. II: Guidelines for Ventilation Requirements in Buildings. Office for Publications of the European Communities. Luxembourg.

Fanger, P. O., 1987.Introduction of the olf and the decipol Units to Quantify Air Pollution Perceived by Humans Indoors and Outdoors. Energy and Buildings 12(1), pp. 1–6.

Karimipanah, T., Awbi, HB. and Moshfegh, B., 2008. The air distribution index as an indicator for energy consumption and performance of ventilation systems. Journal of the Human-Environment System 11, Miller, P.L. and Nevins, R.G., 1970. Room air distribution performance of ventilating ceilings and cone-type circular ceiling diffusers. ASHRAE Transactions 76(1), pp. 186

Mundt, E. (Ed.), 2004. Ventilation Effectiveness. REHVA Guidebook no 2. pp. 77-84.

Yaglou, C.P. and. Witheridge, W.N., 1937. Ventilation requirements, Part 2. ASHRAE Transactions 42, pp. 423-436.

7.6 Indoor visual environment

Association Suisse Des Electriciens ASE 1989. Eclairage interieur par la lumicre du jour. Zürich

Bellia, L., Cesarano, A., Iuliano G.F. and Spada, G. 2008. Daylight glare: A review of discomfort indexes. In: Proceedings of Visual Quality and Energy Efficiency in Indoor Lighting: Today for Tomorrow, Rome, Italy.

Boyce, P.R., 2003. Human Factors in Lighting. New York, Massachusetts (USA): Taylor & Francis.

Carlucci, S., Causone, F., De Rosa, F. and Pagliano, L., 2015. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renewable and Sustainable Energy Reviews 47, pp. 1016-1033.

Chauvel, P., 1982. Glare from windows: current views of the problem. Lighting Research and Technology 14(1), pp. 31-46.

CIE 13.2 1965. Method of measuring and specifying colour rendering properties of light sources. Vienna, Austria: Commission Internationale de l'Eclairage.

CIE Puplication no. 117, 1995. Discomfort glare in interior lighting, Commission Internationale de l'Eclairage. Vienna, Austria.

Davis, W. and Ohno, Y., 2005. Towards an improved colour rendering metric. In: SPIE 5941, 5TH international conference on solid state lighting. DOI: 10.1117/12.615388

DiLaura, D., Houser, W., Mistrick, G. and Steffy, R., 2011. IES The Lighting Handbook 10TH. New York (USA): Illuminating Engineering Society.

Einhorn, H.D., 1979. Discomfort glare: a formula to bridge differences. Lighting Research and Technology 11, pp. 90-94.

Fotios, S.A., 1997. The perception of light sources of different colour properties. PhD dissertation. University of Manchester Institute of Science and Technology.

Guth, S.K., 1963. A method for the evaluation of discomfort glare. Illuminating Engineering 57, pp. 351-364.

Hashimoto, K., Yano, T., Shimizu, M. and Nayatani, Y., 2007. New method of specifying colour rendering properties of light sources based on feeling of contrast. Color Res. Appl. 32(5), pp. 361-371.

IES, 2012. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)., Illuminating Engineering Society.

Iwata, T., Shukuya, M., Somekawa, N. and Kimura, K., 1992. Experimental study on discomfort glare caused by windows - Subjective response to glare from a simulated window. Journal of Architecture, Planning and Environmental Engineering 432, pp. 21-33.

Jakubiec, J. and Reinhart, C., 2012. The 'adaptive zone'- A concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology 44(2), pp. 149-170.

Judd, D.B., 1967. A flattery index for artificial illuminants. Illum. Eng. (USA) 62, pp. 593-598.

Meyer, J.J., Francioli, D., Rey, P. and Benoît, F., 1993. Visual discomfort: Evaluation after introducing modulated light equipment. In: Proceedings right light 2nd European conference on energy-efficient lighting. Arnhem (NL), pp. 348-357.

Luckiesh, M. and Guth, S.K., 1949. Brightness in visual field at borderline between comfort and discomfort (BCD). Illuminating Eng (New York) 44(11), pp. 650-670.

Nabil, A. and Mardaljevic, J., 2006. Useful daylight illuminances: A replacement for daylight factors. Energy and Buildings 38(7), pp. 905-913. S

Nazzal, A., 2005. A new evaluation method for daylight discomfort glare. International Journal of Industrial Ergonomics 35(4), pp. 295-306.

Petherbridge, P. and Hopkinson, R.G., 1950. Discomfort glare and the lighting of buildings. Transactions of the Illuminating Engineering Society 15, pp. 29-79.

Pointer, M.R., 1986. Measuring colour rendering-a new approach. Lighting Res Technol. 18(4), pp. 175-184.

Reinhart, C.F. and Walkenhorst, O., 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings 33(7), pp. 683-697.

