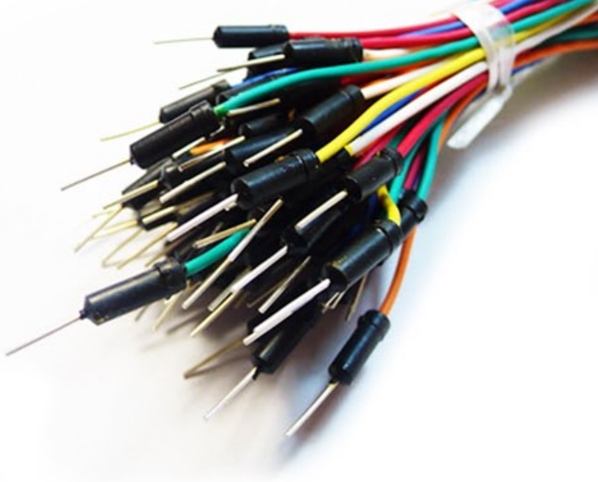

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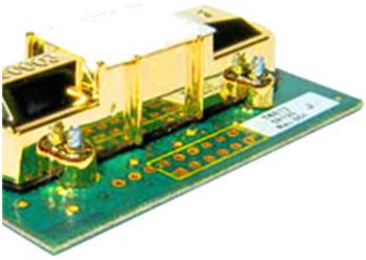

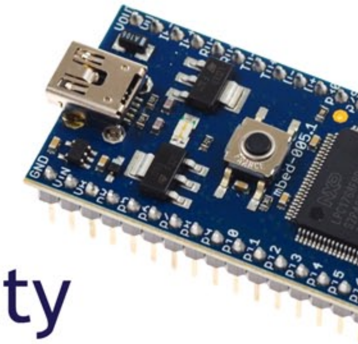

Indoor Environmental Quality Assessment Tool - The Occupant Manikin

10th semester
group: IE9-3-e16

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AALBORG UNIVERSITY
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Synopsis:

This report is a result of a long master thesis project, accomplished by the group of Indoor Environmental and Energy Engineering students from Aalborg University. The main goal of the project was to design and develop Indoor Environmental Quality (IEQ) assessment scheme together with the development of the measuring unit prototype - a manikin. With the realization how challenging and interdisciplinary venture is ahead, project group decided on collaboration with a group of Computer Science students on the measuring unit data acquisition system. Project group succeeded in developing a comprehensive IEQ scoring system that is able to quantitatively and qualitatively assess the indoor environment. Although it is based on broad literature review, long-term evaluation is required to validate its outcome in various spaces. Since it was expected that not all of the project goals will be met, in required time frame, project group tried to adopt modular approach during work, to allow modification and further expansion of the assessment method itself as well as the prototype. The prototyping process is described and project progress evaluated up to the stage that was possible to accomplish before the submission date.

Acknowledgments

We would like to acknowledge project supervisor Rasmus Lund Jensen, for scientific guidance, acquisition of funding for the project and unceasing motivation. We express special appreciation to Flemming Christensen for scientific counseling and knowledge sharing. Moreover, we are indebted to Kim Borup and Nikolaj Holk for their dedication to the project and a considerable amount of work done on the measuring unit customization. Finally, we would like to express special thanks to the group of Computer Science students for their substantial contribution to the project.

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Introduction

This master project aims to design a system able to assess and quantify indoor environment. In order to achieve this goal, the work consists of developing a prototype of a measuring unit, formulating an evaluation method, and designing a tool that will combine these two. Another challenge taken up in this project is to make the system easy to run and understand for regular users.

Measuring and quantifying indoor environment is important for the following reasons, among others, checking the overall well-being of occupants, giving feedback to building owners and designers, providing evidence on the correlation between indoor environment and user satisfaction, health, and productivity. As the time spent indoors increases gradually and was said to equate up to 87 % during a typical day of a statistical American according to Klepeis et al. (2001), the effect of indoor environment on people grows accordingly. Estimated time spent in different places was visualized in figure 1. This does not remain without influence on human comfort and, what is more important, health.

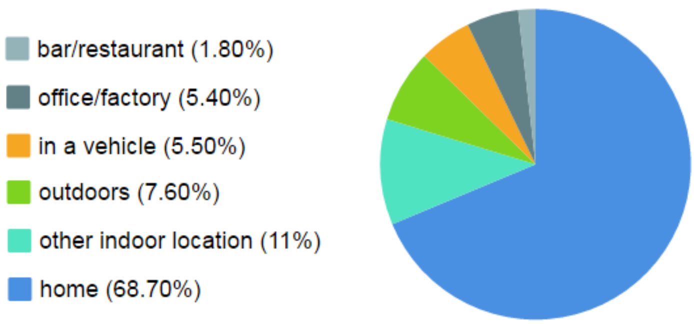

Figure 1: Amount of time spent by people in various locations, (source: Klepeis et al. 2001, page 239).

When we consider a human in a certain environment, his or her body is influenced by a number of factors. Some of these influences are depicted in figure 2. Obviously, not all indoor spaces have negative impacts, however, it is not a trivial task to maintain a good quality of indoor environment. In order to monitor indoor environmental quality, complex Building Monitoring Systems (BMS) are installed, or periodic assessments are performed.

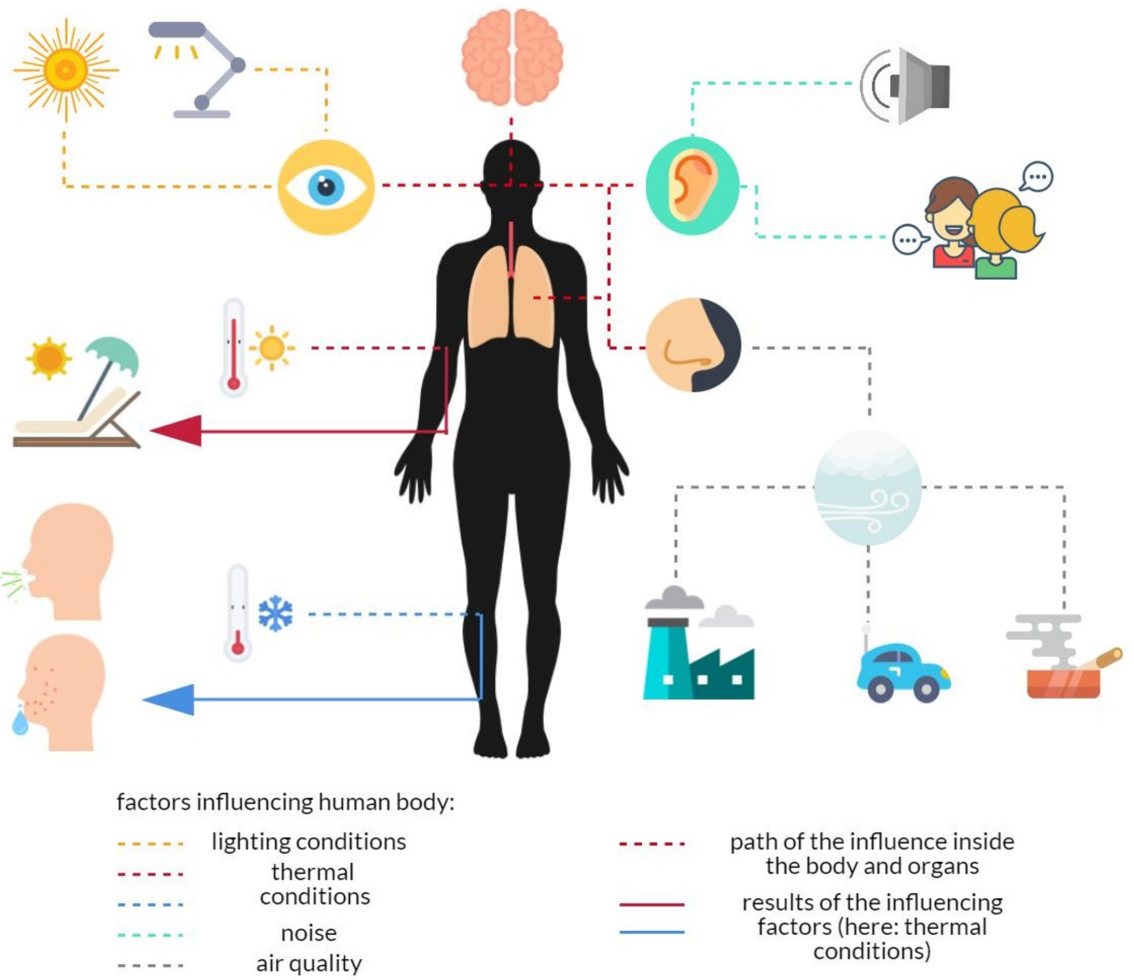

Figure 2: Main environmental factors affecting a human being.

Measuring the "state" of indoor environment can be done in many ways, and with varying degree of reliability. There are some well-described methods of assessing indoor environmental quality (IEQ), most of which either do not include all parameters, important from occupant perspective or are very thorough but focus on a design and pre-occupancy stages. The post-occupancy evaluation is usually performed when there are some alarming issues reported by the occupants. Typically, the so-called post-occupancy evaluation is done objectively, by using measured data, subjectively, by conducting surveys among occupants, or by a combination of the two. However, some issues arise regardless of selected method. First, and the most obvious one, is the equipment required for measurements. Quality tools available on the market are costly, their work depends on cyclic calibration and are usually much too complex to be used by an inexperienced user. Additionally making measurements usually requires a lot of time and labor for setting up the equipment and data processing. Another point is a level of subjectivity associated with questionnaires. Humans

are affected by many more factors than just environmental indicators, such as psychological and physiological issues. For instance, a bad atmosphere among co-workers or non-building related health problems may significantly affect given opinions. Are the researchers able to distinguish between biased and unbiased answers? Typically, no. Those and many more uncertainties are connected to IEQ assessment and have to be addressed in order to provide a reliable evaluation system. This project is an attempt to solve some of the aforementioned problems. The proposed measuring unit has a purpose of mimicking human senses such as vision, hearing, breathing and thermal perception. It is equipped with sensors detecting and measuring environmental parameters, and a controlling module that is gathering data and sending it to a server, where it is evaluated. Assessment of the measured values is done in a few stages. First, each parameter is checked individually, then after weighting their importance within category (visual, acoustic, thermal, air quality), category score is assigned, in the end, an overall score is given for the 'entire' indoor environment (figure 5.1 with representation of this scheme is presented in chapter 5 section 5.1). Then scores are sent to a mobile application, where they can be viewed by users. Additionally, whenever an unwanted event is detected by the unit, warnings are prompted in the application, informing on what is the problem and if an action is required from the user. Entire system is described in detail in part II of the report.
The idea behind the measuring unit was to measure as many important factors as possible, with satisfactory accuracy, possibly cheap technology, and limiting requirement for maintenance. The most complex IEQ measuring units developed before have usually a form of a cart (as in figure 3), and are equipped with advanced, rather expensive instruments. The figure below presents also an example of questionnaire station, with various additional measuring equipment. In order to combine these two types of IEQ assessments into one tool, the unit developed in this thesis has a human shape (a manikin) and the assessment methodology is based on human responses to sensed parameters.

Figure 3: Mobile IEQ assessment cart (BOSSA Nova) and IEQ survey station, (BOSSA 2017).

Primary goals and ideas

Since the topic chosen by the authors of this thesis is very broad, the scope was narrowed down to the range of goals that seemed realistic in a given time-frame. By achievement of described objectives, the development process taken by the authors could be considered complete. The list should be treated as milestones to be referred to during progressing of the work and used for time scheduling and creating more detailed lists of tasks. The order of the goals is caused by a natural consequence of the development process. Every next aim can only be reached if all the previous are completed.

The set of goals that should be accomplished by the project work:

- ☐ Create a list of important IEQ parameters
- ☐ Finding health, performance, comfort impact of selected parameters
- ☐ Development of the scoring system for IEQ assessment
- ☐ Design of the measuring unit
- ☐ Creation of measuring unit prototype
- ☐ Implementation of the scoring system to the prototype
- ☐ Prototype testing and evaluation
- ☐ Development of user friendly application

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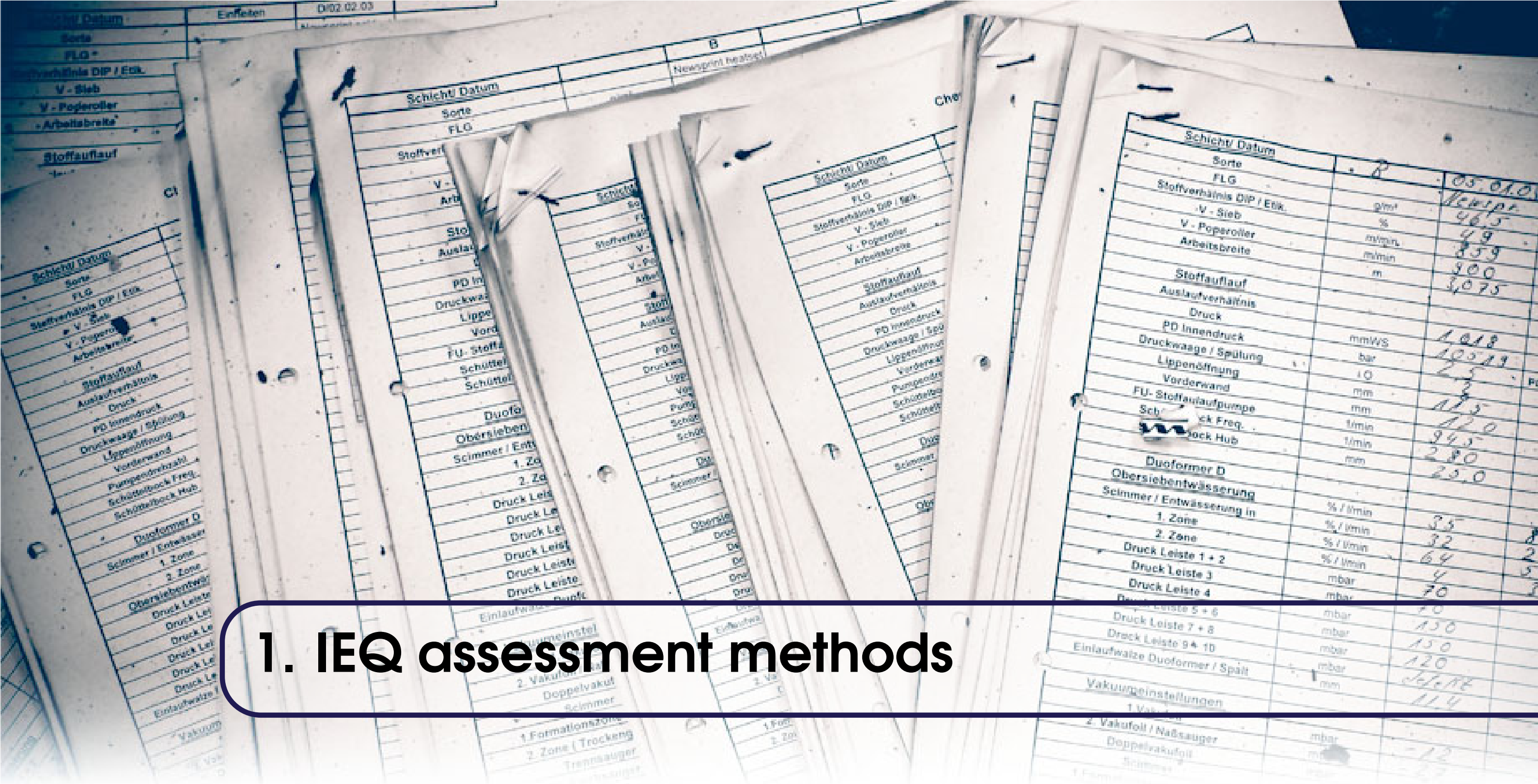

1. IEQ assessment methods

This chapter summarizes the knowledge about measuring and assessing IEQ found in up to date Standards and guidelines. Described methods were chosen due to their wide application and broad view on the topic of indoor spaces and their impact on occupant well-being.