Reinhart, C.F., Mardaljevic, J. and Rogers, Z., 2006. Dynamic Daylight Performance Metrics for Sustainable Building Design. LEUKOS 3(1), pp. 7-31.

Rogers, Z. and Goldman, D., 2006. Daylighting Metric Development Using Daylight Autonomy Calculations in the Sensor Placement Optimization Tool. Development Report and Case Studies, Boulder, Colorado: Architectural Energy Corporation.

Sicurella, F., Evola, G. and Wurtz, E., 2012. A statistical approach for the evaluation of thermal and visual comfort in free-running buildings. Energy and Buildings 47, pp. 402-410.

Thornton, W.A., 1974. A validation of the colour preference index. J. Illum. Eng. Soc. 4, pp. 48-52

Thornton, W.A., 1972. Colour-Discrimination Index. J. Opt. Soc. Am 62(2), pp. 191-194

Wienold, J. and Christoffersen, J, 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy & Buildings 38(7), pp. 743-757.

Walsh, J.W.T., 1951. The early years of illuminating engineering in Great Britain. Transactions of the Illuminating Engineering Society 15(3), pp. 49-60.

Wienold, J., 2007. Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. In: Proceedings of Building Simulation. Beijing, China, pp. 1197-1204.

Xu, H., 1993. Colour rendering capacity and luminous efficiency of a spectrum. Lighting Res. Technol. 25(3), pp. 131-132.

7.7 Indoor acoustic environment

Abdel Alim, O., 1973. Abhängigkeit der Zeit- und Register- durchsichtigkeit von raumakustischen Parametern bei Musikdarbietungen. Dissertation, TU Dresden.

Ahnert, W. and Tennhardt H.P., 2008. *Acoustics for Auditoriums and Concert Halls*. In: Ballou, G.M. (Ed.). Handbook for sound engineers. Oxford: Elsevier, pp: 145-200.

Ahnert, W. and Schmidt, W., 1980. Akustik in Kulturbauten (Acoustics in cultural buildings). Berlin: Institut für Kulturbauten.

Ballou, G.M. (Ed.), 2008. Handbook for sound engineers. Oxford: Elsevier.

Beranek, L., 1947. The Design of Speech Communication Systems. Proc. IRE 35, pp. 880-890.

Beranek, L., 1962. Music, Acoustics and Architecture. New York, London: John Wiley and Sons.

Beranek, L., 1989. Balance noise-criterion (NCB) curves. The Journal of the Acoustical Society of America 86 (650), p. 650. DOI: 10.1121/1.398243.

Beranek, L., 2003. Subjective rank-orderings and acoustical measurements of fifty-eight concert halls. ACTA Acoustica united with Acoustica 89, pp. 494-508.

Beranek, L., 2004. Concert Halls and Opera Houses: Music, Acoustics, and Architecture. New York: Springer.

Beranek, L.L. and Schultz, T. J., 1965. Some recent experiences in the design and testing of concert halls with suspended panel arrays. Acustica 15, pp.307-316.

Berglung, B., Lindvall and T., Schwela, D.H. (Eds.), 1999. Guidelines for community noise. Geneva, World Health Organisation.

Boothroyd, A., 2004. Room acoustics and speech perception. Seminars in Hearing 25, pp. 155-166.

Bradley, J.S., 1986. Predictors of speech intelligibility in rooms. J. Acoust. Soc. Am. 80, pp. 837-845.

Bradley, J.S., 2010. Review of objective room acoustics measures and future needs. In: Proceedings of the International Symposium on Room Acoustics, 29-31 August, Melbourne, Australia.

Bradley, J.S. and Soulodre, G., 1995. Objective measures of listener envelopment. J. Acoust. Soc. Am. 98, pp. 2590-2597.

Bradley, J.S. and Soulodre, G., 1997. Factors influencing the perception of bass. In: 133rd meeting of the Acoustical Society of America, J. Acoust. Soc. Am. 101, pp. 3135.

Davis, D., 1979. The role of Initial Time-Delay Gap in the Acoustic Design of Control Rooms for Recording and Reinforcing Systems". In: Sixty-fourth Audio. Engr. Soc. Convention, 2-5 November 1979, New York, NY.

Dietsch, L. and Kraak, W., 1986. Ein objektives Kriterium zur Erfassung von Echostörungen bei Musikund Sprachdarbietungen (An objective criterion for capturing echo disturbances with music and speech performances). Acustica 60, pp. 205.

Everest, F.A., Pohlmann, K.C., 2009. Master Handbook of Acoustics 5th Edition. New York: McGraw-Hill.

Eyring, C.F., 1930. Reverberation Time in 'Dead' Rooms". J. Acoust. Soc. Am. 1, pp. 217-241.

Gade, A.C., 1989. Investigations of musician's room acoustic conditions in concert halls. Part I: Methods and laboratory experiments. Acustica 69 , pp. 193.