1.1 Standards Review

Standards are documents providing guidelines and rules for a big range of processes, providing standardization in safety, quality, prices any many other benefits. They bring together all the interested parties such as users, customers, manufacturers, and services. A standard represents a variety of technical solutions with a common basis for mutual understanding. Generally, it codifies best practice and is usually state of the art.

1.1.1 EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings (...)

Standard specifies input parameters for designing and assessing the energy performance of a building with respect to indoor air quality, thermal environment, lighting, and acoustics. It specifies mainly the dimensioning of systems and establishing design criteria. The most important parameters are used for energy performance and long term indoor environment evaluation. However, the outcome of the standard is focusing on energy efficiency, and the overall indoor environment quality is at a lower significance. Considering the most recent studies, which show that work, learning capabilities, and absenteeism have improved greatly in buildings with good IEQ. It is important to highlight, that bad indoor environmental quality in some cases is a result of energy saving precautions. However, this intention might yield the opposite effect and the performance of the employees can decrease, resulting in higher costs for the employer.
To clarify, users tend to adapt their behavior to bad IAQ, for example, open windows if odor, excessive temperature or other irritation occurs, adjust heating to their personal needs, operate

window blinds and turning on artificial light, etc.
Main focus areas of the standard are:

- the indoor environmental parameters which have an impact on the energy performance of buildings,
- how to establish indoor environmental input parameters for building systems design and energy performance calculation,
- how different categories of criteria for the indoor environment can be used. Only suggestions are given. Strictly given parameters are up to national regulations or individual project specifications.

Standard does not prescribe design methods, but gives input parameters to the design of buildings, cooling, heating, ventilation and lighting systems, it also does not include criteria for local discomfort factors like draught, radiant temperature asymmetry, vertical air temperature differences and floor surface temperatures.

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Figure 1.1: EN 15251 categories used for the recommended input values, source: *DS/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.*

- **Thermal Environment**
  The standard allows usage of two different methods for thermal comfort evaluation, the PMV - PPD Index, or the Adaptive Comfort Model. The adaptive model tends to suggest low room temperatures for Nordic countries in early and late summer. The indoor operative temperature is based on the *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.* and *DS/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.*
  The ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning) adapted approach is based on a weekly weighted external temperature in EN 15251. Categories within the thermal environment are only specified by recommended temperature intervals for the PPD calculation.

  The standard **does not account** any variability in the usage of PMV - PPD index such as increased air velocity, asymmetric radiant temperature, draught, vertical air temperature difference or surface temperatures. Local phenomena **is only used** for HVAC dimensioning and later energy consumption.

- **Indoor Air Quality and Ventilation**
  Different methods are given in the standard to calculate the recommended ventilation rates. The minimum ventilation rate needs to dilute the bio-effluents (organic contaminants resulting from the human metabolic processes). These contaminants next to odor can be carbon dioxide, methanol, ethanol, acetone and many more according to (Swarzup, Mishra, and Jauhari 1992). In EN 15251 three quality categories are specified based on a percentage of dissatisfied people (based on people entering the space). Humans adapt to biological effluents quicker than to building emissions, what should be accounted also to the ventilation rates. The best-agreed approximation is to use ventilation rate to remove the building pollution (given as l/m^2) and adding ventilation rates per person (diluting the bio-effluents).

  EN 15251 in comparison to (ASHRAE 2013) differs significantly in the ventilation rates and there's **no general agreement** on rates to use. The only IAQ indicator is the CO_2. An auxiliary indicator is used to categorize "pollution". For this indice the Total Volatile Organic Compounds (TVOC) concentrations are recommended for each type of room. Further the standard defines buildings as: very low-polluting, low-polluting and not low-polluting. The pollution category depends on concentration of: total volatile organic compounds (TVOC). For example a few compounds are listed: formaldehyde, ammonia, carcinogenic compounds and not odorous materials.

  The CO_2 levels are not consistent with the ventilation rates. Even though the standard is focusing on designing mainly HVAC systems some drawbacks occur. Air cleaning is not taken into account, however it could lower the energy consumption (need for less fresh air). Air distribution system effectiveness (air leakage, temperature losses in the ducts) are not accounted for in EN 15251.

- **Visual Comfort**
  Categories to assess the daylight comfort level are based on **daylight factor**. Daylight factor (DF)[%] is a ratio of light levels inside the building (working plane height) to light levels outside the building (horizontal plane, unobstructed from the overcast sky or hemisphere). Three categories of daylight factor are recommended. The standard only refers to (CEN 2011b). Another category describing visual comfort is **Seasonal Affective disorder** (SAD) also called as winter depression is a mood disorder that affects people with normal mental health. It generally occurs during the same period of the year (generally winter).

  Even after the newest revision, it stipulates on the single work-plane illuminance requirement at 500 lux without respect to the performed visual task. For glare assessment UGR 2.4.5 static metrics is used.

  Daylight is also accounted, so emphasis is put to distinguish between artificial and natural light. Minimum illumination of walls and ceiling is specified to create an uniformly illuminated working space. Illuminance uniformity is divided into 3 categories.

- **Acoustic Comfort**
  The standard mainly focuses on designing HVAC (Heating, Ventilation and Air-Conditioning) components and recommends noise limits. A-weighted equivalent sound pressure level (explained further in the acoustics chapter) is used to evaluate the noise from HVAC systems and outdoor noise.

There is no specified noise assessment. Only dB(A) noise levels (based on specific room types) are recommended.

Summary

This standard is widely used in the European Union and the above-mentioned part only showed some of the issues related to the topics described in this work. The final output is specifying a design threshold for all the parameters. Given thresholds determine in which "quality category" the parameters are without giving an overall score. The categories are only further used to determine the energy efficiency of the building system. Mainly HVAC design parameters are proposed, with minor focus on human comfort.

1.1.2 DS/EN 3033 - Danish standard for indoor climate

This Danish standard is classifying the quality of the indoor environment in buildings. Applies to new or existing buildings. The following statement introduces the standard: "Our dwellings must have a good and healthy environment that does not make us ill. Our schools and childcare institutions must provide a good and healthy framework for children's upbringing and a good learning environment. Our offices and workplaces must be healthy in order not to reduce our work capacity or motivation."
The standard uses a classification scheme distinguishing four classes:

Class 1 Very good indoor environment - comfortable thermal conditions (entire year) with possible individual adjustments. Low air pollution even in cases where pollutant concentrations are higher than normal. Light and noise conditions are good allowing the occupant making adjustments.

Class 2 Good indoor environment - buildings designed by using European standards and in current use. Only occasional discomfort (temperature in very hot summer days, poor lighting or acoustics, and odor).

Class 3 Satisfactory indoor environment - buildings designed and built in the late 20th century and currently still in use. Same discomfort phenomena as in class 2.

Class 4 Poor indoor environment - Buildings not meeting the current requirements for indoor environment quality. Possible health-related risks and safety problems.

The resulting report contains all the results for each of the eight parameters. Even when the parameter values are shown, the appropriate class value has to be expressed.

The standard covers office buildings, schools, kindergartens and residential buildings. Following parameters are chosen for evaluation:

1. Ventilation rate and CO_2 concentration levels,
2. Thermal conditions,
3. Radon concentration,
4. Formaldehyde and other hazardous chemicals,
5. Particles and fibres,

(6) Dampness and mould,
(7) Light conditions,
(8) Acoustic conditions.

The ensure the robustness of the classification the following points have to be ensured:

- Examined building has to be used with the intended design. Classification cannot be done if building is visibly damaged, it is used for a different purpose or is showing serious health hazard (such as asbestos),
- Hypersensitivity of occupants is examined (some people might be very sensitive, have allergies or asthma),
- Seasonal variations are included in the standard specifications not to affect classifications depending on seasonal changes (or number of occupants)
- Satisfaction surveys are used for cases where the measurements period is not credible enough. Therefore, surveys are supplementing the actual user satisfaction leading to robust evaluation and classification.

Conclusion
This standard provides a comprehensive and simple evaluation of indoor environment. It categorizes all the eight parameters into four different classes.

Document includes the exact measurements and also their locations. Provides fixed thresholds for all the indices evaluated. The standard is applicable for different buildings, also the state of the buildings (either new or older). The main advantages of the standard are: evaluating all the **fundamentals and occurrence** of all the indices, describing **effect on humans**, providing **target values** (thresholds) and **assessment methods**. The supplementing questionnaires are also included.

1.1.3 Performance Measurements Protocols (PMP)

Standardized and consistent set of protocols is needed to establish a way of measuring building performance. Such protocols give also an insight to designers and owners when the designed performance does not correspond to the actual performance. The PMP's were created by ASHRAE, U.S. Green Building Council (USGBC) and Chartered Institution of Building Service Engineers (CIBSE).

PMP's provide a consistent set of protocols to facilitate the measurements of:

- Energy,
- Water,
- Indoor air quality,
- Thermal comfort,
- Lighting,
- Acoustics.

The protocols provide benchmarks and provide a possibility to compare buildings. Comparison either to a reference building or "self-reference" (before and after renovation). Each parameter and the way of how it is measured is described in the supplementing documentation (instrumentation and spatial resolution). There are three levels developed based on **cost/accuracy** :

- Low
- Medium
- High

Each of the mentioned levels provides different ranges of choices, details, effort, and comparison to different benchmarks see table 1.1

Measure Categories	**Levels of Performance Objectives (Cost/Accuracy)**
Energy Use	**Basic** (Simple and Low Cost - Indicative)
Water Use	Annual, Whole-Building Data used
Thermal Comfort	**Intermediate** (Medium Technical Skill Level and moderate cost)
Indoor Air quality	Monthly data used or measurements
Daylight, light	**Advanced** (High Cost and Accuracy, Expert Skill Level needed)
Acoustics comfort	Weekly, Daily and hourly data and measurements are used

Table 1.1: PMP's levels and details, source: *ASHRAE 2010 - Performance Measurement Protocols for Commercial Buildings.*

Energy

Established the energy performance of the building (related to peer buildings), characterizes the annual energy use and cost. The annual energy use and cost are calculated by the last 12 consecutive months data logs. Benchmarks used for comparison are:

- Energy Performance of Buildings Directive (rating in Europe)
- Energy Star Portfolio Manager (rating in U.S.)

Uses building plans and specifications to evaluate, also the process is supplemented by a walk-through audit. *ANSI/ASHRAE 105-2007 - Standard Methods of Measuring, Expressing and Comparing Building Energy Performance.* is including all the necessary forms.

Water

Water consumption is measured, the whole-building usage and cost are evaluated. Identifies any saving potentials. The basic level measurement of water is taken typically monthly. Later the annual water use and cost are normalized by m^2 of the building and number of occupants.
As the difficulty level increases, for intermediate measures weekly and monthly data is statistically treated to find patterns and further improvements. Advanced measures include daily and hourly data treatment. Benchmarks used for comparison are DOE/FEMP and European indices (depending on building type).

Indoor Environmental Quality Measurement Protocols

Observation of the building is the first step to evaluate IEQ, followed by questionnaires to determine the satisfaction of the occupants.

- **Thermal comfort** measurement include spot measurements, complaint logs, and survey outcomes. Spot measures are relative humidity, mean radiant temperature, air velocity to determine the cause of any complaints.

Benchmarks in this case are peer buildings and older questionnaires and past surveys. An outcome is compared to several hundred peer building and can be visualised as a "Satisfaction score with a percentile rank".

- **Indoor Air Quality** observations are based on complaint logs and operation documents of the HVAC system. Determines the occupancy satisfaction based on surveys. Ventilation rates are checked if they comply with *ANSI/ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality.*
  Intermediate levels of measurements are optimizing the HVAC system by continuously measuring the indoor environment and prevent failures. Advanced level characterizes asymmetrical environments in temperature, radiant cooling/heating, draught and transient environments. Occupants are surveyed for 2 weeks on-line for a "right now" response. For evaluation, the ASHRAE 55 standard is used. Advanced levels require measurements and evaluation of:
  - Airflow patterns
  - Duct leakages
  - Outside air contaminants
  - CO_2 levels in representative spaces
  - base levels for CO_2, PM 2.5 and TVOCs
  - Formaldehyde, VOCs, Radon, and microbial are only measured if these substances are suspected.
- **Lighting quality** is established based on spot measurements of general photometric parameters to identify the location of problems and occupants dissatisfaction. For the basic level of evaluation, only the illuminance at representative work surfaces is evaluated. Measured data is compared to recommended levels by IESNA and EN 12464 (by space type). For advanced measures, HDR photography can be used to determine luminance or evaluation of glare takes place.

HDR photos are taken to obtain luminance levels, uniformity ratio is calculated, glare assessment based on the UGR indice is calculated. Very detailed analysis of lighting conditions is proposed at the highest level of accuracy.

- **Acoustics** Occupants are surveyed to identify noise problems, evaluation of background noise is done using A-weighted sound pressure level (spot measurements). The measurements are done during full HVAC operation. For the intermediate level, the idea is to provide a more detailed evaluation and discover potential issues. At advanced levels, high-resolution data is obtained for critical situations (special acoustic need such as privacy or high levels of speech communication).

For intermediate and advanced measurements, the following parameters are assessed:

- Speech privacy rating,
- Speech intelligibility rating,
- Reverberation time,
- Background noise in octave bands.

Conclusion

PMP's are mainly based on surveys and spot measurements. Between each level of accuracy, there's a significant difficulty increase of performing the measurements or calculations. Considering the basic level, only rough performance estimations are possible. With the increasing evaluation complexity, the building performance assessment is more accurate. Advanced levels of performance measures were up to the newest trends and possibilities in the building industry when they were developed.

1.2 Scoring systems/schemes

To integrate environmental criteria into the design process, assessment tools are becoming commonplace in the design procedure. A new layer of restrictions is added, increasing the complexity of criteria to create a solution that satisfies all parties involved in the building process. The schemes should be transparent in their assumptions, easy to adapt, robust and unbiased.

1.2.1 German Sustainable Building Council: DGNB

In terms of sustainability, the performance of a building is assessed using 40 different criteria. The DGNB mainly focusses on buildings' or districts' performance rather than measured parameters. It is a voluntary scheme, based on building's life cycle and the impact of materials used for construction. Every international scheme has the same core criteria application, which is used in combination with scheme sheets, that provide detailed information. Points are awarded in all criteria for precisely defined evaluation requirements. Points are then collected and accordingly weighted in the evaluation matrix. Finally, an overall assessment of all criteria from the matrix is carried out. As a characteristic of DGNB one score is given for the building and one score for the construction site area. The core catalog has the 6 core criteria presented if figure 1.2.

Figure 1.2: DNGB core criteria weights, source: http://www.dgnb.de/en/

Relevant criteria in **DGNB** concerning the human perception of comfort, are included in the Sociocultural and Functional Quality:

- **Thermal Comfort**
  The share of total building score is **4.3%**. Thermal comfort in DGNB depends on the:
  - Room temperature
  - Surfaces' temperature and temperature asymmetry
  - Draught
  - Relative humidity

  In addition to the overall comfort, local phenomena have to be accounted. However, assessment is conducted by the means of a thermal building simulation or measurement in accordance with EN 15251 (with all the drawbacks) for thermal comfort and *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.* for draught evaluation.

A DGNB scheme expands the thermal and draught evaluation with local thermal comfort assessment, therefore it creates a more robust thermal comfort evaluation.

- **Indoor Air Quality**
  The share of total building score is **2.6%**. The aim is to ensure air quality, that does not affect users' health and well-being. Buildings with indoor air containing TVOC in concentrations greater than $3000\mu g/m^3$ or a formaldehyde concentration greater than $120\mu g/m^3$ are excluded from the certification. EN 15251 predicts the percentage of dissatisfied users based on the ventilation rate. EN 15252 is used to design "very low emission building", where VOC emissions are limited to the levels set out by VOC and formaldehyde indicator. Indoor air check-list includes quantitative and qualitative indicators, which are combined to give an IAQ score. The following indicators are described:

  – Indoor air quality - Volatile Organic Compounds (VOC),
  – Perceived air quality (not used yet),
  – Microbiological contamination (not used yet),
  – Occupancy-based ventilation rates.

  TVOC concentration limits are based on EN ISO 16000-6 and ISO 16000-3. The different substances list can be found in Appendix. Perceived air quality and microbiological contamination is not yet scientifically verified.

  Perceived air quality and microbiological contamination measurements could be included. Scheme assessment is limited only to VOC as harmful substances, whereas particles and other gases are neglected.

  Templates for further development are prepared, such as perceived air quality and microbial contamination. Their implementation is going to give more emphasis on humans comfort and overall well-being.

- **Visual Comfort**
  Share of the total building score is **2.6%**. User satisfaction is linked to their sense of comfort. Daylight has a positive effect on human physical and mental health. Therefore, emphasis is put on ensuring uninterrupted supply of daylight and artificial light in the interior. Visual comfort is evaluated by means of the following indicators:
  – Availability of daylight throughout the building,
  – Availability of daylight in working areas for regular use,
  – View to the outside,
  – Preventing glare from daylight,
  – Preventing glare from artificial light,
  – Colour rendering,
  – Sunlight.

  Daylight is calculated according to simplified (CEN 2005a). Daylight availability is obtained with utilization of the usable floor area with one determined daylight factor. Daylight factor is calculated in accordance with *DIN 5034-1:2011-07 - Tageslicht in Innenräumen.*

The illuminance requirement is specified from the EN 15251, by that said only a single level of 500 lux, is required. Daylight factor and seasonal affective disorder (SAD) should be included also. Another drawback is the use of static visual indices. However, few indices such as color rendering, glare, etc. need to be evaluated by people. Automatization of this process is very difficult.

Including criteria such as glare and color rendering is a benefit. However, the indices used are static and based on out-dated researches. Including psychological factors such as an outside view is a benefit.

- **Acoustic Comfort**
  The share of total building score is **0.9%**. The aim is to assure suitable acoustic quality with respect to room function. The acoustic comfort has a significant influence on human performance at the workplace according to (Hughes 1978). The criterion refers to *DIN 18 041:2016-03 - Acoustical quality in small to medium-sized rooms.* application of this standard is justified by its international application and existence of its English translation. The main objective is to enhance performance and comfort of the occupants. Only an appropriate room acoustic will guarantee a sufficient level of user comfort. Depending on the use of the room, different measures are required. In spaces where speech communication is important a good level of speech intelligibility is desired. By that said, a good value of the speech intelligibility index is desired.

Only reverberation time is used for evaluation and therefore the method focuses mainly on design phase. Impact of furnishing is not accounted for, instead the shape factor is used for describing the furnishings' damping.

DGNB scheme is based on an individual assessment of each criterion, which can receive a maximum set of points. Next step. After obtaining the group performance index, each group is weighted accordingly to obtain the overall certification level. In figure 1.3 the detailed structure of each criteria groups is depicted with their relevant weight to the overall score.

Evaluation Area	Criteria Group	Criteria	Criteria Points Max.Possible	Weighting Factor	Weighting Points Max. Possible	Group Points Max. Possible	Group Weight
Health, Comfort and User Satisfaction	Thermal comfort	Operative temperature (Heating period)	10	3	30	100	4.3 %
		Drafts (Heating Period)	10	1	10		
		Radiant heating asymmetry and floor temperature (Heating period)	5	1	5		
		Relative humidity (Heating period)	5	1	5		
		Operative temperature (Cooling period)	10	3	30		
		Drafts (Cooling Period)	10	1	10		
		Radiant heating asymmetry and floor temperature (Cooling period)	5	1	5		
		Relative humidity (Cooling period)	5	1	5		
	Indoor Air quaility	Volative organic compounds	10	5	50	100	2.6%
		Ventilation rate	10	5	50		
	Acoustic comfort	Indiviual office/ meeting room <40m^2	35	1	35	110	0.9%
		Landscape office > 40m^2	20	1	20		
		Lecture-room / conference room	35	1	35		
		Canteens > 50m^2	20	1	20		
	Visual comfort	Availability of daylight throughout the building	20	1	20	120	2.6%
		Availability of daylight throughout areas for regular use	20	1	20		
		View to the outside	20	1	20		
		Glare in daylight	20	1	20		
		Glare in artificial light	20	1	20		
		Distribution of artificial light	20	1	20		
		Colour rendering	20	1	20		

Figure 1.3: DNGB relevant category groups and its scoring

Summary

DGNB is very complex and requires significant effort to finish the certification and verify it. Therefore the method, for now, is more applicable for high-budget or highlight projects where sustainability experts can be afforded. Automatizing this process is rather difficult with the indices specified by DGNB and therefore an engineers input is inevitable. Usage of a manikin measuring and evaluating indoor comfort could be a huge asset in the near future. More emphasis should be put to evaluate the comfort of people. Since the relevant comfort criteria have only 10.4 % share in the overall score. Despite the fact of the socio-cultural group in the evaluation has a lot of criteria accounted the building quality and usage is the main concern. DGNB evaluates thoroughly the building site, building, and its usage, but the occupants' well-being is a minor concern.

Total-Performance Index	Minimum Performance Index	Awards
from 35 %	— %	Bronze*
from 50 %	35 %	Silver
from 65 %	50 %	Gold
from 80 %	65 %	Platinum

Figure 1.4: DGNB scoring awards based on performance index, source: http://www.dgnb.de/en/

1.2.2 Eco-factor Method

Basics of the Eco-factor comes from office building problems related to the design of the indoor environment and the building as an energy system. The aim is to achieve energy efficient buildings with the good quality indoor environment and low environmental impact. The assessment was created from different methodologies and tools to make a concept that will meet today's requirements in the decision-making process during all stages of building. These requirements are:

- Tool communicating between different parties involved in the building process
- Advice to the engineers working on the design
- Fixed and transparent reference frame
- Flexibility in input data

Two main levels are specified. The first is the concept design level. It provides a fast and intelligent overview of alternative designs avoiding difficult simulations. This level is containing catalogs, principles and coarse methods that will give suggestions(possible scenarios) for an optimal design. For example, the concept level usage gives insight into energy demand (heating and cooling) for a reference building or different cases for indoor comfort are evaluated (seasons, day and night cycles). Eco-factor, in this case, does not work as a stochastic model (mathematical method of how different inputs influence the overall result), however, it uses its fixed reference frame for an estimation.

The second level is more a detailed design. It builds on the two or three sketches (cases) from the first level evaluation and creates a more detailed model. In this case, more advanced simulation tools can be used. The final case is then evaluated by the Eco-factor method. High score means a satisfactory result of these factors: low environmental impact, good indoor comfort, low usage of energy.

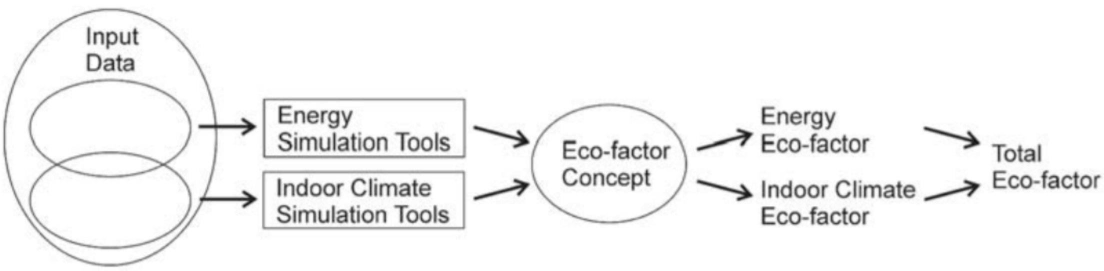

Figure 1.5: Different existing simulation tools usage and the Eco-factor evaluation frame, source: Eco-factor

The concept can be summarized as:

- Application in every stage of the building process
- Same output of different energy sources and their environmental impact
- Assessment of the complete energy system: building design and also various technical solutions
- Indoor comfort, environmental impact, and energy use in usage phase.
- Tool for engineers to compare different solutions

Eco-factor evaluates environmental effects of energy used with indoor comfort(thermal and air quality). Assessment has a fixed reference frame with a score value from 0% - 100% covering a range of categories. The two core impact categories: **Environmental impacts** due to energy use and **Indoor Environment**. Both of the categories are calculated individually. The weighting method is shown in 1.6.

The figure shows all the subcategories, weight $W_i = 0.5$ means both of the categories are weighted by 50%. The "min $W_i = 1$ else $W_i = 0$" means that the worst performing subcategory defines the level. Basics of the equal weighting comes from IDEEB, meaning 50/50 and the reasoning is the different physical nature of the categories.

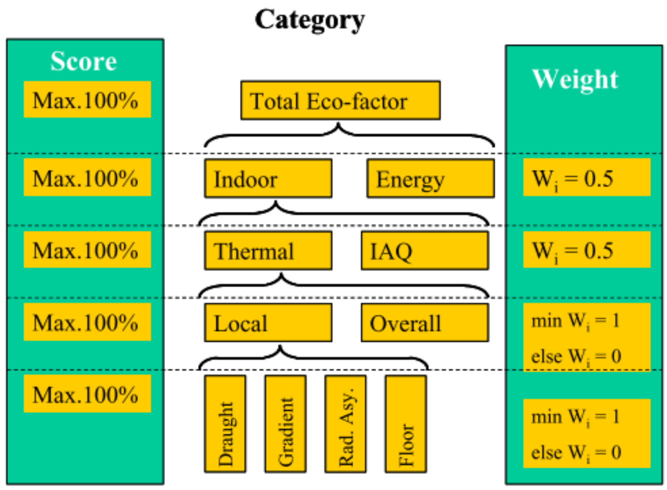

Figure 1.6: Eco-factor scoring method, source: REFERENCE

- **Thermal comfort**
  Thermal comfort is assessed based on the idea from the Eco-Factor: "Despite the fact that a person is in "overall" thermal balance, feels no discomfort due to radiant temperature asymmetry, floor temperature, or air temperature gradient, it is still perfectly possible to feel highly uncomfortable due to draught. So, it would not be reasonable to have a high "score" if only 4 out of 5 objectives are fulfilled. If you fail on one of the objectives, the whole solution has failed." Indicators evaluated in the thermal category are:
  - Overall thermal comfort: PPD (Predicted Percentage Dissatisfied)
  - Local thermal comfort:
    - Draught rate (DR),
    - Air temperature gradient, Percentage dissatisfied (PD),
    - Radiant temperature asymmetry, Percentage dissatisfied (PD),
    - Warm or cold floor, Percentage dissatisfied (PD).