Gade, A.C., 1989. Investigations of musician's room acoustic conditions in concert halls. Part II: Field experiments and synthesis of results. Acustica 69 , pp. 249.

Gade, A., 2007. Acoustics in hall for speech and music. In: Rossing, T.D. (Ed.). Springer Handbook of Acoustics. New York: Springer, pp 301-350.

Cerdá, J.S., Giménez, P.A., Romero F.J., Cibrián, O. and De Anda, R., 2011. A Factor Analysis Approach to Determining a Small Number of Parameters for Characterising Halls. Acta Acustica united with Acustica. 97(3), pp. 441-462. DOI:10.3813/AAA.918425.

Griesinger, D., 1999. Objective Measures of Spaciousness and Envelopment. In: AES 16th International Conference on Spatial Sound Reproduction, 10-12 April, Rovaniemi, Finland.

Gover, B.N., and Bradley, J.S., 2011. ASTM metrics for rating speech privacy of closed rooms and open plan spaces. Canadian Acoustics 39(3), pp. 50-51.

Hongisto, V., 2005. A model predicting the effect of speech of varying intelligibility on work performance. Indoor Air 15(6), pp. 458-468.

Jamagushi, K., 1972. Multivariate Analysis of Subjective and Physical Measures of Hall Acoustics. Journal of the Acoustical Society of America 52 (5A), pp. 1271–1279.

Januska, I., 1968. Experimentally Stated Correlation between Objective Echogramm Evaluation and Speech Intelligibility. Archivum Akustiki 140.

Klein, W., 1971. Articulation loss of consonants as a basis £or the design and judgment of sound reinforcement systems, J.Audio Erg.Soc. 19(11) pp. 920-922.

Kuhl, W., 1978. Räumlichkeit als Komponente des Raumeindrucks. Acustica 40, pp. 167.

Kürer, R., 1971. Einfaches Messverfahren zur Bestimmung der 'Schwerpunktzeit' raumakustischer Impulsantworten (A simple measuring procedure for determining the "center time" of room acoustical impulse responses). In: Proceedings of the 7th International Congress on Acoustics, Budapest, Hungary.

Lacatis, R., Gimenez, A., Barba Sevillano, A., Cerda, S., Romero, J. and Cibrian, R., 2008. Historical and chronological evolution of the concert hall acoustics parameters. J. Acoust. Soc. Am. 123, pp. 3198–3204.

Lehmann, P., 1976. Über die Ermittlung raumakustischer Kriterien und deren Zusammenhang mit subjektiven Beurteilungen der Hörsamkeit. PhD dissertation: Technische Universität Berlin, Germany.

Lehmann, U., 1974. Untersuchungen zur Bestimmung des Raumeindrucks bei Musikdarbietungen und Grundlagen der Optimierung. PhD dissertation: Technische Universität Dresden.

Lochner, J.P.A. and Burger, J.F., 1961. The Intelligibility of Speech under Reverberant Conditions. Acustica 11, pp. 195.

Peutz, V.M.A., 1971. Articulation loss of consonants as a criterion for speech transmission in a room. J.Audio Eng.Soc. 19(11),. pp. 915-919.

Reichardt, W., Abdel, A.O. and Schmidt, W., 1974. Abhängigkeit der Grenzen zwischen brauchbarer und unbrauchbarer Durchsichtigkeit von der Art des Musik Motives, der Nachhaltikeit und der Nachhaleinsatzzeit. Appl Acoust 7, pp. 243-264.

Reichardt, W., Abdel, A.O. and Schmidt, W., 1975. Zusammenhang zwischen Klarheitsmaß C und anderen objektiven raumakustischen Kriterien. Zeitschrift für elektrische Information und Energietechnik 5, pp. 144-155

Rossing, T.D. (Ed.), 2007. Springer Handbook of Acoustics. New York: Springer.

Sabine, W.C., 1922. Collected Papers on Acoustics. Cambridge: Harvard University Press

Soulodre, G. and Bradley, J.S., 1995. Subjective evaluation of new room acoustic measures. J. Acoustic. Soc. Am. 98(1), pp. 294-301.

Thiele, R., 1953. Richtungsverteilung und Zeitfolge der Schallrückwürfe in Räumen. Acustica 3. pp. 291.

Tocci, G.C., 2000. Room noise criteria-The state of the art in the year 2000. Noise/News International 8, pp. 106-119.

Seddeq, H. S., 2012. Acoustics of Suspended Ceilings and Speech Privacy. Canadian Acoustics 40(4), pp. 23-27.

Schmidt, W., 1979. Raumakustische Gütekriterien und ihre objektive Bestimmung durch analoge oder digitale Auswertung von Impulsschalltestmessungen. PhD Dissertation: B Technische Universität Dresden, Germany.