  Usage of local thermal comfort is a big advantage. However, using the predicted percentage dissatisfied and percentage dissatisfied calculations could be substituted by advanced external calculations in the second level of Eco-factor assessment.

- **Indoor Air Quality**
  IAQ (or atmospheric comfort as it is referred to in Eco-factor) is assessed from the perspective of pollutants in the air. Sources emitting pollutants listed in the documentation are:
  - People (CO_2, odour, bio-effluents),
  - Building (VOC, chemical compounds),
  - Ventilation system (dust),
  - Building components (fungus and mould).

  Specifically to name the substances used for emission scoring are: CO_2 (carbon dioxide), CH_4 (methane), CO (carbon monoxide), N_2O (nitrogen dioxide), NH_3 (ammonia), $NMVOC$ (non-methane volatile compound - chemicals usually found in paints and varnishes), NOx (other nitrogen oxides), PM_x (particulate matter) and SOx (sulphur oxides). All mentioned substances are measured in Elu/kg (Environmental load index). ELU is an indicator, quantifying the materials relative environmental impact during its production, usage, and disposal. This subcategory describes the environmental load caused by emission of agents into air.

Emphasis is put on the environmental load rather than human well-being and comfort. More weight should be put on the occupants indoor conditions or the pollutants impact on people.

Conclusion

Eco-factor uses a transparent scheme of weighting and normalization. The emphasis is on the indoor climate and energy-related environmental aspects. It is simple to understand and supports iterative procedures. The scoring system helps the designer to highlight the benefits or possibilities for design improvements. However, to the newest knowledge, the method omits a lot of important environmental parameters. Light quality and noise evaluation are not included at all, and the reasoning behind was the lack of theoretical foundation but was proposed by the authors to be considered during further development.

1.3 Summary

The brief summary contains the advantages or details of the above-mentioned document's scoring systems. Further, the points limiting or enhancing the use of manikin are mentioned.

EN 15251 The evaluation systems uses **three quality levels** specified by fixed thresholds. Few different types of spaces are specified. This standard focuses mainly on HVAC design parameters. It was created for the current **possibilities**(limitations) of the EU market.

DS 3033 This document specifies four quality classes for a wide range of buildings. Thresholds of these classes are fixed and explained. The method is **robust**, since the measures are supplemented with surveys. Standard is strongly **occupant** focused .

PMP's Protocols are using three levels of measurement quality. The most advanced level uses the **newest technical solutions** and is the state of the art in the United States. Together with measurements it is **complemented** with the BMS (Building management system) data.

DGNB **Very complex** assessment method based on EU standards. Evaluated parameters are given score (based on thresholds) and accordingly weighted. The weighting system is rather **complicated**, but robust. DGNB is mainly focused on the building itself.

Eco-factor Has four levels of weighting resulting into the final score. It uses a **complex** weighting scheme **coupling** physically different parameters. The worst performing subcategory defines the level score. This assessing tool is focused mainly on the environment impact and design, than human well-being.

Manikin ideas and possibilities based on standard and scheme evaluations are:

- **Manikin** should categorize the measured parameters into quality levels,
- Thresholds used for evaluation should be ahead of the latest standard requirements and methodologies,
- Robustness of the evaluation scheme could be enhanced by coupling the measurements with occupant surveys (on-line),
- Couple the measurements with the BMS system to obtain an overall building overview and find patterns,
- Store the data for reference buildings and create statistical outcomes,
- Use a dynamic weighting scheme according to the severity of the parameter value.

2. Important IEQ indicators

This chapter contains a detailed description of each category of comfort sensation and parameters affecting it. Investigations are focused on finding comfort, performance and health implications. Since comfort is usually divided into categories, for simplification this structure is also followed in this report.

2.1 Thermal comfort

Thermal comfort is defined as a "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" in *ANSI/ASHRAE 55-2013 - Thermal Environmental Conditions for Human Occupancy.*
It is a process of exchanging mass and energy between the human body and the environment, where the result of the process is perceived by the skin. Which is also a thermoregulation receptor and translates the energy exchange into an overall comfort feeling. According to DGNB: "Acceptance of the indoor climate depends on the room temperature, the temperature of the surfaces surrounding the people inside, the air speed in the room, and the relative humidity during both the cooling and the heating period. In addition to the overall comfort, it is also necessary to take into account the possible occurrence of local phenomena which affect thermal comfort. In this way, a person may feel overall thermal comfort but still be affected by a local draught on one body part." Unbalanced thermal conditions can cause (1) heat stress, (2) thermal discomfort, (3) cold stress.

2.1.1 Introduction

The human body is adapting to a dynamic thermal environment by using its self-regulatory system, which includes a series of complex **physiological processes**, such as (1) shivering, (2) blood vessels constriction and dilatation, (3) sweating, (4) increased breathing rate and **behavioural processes**.

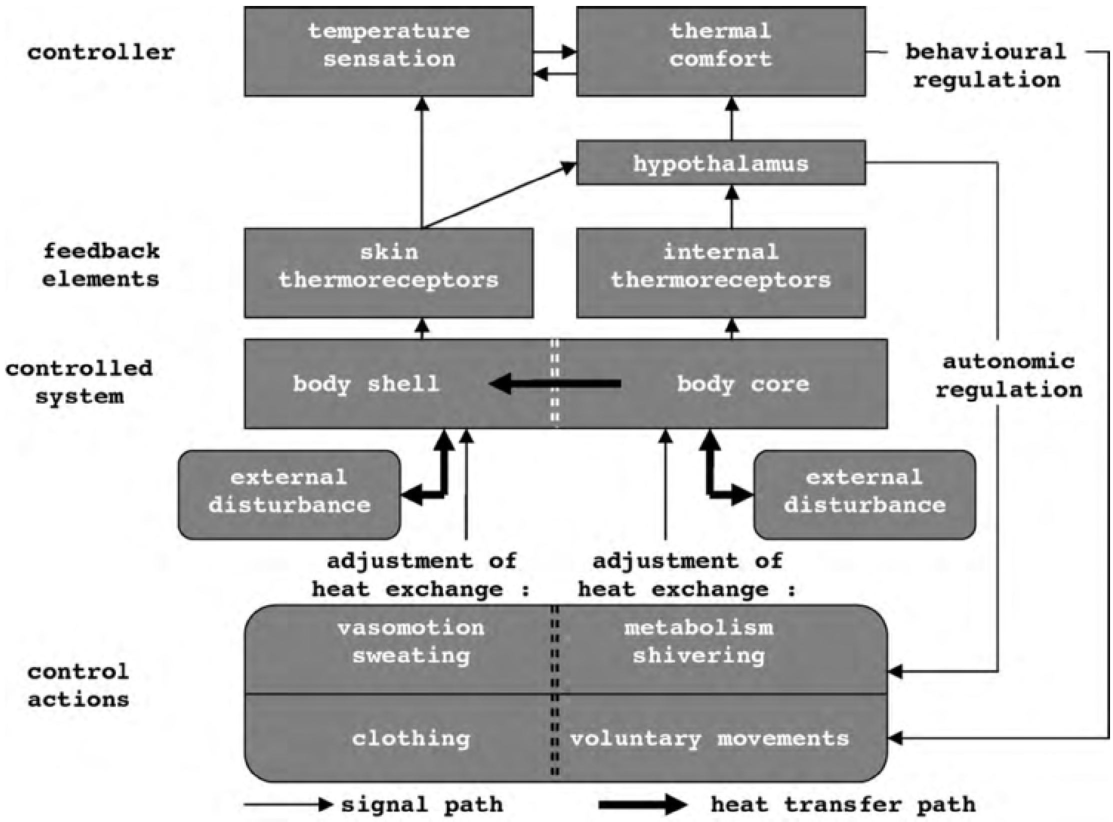

Figure 2.1: Autonomic and behavioural human thermoregulation system source: (Djongyang, Tchinda, and Njomo 2010)

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The overall heat-transfer between the human body and its surroundings is very complex. Figure presents the simplified energy exchange. Human body can be evaluated as a thermodynamic system

exchanging heat with the surrounding environment.
Parameters of a micro-climate affecting the heat exchange are:

- **Air Temperature** $[T_a]$ is measured in $[^oC]$. describes the kinetic energy (energy of motion) of the gases that are making up air. The temperature difference between the body and the environment characterizes the exchange of thermal energy between the body and the environment. The above-mentioned body means either the naked layer of skin (as an organ) or clothed skin.

- **Relative Humidity** $[RH]$ is given in $[\%]$. It is a ratio between the partial pressure of water vapor to the equilibrium vapor pressure of water at a given temperature. In other words: relative humidity is the amount of moisture in the air compared to its full saturation at the same temperature. After saturation, the moisture condenses as dew. RH depends on temperature and pressure. Higher percentage means more humid air.

Discomfort caused by *high relative humidity* restrains humans' evaporative cooling, enabled by perspiration. Skin perspiration under humid conditions is slowed down. Human body feels more discomfort if the humidity is high than low, at the same temperature. Condensation can occur on building's surfaces and leads to problems with corrosion, mold and other moisture related deterioration, which implies to indoor air quality decrease

On the other hand *low relative humidity,* also causes discomfort. Long exposure to such conditions may effect in such health problems: (1) dry cracked skin, (2) irritation of nose mucous membrane (leading to nosebleeds), (3) irritation of Human Respiratory Tract (leading to decreased immunity against viruses, bacteria and allergens).
Humans are comfortable with a wide range of humidity (depending on temperature) from 30 % - 70 %, ideal values to avoid any before-mentioned issues are between 50 % - 60 %.

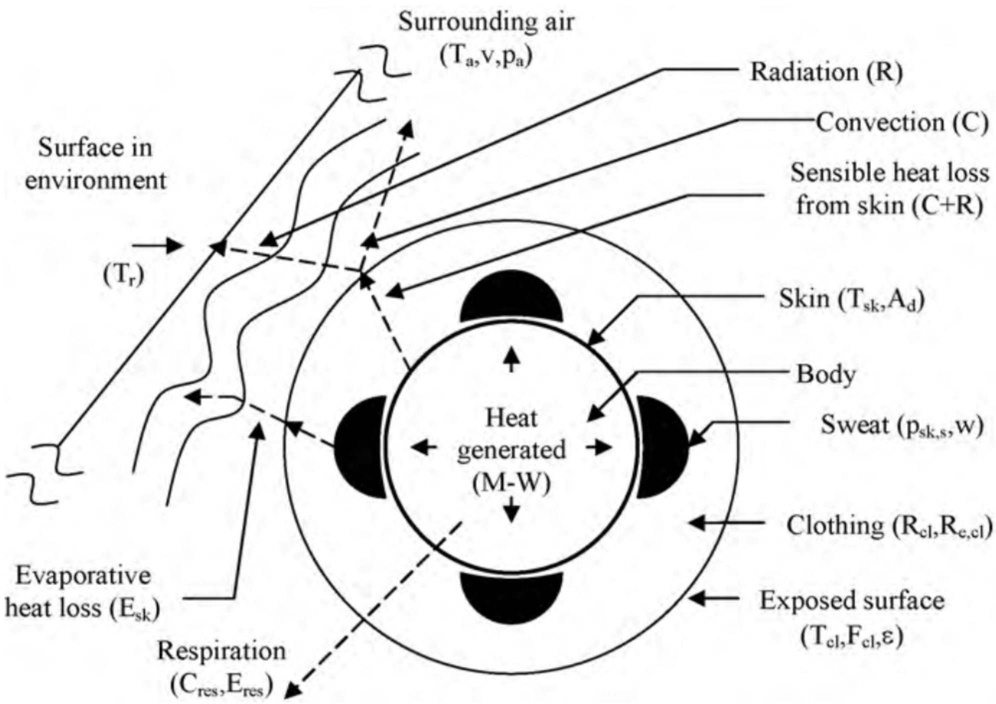


Figure 2.2: Schematic energy exchange of a human body, source:(Djongyang, Tchinda, and Njomo 2010)

- **Mean Radiant Temperature** $[MRT]$ is a uniform surface temperature of an imaginary black enclosure which would result in the same heat exchange by radiation from the person as the actual enclosure in the local environment. It is a weighted average of various radiant surfaces in the local space. It can be measured using the globe thermometer.

On the other side of the thermal balance, the following factors are affecting the thermal comfort:

- **Metabolism (met)** the metabolic rate of a human depends on (1) health, (2) age, (3) sex, (4) diet, and it is representing the basal energy of the body, necessary for the maintenance of vital functions. Metabolism is also related to the body position and the type of work carried out. The metabolic activity is expressed in $[W/m^2]$ where $[m^2]$ refers to the human body surface, or directly in [met]. These values are provided directly by the standard *ISO 8996:2004 - Ergonomics of the thermal environment - Determination of metabolic rate*.

- **Heat Loss by Skin Diffusion** (E_d) or evaporative heat transfer (E) is the amount of energy lost through skin evaporation. The amount of dispersed vapor through sweat indicates the energy loss, a process not linked to thermoregulation. Skin diffusion also can be the component of thermoregulation due to adjustment through thermal tachypnea (rapid breathing) and thermo effectors such as saliva spreading, swallowing or other surface wetting.

- **Latent Respiration** (E_{re}) depends on the amount of mass and energy exchanged through water vapor by inhalation and exhalation of air. The evaporation through mucosal lining of the respiratory tract needs to be accounted also. The temperature difference between exhaled and inhaled air (Sensible Heat) leads to dry respiration heat loss.

- **Heat Conduction Through the Clothing** expresses the transfer of heat from the skin to the outer surface of the clothing. The overall thermal resistance of the clothing is calculated based on tabular values and the actual items of clothing (and their material). The measurement method and the values are defined in *ISO 9920:2007 - Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble*.

- **Heat Loss by Radiation (R)** the heat exchange by radiation between the human body and the ambient environment is due to the temperature difference between the outer surface of the skin or clothed skin and the mean radiant temperature of the walls (Stefan-Boltzmann Law).

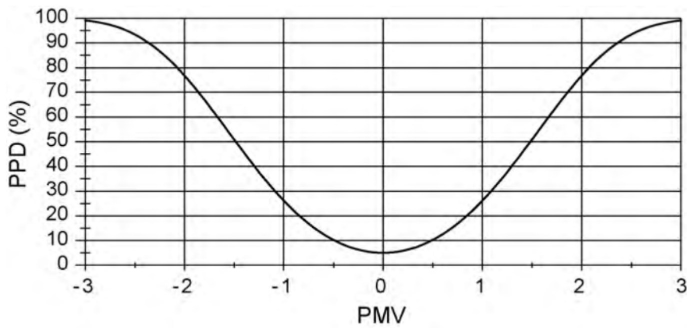
- **Heat Loss by Convection (C)** is a heat transfer occurring within a fluid due to the combined effects of conduction and bulk fluid motion. Convection for the case of the humans it the heat exchange from the outer surface of the body or clothed body to the ambient air.

2.1.2 Comfort assessment indexes

Commonly used international standards to evaluate thermal comfort are ISO 7730 (2005) (EU) and ASHRAE 55 (2013) (US), where the thermal sensation is predicted through a heat-balance approach using indicators called Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD).
The following variables are used for the PMV calculation:

- Metabolic rate
- Indoor air temperature
- Indoor mean radiant temperature
- Air velocity
- Clothing level
- Relative humidity

This approach is a steady-state model developed by **Fanger** in the 1970s. It is applicable for the indoor environment. The basis of the index is the heat balance model of the human body with the physiology of thermoregulatory system. Humans' physiological processes are maintaining a balance between the heat gain and heat losses of the body. Fanger in (Fanger 1967) determined that the only physiological process influencing the heat balance is the sweat secretion rate and mean skin temperature. Two linear relationships between the activity level on one side and sweat secretion or mean skin temperature on the other side are the inputs to the heat equation. The obtained equation predicts conditions in which humans will feel thermally neutral. The **PMV index** is the imbalance between the actual heat flow between the body in the specified environment and the heat flow needed for neutral comfort level for a given state and activity. Today the most recognized modification of the PMV-PPD is an ASHRAE 7-point thermal sensation scale. The **PPD index** predicts the percentage of people who felt more than (+1) slightly warm or (-1) slightly cold. That means people who complained about the thermal environment. Using the 7-point scale mentioned above (+3 to -3), **Fanger** stated that people who responded $\pm 2\, and \pm 3$ are uncomfortable and those who responded $\pm 1\, and\, 0$ are comfortable. This variable is called PPD. The PMV-PPD relationship is presented:



PMV vote	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
1	Slightly cold
2	Cool
3	Cold

The relation between PPD and PMV shows perfect symmetry with respect to PMV equal to 0. Even at thermal neutrality (PMV = 0), there is a level of 5 % of occupants dissatisfied with the temperature. Three comfort zones can be introduced based on the PPD-PMV ranges

Steady-state heat-balance theory where a person is a passive recipient of external thermal stimulus. It does not include adaptations of the human body, which is the main reason to determine thermal sensation and perception(very subjective). de Dear in 1998 (Dear 1998) claimed that "the ISO 7730, which is based on the heat-balance model (steady-state), overestimates the occupants responses on the ASHRAE scale at high temperatures and underestimates them at low temperatures"

Another approach for thermal sensation is the **adaptive model**. It is derived from field experiments and simulations, to analyze the real sensation of the thermal environment. For this indicator the users are, in contrary to PMV-PPD, responding actively to their thermal environment. The core of the adaptive model is based on studies in naturally ventilated buildings as a "Black box" theory(explained further). Experiments were conducted by (1) Auliciems, (2) Nicol and Humphrey, (3) de Dear and Brager, (4) de Dear, Brager and Cooper. Considering factors such as

- Psychological adaptation
- Behavioural adaptation
- Social
- Climate
- Culture

The model is called Adaptive Predicted Mean Vote (aPMV). The fundamental assumption stated by (Humphreys and Nicol 2002): "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort." An another adaptive hypothesis is a condition where the indoor environments thermal state is matched by one's thermal expectations. The first two above mentioned aspects have been defined by (Cabanac 1971) as "alliesthesia" and revisited by De Dear. The term alliesthesia can be defined as "a given external stimulus can be perceived either as pleasant or unpleasant depending upon signals coming from inside the body", the concept is not yet established in any standard. (Dear, Brager, and Cooper 1997) highlighted that thermal neutrality (PMV = 0) does not necessarily result in thermal pleasure.

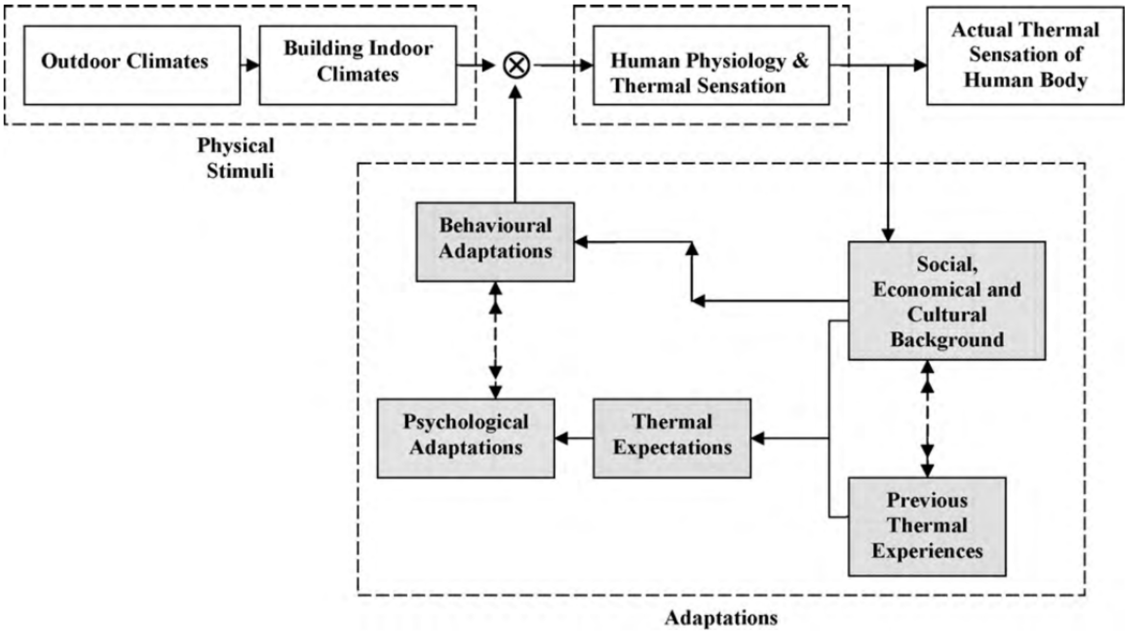


Figure 2.3: Scheme of the adaptive thermal comfort model and comfort zones, source: N.Djongyang et al. 2010

It was first introduced in the ASHRAE standard 55 (2004). Intension was to provide an optional method for naturally ventilated buildings derived from the ASHRAE RP-884 database. Later in 2007 it was implemented in EN 15251 and the Dutch ATG guideline. The adaptive thermal comfort model is used in EN 15251 (modified by the European project Smart Controls and Thermal Comfort).

Researchers afore mentioned revealed the relationship between outdoor air temperature and thermal comfort temperature.

Fanger's method (PMV) predicts the mean thermal sensation vote on a standardized scale **based on a large group of people** for the all variables mentioned in the relevant subsection. Fanger (Fanger and Toftum 2002) stated about the adaptive model: "an obvious **weakness** of the adaptive model is that it does not include human clothing or activity or the four classical thermal parameters that have a well-known impact on the human heat balance and therefore on the thermal sensation."

Adaptive model predicts the thermal sensation for non-air-conditioned buildings accurately, however for buildings built in a late 20th century. The concern arises when modern offices are evaluated.

Researchers aforementioned revealed the relationship between outdoor air temperature and thermal comfort temperature. Behavioral adaptation to broader ranges of temperature variations developed in humans, that being said people tend to open or close doors and windows, change clothes, activity level or intake beverages(either cold or hot). The "Black Box" method treats the human's thermal sensation as an unknown system consisting of the following reactions:

- **Physiological** - First subcategory: genetic adaptation (one generation to the next) and acclimatization (within a generation). Second subcategory: perspiration, blood vessels dilution and restriction
- **Psychological** - Cannot be quantified and directly pointed out. For example, if a human being is continuously exposed to a thermal stimulus, the sensitivity boundaries adapt.
- **Behavioural** - conscious and unconscious behavior is constantly performed by people on an everyday basis. Including: changing clothing, turning on ventilation, drinking beverages. Some countries have a "siesta" which is a culturally developed behavior habit.

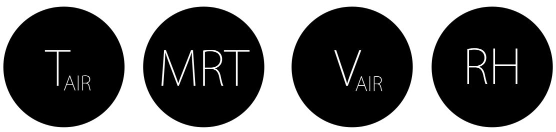
The method principle is: (1) system input (external stimulus) is given to the system, (2) reaction of the system is observed, (3) statistical relationship is carried out.
The advantage is that it can understand the system and **predict relationships** between the (input-output). Therefore complex systems can be evaluated without knowing all the relationships within the "Black Box". The adaptive model includes the mentioned reactions to the general heat-balance system. The **aPMV** method determines an adaptation coefficient based on survey and experiment correlations based in summer and winter. It explains the over/underestimation of the original steady-state method. For the case of the aPMV, the occupants were allowed to **"adapt"** (change clothes, open windows, etc.). The outcomes show a linear correlation between the PMV and external air temperatures.

Summary

The universal usage of PPD-PMV is not the most suitable approach to establishing thermal comfort. Fanger based his theory on **physiological adaptation** of humans to an external thermal stimulus. The thermoregulatory system maintains the heat balance (within a very wide range of temperatures). Later proposed by (Dear 1998) , human thermal sensation is significantly affected by **psychological** and **behavioural** adaptation. Standards applying Fanger's PMV-PPD method should consider testing the laboratory based experiments in the field.

For the manikin evaluation, the **Fanger's PPD-PMV method** is used despite the aforementioned drawbacks. Local phenomena as the draught are also evaluated. Reasonable accuracy can be obtained and **further development** can be done by creating questionnaires, regression models and also account the adaptation factor. **Behavioural reactions** are up to today's knowledge impossible to mimic with an artificial "human" manikin. Physiological processes can be approximated by thermal manikins based on difficult mathematical models, resulting in skin temperature variations. Lately, CFD models of thermal manikins are developed extensively, however, the subject of thermal comfort is still **very difficult** to specify.

The manikin thermal evaluation process requires the following parameters to be measured: air temperature $[^oC]$, mean radiant temperature $[^oC]$, air velocity $[m/s]$ and relative humidity $[\%]$



2.2 Indoor Air Quality

Indoor Air Quality (IAQ) refers to the air purity within buildings, and it is especially related to the health and comfort of the occupants. In the design of buildings and ventilation systems, the focus is on assuring comfort conditions in respect to a fresh air supply. The problem with this approach was noticed by Asikainen et al. (2016): "There are no European guidelines to recommend how the buildings should be ventilated to reduce the health risks of the occupants' exposed to indoor air pollutants." However, limitation and control of typical air pollutants can help to reduce the risk of various health issues and improve the performance of people as well as their overall well-being. While comfort and performance implications are also investigated in this chapter, the most important findings concern relationships between health and air pollutants.
Substances found in indoor air impact not only physical body functions, such as breathing but also mental capabilities and psychological health. Symptoms caused by bad IAQ are presented in figure 2.4. What makes air quality especially troublesome, is the fact that many air contaminants are untraceable by human senses. Even though they cause unwanted symptoms, they cannot be easily discovered. This is the reason for including most dangerous parameters into evaluation system, despite their relatively rare presence. Therefore, a list of selected factors should be created as a compromise between the most frequently detected agents, and those that are most hazardous. Proceeding sections provide a summary of scientific research concerning various air pollutants, resulting in a final list of chosen indicators.

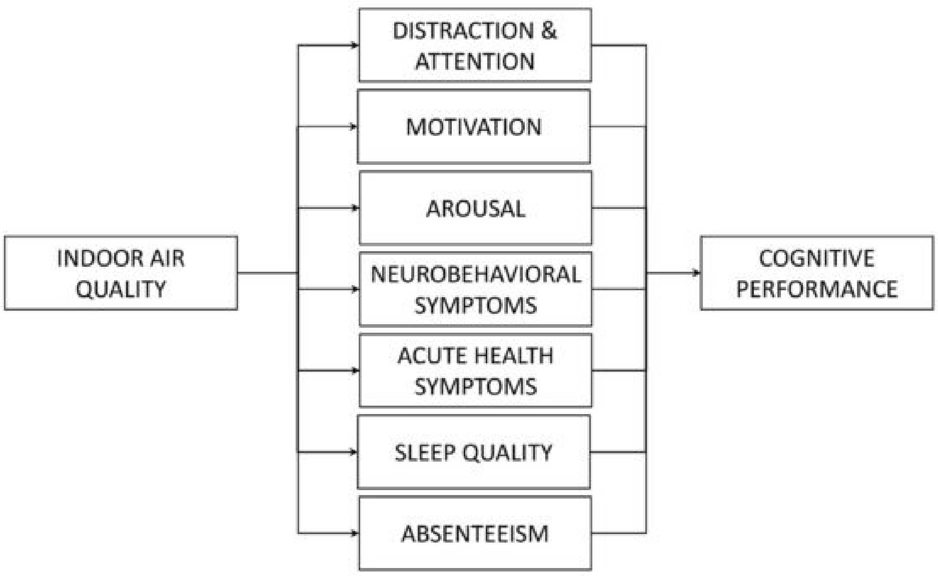


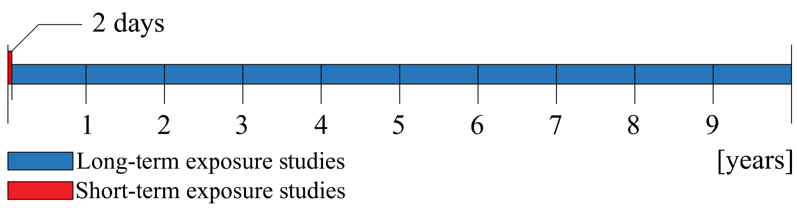
Figure 2.4: The mechanisms by which air quality is affecting people (source: Wargocki and Wyon (2016, page 361)).

Finding parameters with high importance can be done by checking statistical research concerning prevailing indoor and outdoor pollutants. Health problems in European countries in correlation with different indoor and outdoor air pollutants were studied by Hänninen and Asikainen (2013), the outcome is presented in table 2.1. Outcomes are given as Burden of Disease (BOD), in this case, it represents the share of each parameter in the sum of years lost by population due to diseases caused by poor air quality (also listed in the table). Other exposure-disease correlations found in the literature will be described together with specific indicators.

Exposure	Health endpoints	Part of total BOD
$PM_{2,5}$	Asthma Lung cancer Cardiovascular diseases Chronic Obstructive Pulmonary Disease	78 %
Radon	Lung cancer	8 %
Dampness	Respiratory infections Asthma	5 %
Second Hand Smoking	Lung cancer Ischaemic heart disease Asthma	4 %
Bioaerosols	Asthma	3 %
VOC	Asthma	1 %
CO	Acute poisoning	1 %

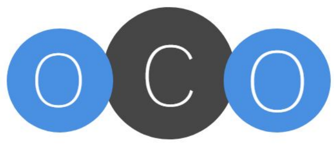
Table 2.1: Diseases and exposure-response to selected air pollutants (source: Asikainen et al. (2016)).

Effects of inhaling air pollutants are typically referred to in the context of short-term or long-term exposure. The short-term presence of polluting agents takes into account all negative symptoms that occur instantly to those starting from 15 min after the beginning of the exposure, to these that show even a few days after the exposure ended. Long-term exposure might consider periods of weeks, month or years. These times are not strictly defined and are chosen by researchers, what sometimes creates difficulties with interpretation of results from more than one report.



Air quality is commonly understood as an adequate ventilation rate. Even though the amount of fresh air supplied to the room might not affect human health or comfort directly, it is responsible for diluting pollutant concentrations and individual perception of a given space. However, it has to be taken into account if the ventilation is natural or mechanical, and what is the quality of outdoor air in the area of interest. The fact that various pollutants are also found in the outdoor air shouldn't be neglected. That is why ventilation rate is not treated as an ultimate indicator of air quality but it can be used in correlation with CO_2 concentration as a preliminary assessment value.

2.2.1 Carbon dioxide



Carbon dioxide (CO_2) is a colorless, odorless, noncombustible gas. The main sources of CO_2 in the indoor air are human exhalation, cooking or heating processes involving a fuel combustion, and tobacco smoking. In the outdoor air, levels of CO_2 are currently above 400 ppm, depending on the location. The level of atmospheric CO_2 is still on an increasing trend, from 2005 to 2014 it rose by 20 ppm. (CO2.Earth 2017)

CO_2 concentration is a proper indicator only for spaces where the main sources of pollution are human metabolism and human activities. It is, for example, a case for residential buildings, where an additional reason for using it, yields from occupants' tendency to limit ventilation rates in order to reduce the energy required for heating and cooling. CO_2 level measurement gives an overview on the efficiency of ventilation, indicating whether problems reported by the occupants might be related to the insufficient amount of fresh air and pollution deposition.

Carbon dioxide metrics

CO_2 concentration is the most commonly used parameter for determining IAQ, it can be found in every standard or guideline on the subject of air quality. Limits of concentrations, however, differ throughout the literature. Several chosen thresholds are provided for comparison in figure 2.5.

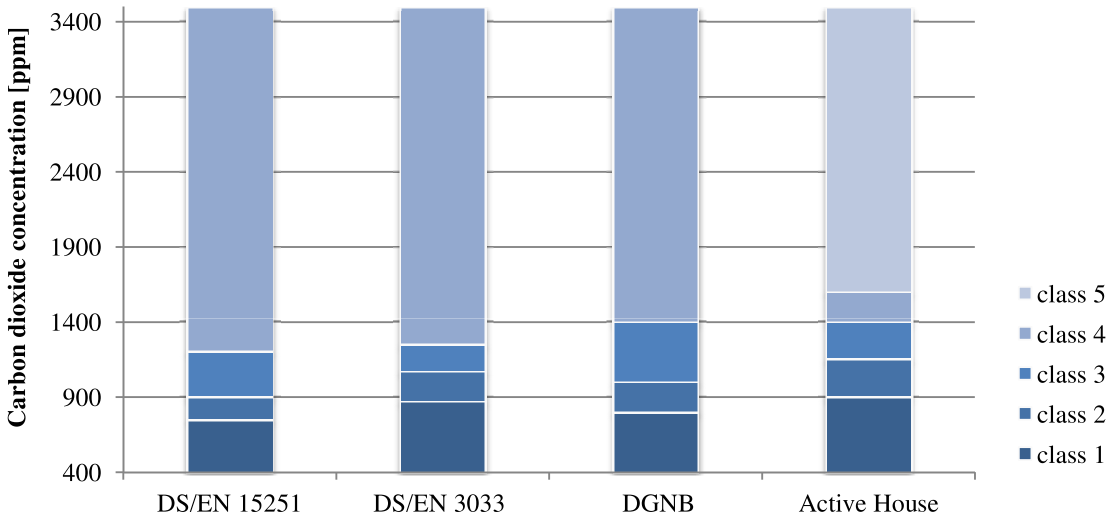


Figure 2.5: Assessment of CO_2 concentration according to different methods (sources: CEN (2007a), CEN (2014a), DGNB GmbH (2014), Active House Alliance (2015)).

The maximum threshold for prevailing exposure, given in WHO (2000a), is equal to 3500 ppm, and this value was used as the limiting concentration for all classes. Usually, the allowed level of CO_2 concentration in a room for long occupation is around 1000 ppm, this limit is well below the value recommended by WHO, however, various studies on IAQ provide evidence of the beneficial effects of increased ventilation rates for comfort and performance of people, thus lower concentrations of pollutants. Specific examples are described in following sections.

Carbon dioxide impact

CO_2 was used in numerous studies carried out since the 19th century, as a marker of air quality in buildings. Initially, high concentrations were correlated with various negative effects on people, such as Sick Building Syndrome. However, when more detailed studies with controlled levels of pollutants were done, it was discovered that none of the physiological and psychological problems are directly connected with exposure to carbon dioxide. In a study done by Zhang, Wargocki, and Lian (2016) concentrations up to 5000 ppm were tested in relation to the perception of air quality, performance with simple cognitive tasks and physiological responses (among others blood pressure, breathing rate). It was concluded, that investigated CO_2 levels do not show the significant negative effect on any of tested parameters, during exposure of people for maximum 2.5 h. In Pohanish (2012) the lowest level below which negative effects on human health were not observed anymore, is around 10 000 ppm. Such high concentrations, as 5000 or 10 000 ppm, occur very rarely, and in extreme situations.

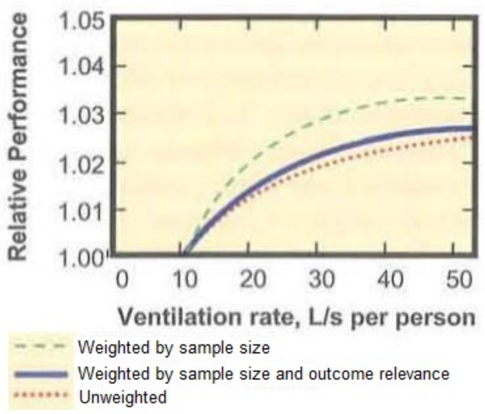


Figure 2.6: Effect of increasing ventilation rate on performance relative to the reference ventilation rate set 10 L/s per person (source: Wargocki, Seppänen, et al. (2006)).

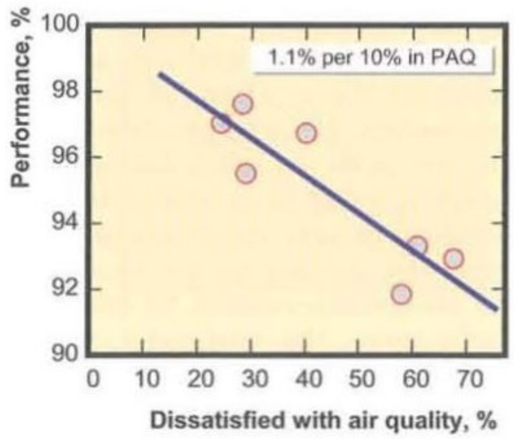


Figure 2.7: Performance of simulated office work as a function of proportion of dissatisfied with air quality (source: Wargocki, Seppänen, et al. (2006)).

It is currently well known, that increased ventilation rates in office buildings improve performance. The reason for this might be the reduction of pollutant concentration, what reduces negative symptoms such as headaches, problems with concentration, annoyance with air quality and odours Wargocki, Seppänen, et al. (2006). Experiments carried in simulated office situations provide some evidence and repeated trend between performance and ventilation rate, and performance and satisfaction with air quality. Chosen outcomes are shown in figures 2.6 and 2.7.

Carbon dioxide does not pose threat to human health according to up to date research. It can be utilized in IEQ evaluation as indicator of concentration of bio-effluents and other pollutants. Other parameters should be included in order to perform detailed analysis of the air quality and its consequences for occupants.
CO_2 can be correlated with estimated air quality in a space, using people and outdoor air as sources and "concentration" equation. From established link, using trends presented in figures: comfort and performance impact of CO_2 can be predicted for evaluated space.

2.2.2 Carbon monoxide

Carbon monoxide (CO) is a flammable, colorless, odorless, tasteless gas, that is slightly lighter than air. Roughly 40 % of global annual *CO* production arises from natural sources such as volcanoes, forest fires, marsh etc. Other 60 % is usually encountered as a waste product of incomplete fuel combustion, refuse disposal, tobacco smoke, and vegetation burning. In the indoor air, the sources might be similar, tobacco smoking, malfunctioning stoves or furnaces, and infiltration of outdoor air. Local outdoor concentration varies according to locations characteristics, among others is a degree of urbanization, the amount of road traffic and population. The average level of *CO* in outdoor air in urban areas in Europe is around 17 ppm, with short-lasting peaks up to 50 ppm (WHO 2000a).

Carbon monoxide metrics

Limits for CO concentration in indoor air are well established in the literature. Three chosen assessment methods are presented in figure 2.8. Air Quality Index provided by USEPA (2014) is based on values of concentration averaged over 8 h. Limits established by Chiang and Lai (2002) are used for assessment of instantaneous measurements. In the figure, the background colors represent limits given by WHO (2010). These values represent thresholds for *CO* concentration averaged over 4 time-periods.

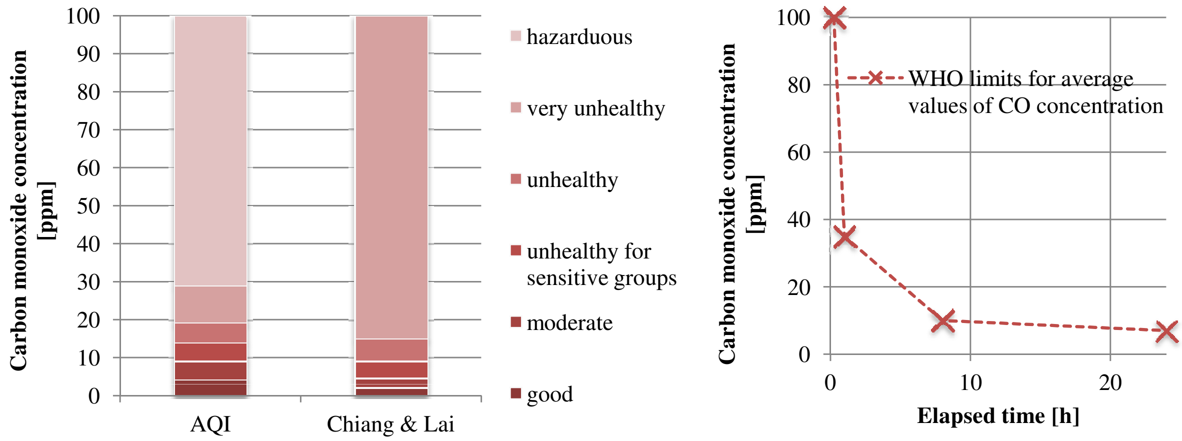


Figure 2.8: Assessment of CO concentration according to different methods (sources: USEPA (2014), Chiang and Lai (2002), WHO (2010)).

Carbon monoxide impact

Carbon monoxide is especially dangerous since it is not sensed by people until the inhaled dose starts to show in typical poisoning symptoms. Carbon monoxide enters the bloodstream of a human during inhalation and causes a reduction in the amount of oxygen delivered to the organs and tissues, by combining with hemoglobin. Through this reaction carboxyhemoglobin (COHb) is created. A healthy human has typically from 0 to 1.5 % of COHb in blood. Half life of carboxyhaemoglobin in the blood of adult person is in the range of 2-6.5 h. WHO (2010) limits for *CO* concentration are established in order to assure that COHb level in a blood of a non-smoking adult won't exceed 2.5 %. Symptoms of exposure to high concentration of *CO* are (in order correlating to the increasing time of exposure):

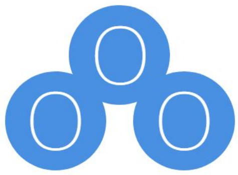
- headache,
- physical weakness,
- nausea,
- dizziness,
- dimness of vision,
- acute poisoning and death.

Acute poisoning cause by *CO* might lead to irreversible defects in nervous and cardiovascular systems if the medical help is not applied on time. The concentration of COHb 50 % in blood might cause death for most humans. However, when studies on *CO* exposure became more widespread, it was discovered that even 20 % of the population might die from acute poisoning having lower levels of COHb in their blood when exposed to automobile exhaust pollution. There is also evidence that male subjects are more susceptible to die due to carbon monoxide exposure. (Hirschler 2005)
Research concerning *CO* exposure and impact on a human cognitive performance, including various studies on the subject, done by Townsend and Maynard (2002) concluded that:

- short-term exposure to high concentrations of carbon monoxide impacts brain functioning, for example causing decrements in the abilities to perform mathematical calculations and vision impairment. After exposure stopped, full mental recovery was observed.
- elevated levels of COHb in blood led to limiting physiological abilities of subjects while exercising.
- smoking adults show "immunity" to increased COHb levels (up to 13 %). They do not suffer from the same physiological and cognitive problems as non-smoking people.
- exposure to CO of pregnant women during last trimester was associated with lower birth weight in babies. The effect was said to be the same as in babies, which mothers were smoking a pack of cigarettes per day during entire pregnancy.
- long-term exposure may cause lasting neurological effects, even after the exposure stopped. Symptoms reported by subjects are changes in memory, sleep, vision, sense of smell and sense of direction, anxiety, balance problems and others.

Carbon monoxide is dangerous to humans even in small doses. It should be monitored in spaces where any equipment using fuel combustion is present or where natural ventilation is used in highly urbanized areas. CO has an impact not only on health but also on comfort and performance of people. Specific numerical correlation for those two impacts was not yet established and requires more evidence, but without doubt, such relationship exists.

2.2.3 Ozone



Ozone (O_3) is a colorless or blue gas. It has an unpleasant, characteristic odor, associated with electrical equipment that due to a malfunction caused sparking (Pohanish 2012). Even though O_3 has an odor, the olfactory detection appears unreliable, especially if the exposure is continuous. The reason for this is an adaptation to the odor. Sensibility threshold varies between 2 and 100 ppb depending on a person, but most people are able to sense about 15 ppb when they enter a contaminated area. (Boeniger 1995)
O_3 is a product of photochemical smog, specifically of chemical reactions between nitrogen oxides and volatile organic compounds. That creates additional possibilities of its detection by measuring these substances. Additionally, ground ozone level might be increased by downward mixing from the stratosphere, and transport from other locations. Ground concentrations in rural areas are around 10-25 ppb, in urban areas they might be as high as 100-300 ppb. Ozone levels are highest during summer and lowest during the winter period, due to variations in the amount of solar radiation. Indoors ozone might be a product of copying machines, electrostatic air cleaners, and infiltration. Penetration factor of O_3 from outdoor air into the buildings, lies in a range of $0,2$-$0,7$, meaning that more than SI30% of it is filtered out by the building envelope. (Altshuller 1987)

Ozone metrics

O_3 is considered toxic for people, with a dose-response correlation (dose is described in a relation below). The method for outdoor air monitoring established by USEPA (2014) provides 6 levels of health concern corresponding to ozone concentration averaged over 8 h. Specific limits used by this method are given in figure 2.9. What is more, WHO (2000a) specified maximum level for indoor air equal to 64 ppb for 8 h average concentration, what corresponds to moderate health risk according to AQI.

$$\text{dose} = \begin{array}{c}\text{ambient}\\\text{concentration}\end{array} \times \begin{array}{c}\text{level of exertion}\\\text{(minute ventilation)}\end{array} \times \begin{array}{c}\text{duration of}\\\text{exposure}\end{array}$$

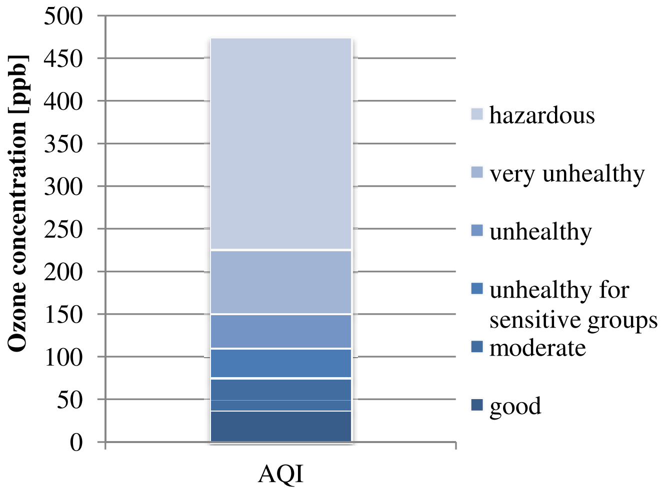


Figure 2.9: Ozone concentration level evaluation according to Air Quality Index (source: USEPA (2014)).

Ozone impact

Inhalation of O_3 might lead to both temporary and irreversible health symptoms. Toxic impact of ozone on health gets stronger with raising concentration level, longer exposure duration, and increasing activity level. Inhaled ozone might damage the lungs, and sensitize them to other irritants. Short term exposure to the gas might cause:

- levels below 300 ppb - coughing, throat irritation, mouth and nose dryness,
- levels of 300 ppb and above - tightness in the chest and throat, irritation of lungs, within 30 minutes,
- levels of 500 ppb - headache, loss of coordination, accumulation of fluid in the lungs,
- levels of 10 000 ppb and above - severe irritation of throat and lungs, severe chemical pneumonia; longer exposures to that high concentration level might cause death.

However, research shows that there is a large variation in response among different people. For example, if two people - one least sensitive, and other most sensitive to ozone, are exposed to the same high concentration of ozone, and both subjects are performing the physical activity of the same level, one of them may experience no symptoms, while the other may suffer from acute symptoms mentioned above. This fact is illustrated in figure 2.10, where three persons were exposed to different levels of ozone and their response was examined. Moreover, some differences in sensitivity to O_3 are associated with age. That is why it has to be noted that the levels at which negative health effects are observed, depend on the sensitivity of the individual in question, and dose delivered to the respiratory tract. (Utell and Frank 1989)
Symptoms such as coughing, throat irritation, chest tightness and shortness of breath should start to resolve immediately when the exposure is reduced and should concede within 1-2 days after the exposure ends.
Long-term, chronic inhalation of increased ozone levels is linked to the development of asthma, reduced lung function, lung cancer and increased mortality level. Overall daily mortality risk rises by 0.5 % per each 20 ppb increase in the 24 h average ozone concentration (if conditions of increased O_3 levels last a week). Peak O_3 concentrations during the year are connected to increased

complaints about the symptoms and more hospital and clinic admissions. (Utell and Frank 1989)

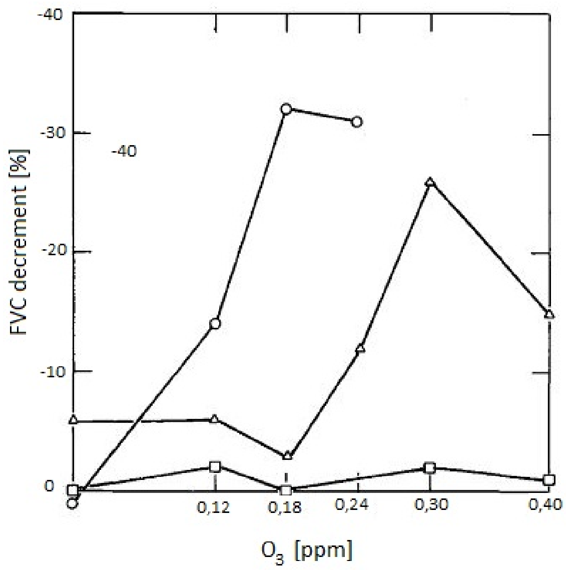


Figure 2.10: Concentration-response curves for three individuals exposed to different levels of ozone. The health effect used for comparison of response (FVC) is the amount of air that can be forcefully exhaled by a subject (source: Utell and Frank (1989)).

Several studies on ozone conclude that it tends to react with other air pollutants and produce various substances, such as formaldehyde, organic acids, highly odorous aldehydes and much more. (Weschler (2000), Weschler (2006)) This means that O_3 is not only an irritant itself but it also participates in increasing the levels of other toxic substances, and by doing so increasing their negative effects on people. Experiments showed that ozone and its chemistry cause a reduction in perceived air quality, due to reactions with surfaces of ventilation filters. Another study reported, that simultaneous exposure to O_3 and dust also caused an increase in discomfort among subjects, than either of them separately. (Birchby et al. 2014)

The first study that covered the topic of reduced performance due to exposure to high ozone concentration was done by Walborg and Wayne in 1967. Afterward, there were some more studies confirming that in fact O_3 has an impact on performance and that the severity of this effect is related to the level of activity performed by people. The higher the activity level the worse the physical performance of the subject. (Mullins 2016) Based on results of a study Impact of pollution on worker productivity, it was stated that performance increases by 4.2 % per each 10 ppb decrease in ambient air concentration (Graff Zivin and Neidell 2011).

Ozone is known to affect human comfort and health. However, more research is required on its potential negative impact on the cognitive and physical performance of people. Nonetheless, symptoms occurring even after short-term exposure can lead to lung damage. It is a factor that should be included in IAQ assessment scheme.

2.2.4 Particulate Matter

Particulate matter (PM) refers to airborne particles that include both solids and liquid droplets suspended in the air, also called aerosols. Airborne particles are divided into classes according to their size, coarse particulate matter (PM_{10} with aerodynamic diameter $< 10\mu m$), fine particulate matter ($PM_{2,5}$ with aerodynamic diameter $< 2,5\mu m$), and ultra-fine particulate matter ($PM_{0,1}$ with aerodynamic diameter $< 0,1\mu m$). According to WHO (2010) in most locations in Europe 50-70 % of PM_{10} concentration constitutes of $PM_{2,5}$.
The PM is primarily produced from combustion of fuels, in engines, solid-fuel production, and usage of fuels for energy production. Another source is an erosion of the roads, buildings and other anthropogenic and natural structures. Secondary formation of PM occurs due to chemical reactions of gaseous pollutants in the air, mostly by transformation of nitrogen oxides and sulfur dioxide produced by traffic and industry. Last but not least, soil and dust resuspension gives origin to the substantial amount of total airborne particles. (Lippmann 2008)
Some research was carried out concerning the level of penetration of particulate matter from the outdoor environment into the buildings. The particle penetration factor depends on various aspects, among them the characteristics of the building shell, type of the ventilation, and size of particles. Investigation described in Tran et al. (2015) yielded values of penetration factor equal to $0,7$-$0,9$ for $PM_{2,5}$, and $0,3$-$0,5$ for PM_{10}. Taking into account this strong correlation between outdoor and indoor concentration, in order to find a source of particle pollution in a space, outdoor values should be examined simultaneously.

PM metrics

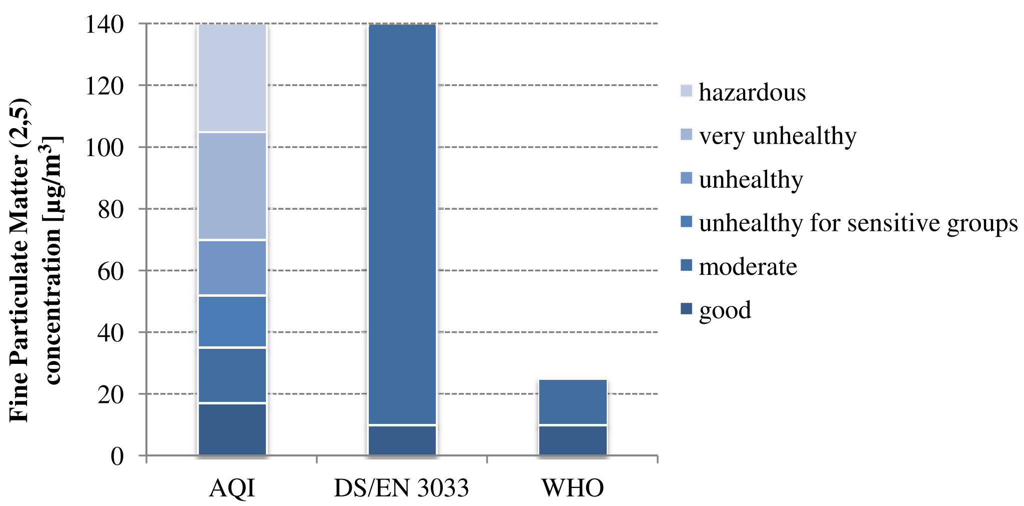


Figure 2.11: IAQ assessment methods based on fine particulate matter ($PM_{2,5}$) concentration (source: USEPA (2014), CEN (2014a), WHO (2010)).

The concentration of coarse particulate matter is constantly monitored in the outdoor air, as it is an important indicator of how unhealthy the air is for people. WHO reported that about 80 % of the population of the cities, for which PM_{10} data exist, is exposed to levels higher than the established annual thresholds (Guerreiro et al. 2016). Currently used limits of concentration of PM are given in figures 2.11 and 2.12. It is important to have in mind that there is no threshold concentration of $PM_{2,5}$ below which no health effects are observed. (Moeller 2005)

There are also few classification methods for IAQ that include the concentration of particulate matter, some of them are presented in figures 2.11 and 2.12. The thresholds, based on EPA Air Quality Index method are applied to daily measurements of concentration in outdoor air. Other methods, shown in the figure 2.12 are assigned to indoor air monitoring, however, method described in Chiang and Lai (2002) provide rather high values in comparison to the guidelines from WHO (2010).

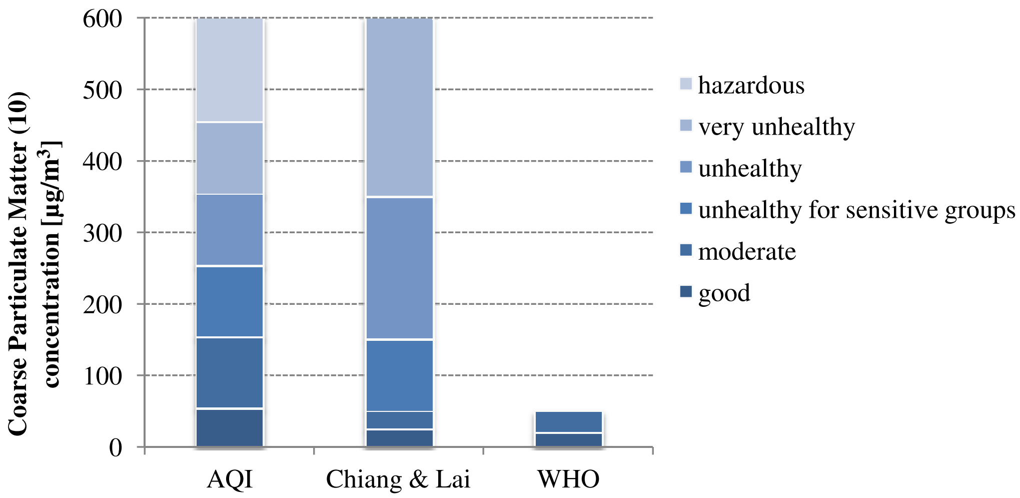


Figure 2.12: IAQ assessment methods based on coarse particulate matter (PM_{10}) concentration (source: USEPA (2014), Chiang and Lai (2002), WHO (2010)).

PM impact

Inhaled coarse particles can settle in the bronchi and lungs (see figure fig:pm1), and cause a variety of health problems. Fine particles are shown to have the greatest impact on health. Due to their small size, $PM_{2,5}$ can travel deep into the lungs, where they trigger inflammation or deposit potentially cancerous substances. The rate of deposition of particles in human airways is presented in figure 2.13.

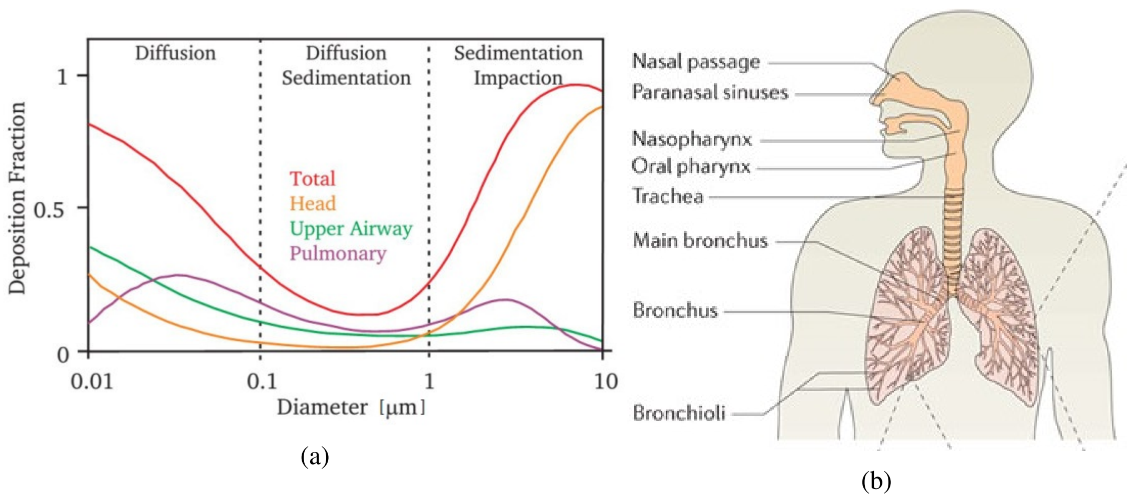


Figure 2.13: The location in the respiratory tract where aerosol particles deposit, according to the ICRP lung deposition model (sources: Davies (2017) and Folkesson et al. (2012)).

Evidence indicates that particulate matter causes:

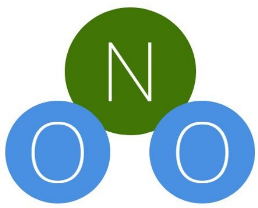
- premature mortality from cardiovascular and respiratory diseases,
- increased hospital admissions for cardiovascular and respiratory diseases,
- increased prevalence of bronchitis,
- increased risk of lung cancer,
- deterioration of asthmatic symptoms,
- a decrease in lung function.

Guerreiro et al. (2016) based on various health studies, established index of increase the cardiopulmonary disease related mortality equal to 6-13 % per 10 $\mu g/m^3$ increase of $PM_{2,5}$ in inhaled air. The most vulnerable to adverse effects of aerosol inhalation are children, elderly people suffering from pulmonary problems, and asthmatics.

The impact of inhalation of particulate matter on human performance can be established in connection with increased illness and hospitalization rates, mostly among people suffering from asthmatic symptoms. Exposure to $PM_{2,5}$ is particularly dangerous since these small particles penetrate deep into the lungs and may affect blood flow and circulation, what limits cognitive performance. Thus the consequences of particle inhalation may impact a variety of everyday activities that require mental awareness. Two studies reported a correlation between lost school days and an increase of PM_{10} concentration in the classroom air, showing respectively 4 % and 1.4 % raise in school absenteeism per 10 $\mu g/m^3$. (Birchby et al. 2014) Another experiment carried out by T. Chang et al. (2014) on pear-packing factory workers showed, that 10 $\mu g/m^3$ increase in outdoor $PM_{2,5}$ concentration leads to 6 % drop in productivity. Negative effects were occurring when outdoor fine particle level reached 15-20 $\mu g/m^3$. What is more, there was no correlation between $PM_{2,5}$ and amount of worked hours or sick leave.

The particulate matter is one of the most influencing factors among air pollutants related to health problems and diseases decreasing lifespan of the population. Therefore it should be monitored especially in spaces where people spend most of their time. It is important to not only measure the total amount of particles in the air but also the concentration of smaller fractions ($PM_{2,5}$, PM_1) since they are the most dangerous.

2.2.5 Nitrogen dioxide



In the ambient air can be found seven nitrogen oxides. The most common are nitric oxide (NO) and nitrogen dioxide (NO_2). They are both associated with fuel combustion. In urban areas yearly mean NO_2 concentration is in between 10-47 ppb in outdoor air. Usually, those levels are the highest during winter, and lowest during summer (with a ratio: $3/2$). Nitrogen dioxide (NO_2) is a brick red to brown gas with an irritating odor, which threshold for human detection equals 0.1 ppm. It is heavier than air. The predominant outdoor sources of NO_2 are road traffic and power plants. Indoor sources consist of tobacco smoke, cooking and heating appliances utilizing fuel combustion. In absence of indoor sources, nitrogen dioxide level will be lower in the indoor air than outdoors. Penetration factor of NO_2 into the buildings varies from $0,88$ to 1. (WHO 2010)

Nitrogen dioxide metrics

There is not much written about NO_2 in the currently enforced standards concerning IAQ. However, Guerreiro et al. (2016) based on statistical data and research on NO_2 impact on people set limits for daily and yearly mean concentration, they can be seen in figure 2.14.

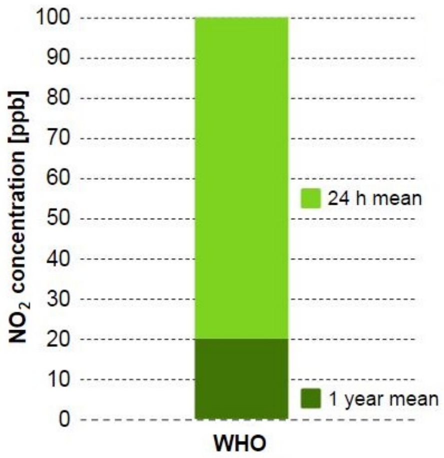


Figure 2.14: WHO limits for mean NO_2 concentration (source: Guerreiro et al. (2016)).

Nitrogen dioxide impact

Nitrogen dioxide can be harmful to people, when occurring in relatively high concentrations. Symptoms of exposure to this pollutant are:

- 10-20 ppm mild irritation of the nose and throat,
- 25-50 ppm inflammation of the lungs, such as bronchitis or pneumonia,
- $>$100 ppm death.

Only highly concentrated fumes cause immediate symptoms, such as coughing, headache, nausea, and stomach or chest pain. But, exposures to less concentrated fumes may result in such symptoms even after 5-72 h. Long-term exposure can cause a headache, weakness, loss of sleep and appetite, sores in the nose and mouth, nausea, and erosion of teeth. Nitrogen dioxide may also affect the immune system, resulting in a decreased resistance to infection. However, concentrations mentioned above are extreme and don't occur in normal conditions. (Pohanish 2012)
Research done throughout the years, aiming to establish a correlation between exposure to NO_2 and health issues were summarized by Bingheng and Haidong (2008). Conclusions coming out from this meta-analysis are that increase in NO_2 concentrations for periods from 1 to 24 h result in increased all-cause daily mortality, however, usually it is not possible to state whether the effects were caused by NO_2 only or by its products (O_3, fine particles). Nitrogen dioxide can be used as an indicator of traffic-related pollution.

Effects of inhaled NO_2 on human performance was not studied extensively, and therefore requires more focus in the future.

Nitrogen dioxide is posing a threat to human health, especially of the part of population living in a highly urbanized areas. This substance should be monitored due to its negative effects of people and its reactivity with other pollutants.

2.2.6 Volatile Organic Compounds

Volatile Organic Compounds (VOC's) are organic chemicals containing carbon along with other components. Since these components are a common air pollutant, exposure is normal while inhaling outdoor air. Higher exposure is present in the summer months, where the increased air temperature react with pollution (forming smog). The same rule applies for interiors, where increased air temperature leads to higher VOC emitting from materials and furnishing used in the given space. On the other side, every living being contains and emits VOC's. Therefore, inhalation exposure by humans is aggregated. The compounds easily change phase into vapor or gas. They are released by

- Biological emitting,
- Burning fossil fuel,
- Paints, glues, solvents and other products used in furnishing or materials,
- Activities such as smoking, cooking or cleaning.

The VOC sources can be divided into three main categories (in a ventilated room) shown in the following pie-chart:

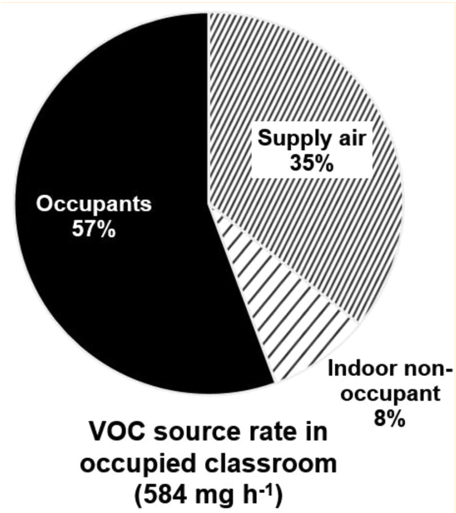


Figure 2.15: Sources emitting VOCs (source: Xiaochen et al. (2016)).

Since VOC release might be a produce of human's metabolic emission, not all of the compounds imply to health hazards. However, modern human being releases compounds reacting to the personal care produces (shower gels, deodorants, and perfumes). To give an example, the products of such reactions might be:

- Isoprene,
- Methanol,
- Acetone,
- Acetic acid.

These examples are only mentioned so the reader will have a general overview. Further reactions of metabolic effluents are between ozone and human skin oil creating more complicated VOCs.

A review done by (Costello et al. 2014) tabulated 1840 VOCs being released by healthy individuals. The release is associated with "breath, saliva, blood, milk, skin secretion, urine and faeces.

VOCs metrics

TVOC (Total Volatile Organic Compounds) are generally in non-industrial environments are below 1 mg/m^3 and a few exceed 25 mg/m^3. Within this range the sensory irritation response increase is expected. At concentrations above 25 mg/m^3 health effects become greater concern.

For various chemicals included in TVOCs, the acceptable levels are much lower than the limit for the total concentration – 500 $\mu g/m^3$, e.g. for phenol limiting concentration is equal to 0.019 $\mu g/m^3$. Therefore, if only TVOCs measurements are carried in the building it can be chosen to lower down the limiting value to e.g. 250 $\mu g/m^3$, for safety reasons. Also, since the chemical compounds have a specific smell, it is a good assumption to limit the possible odors. Table 2.2 below might also give reasons for such decision.

TVOCs concentration $[mg/m^3$	Health effects
$< 0,2$	No response
$0,2-3,0$	Irritation and discomfort
$3,0-25$	Discomfort
> 25	Neuro-toxic health effects

Table 2.2: TVOC concentrations and related health effects

Seifert 1990 derived empirical data from a **field study** in Germany. Ready dwellings and flats should not exceed the following **upper limits** of TVOC's divided into different chemical classes:

- 100 $\mu g/m^3$ for **Alkanes**,
- 50 $\mu g/m^3$ for **Aromatics**,
- 30 $\mu g/m^3$ for **Terpenes**,
- 30 $\mu g/m^3$ for **Halocarbons**,
- 20 $\mu g/m^3$ for **Esters**,
- 20 $\mu g/m^3$ for **Carbonyls** (excluding Formaldehyde),
- 50 $\mu g/m^3$ for **Others**.

VOCs impact

Health effects of VOC's depend solely on the compound accompanying the carbon. Based on the reactant a broad range of health effects can occur, from no known health issues to highly carcinogenic or toxic. The overall health effects depend not only on the substance but also on the exposure time and dose. To recent knowledge about VOC's the following compounds are considered as carcinogens:

- Benzene,
- Formaldehyde,
- Styrene,
- Diesel exhaust particulates.

The list above only mentions the most referred substances, there are many more VOCs harmful to a human being. Even non-carcinogenic compounds can lead to the following health risks:

- Liver damage,
- Kidney damage,
- Respiratory tract irritation,

- Eye strain, headache, dizziness and visual disorders.

VOC levels are recommended to be kept as low as reasonably achievable (ALARA) with respect to health, comfort, energy efficiency and sustainability. Based on toxicological knowledge some of the pollutants even at low concentrations react with each other which leads to hardly predictable effects on the human being. By that said, some percentage of VOCs cannot be identified. There's no general agreement on specific compounds that should be included in an evaluation of a TVOC scoring.

To give an example one of the most recognized volatile organic compounds is *Formaldehyde*. It is emitted from plywood, particle boards, furnishing (carpets and draperies), insulation(foam), unvented gas combustion units, personal care products, cleaning materials, paints, hobby supplies, lacquers, and any chlorinated compounds (acetone, ammonia...).

Quantification and identification of all VOCs contained in inhaled air are impossible or extremely difficult. To obtain accurate results, every single case would need a large number of samples and various processes to analyze different VOC's. An assumption of a relation between VOCs and health effects and discomfort have not been yet exactly formulated. These reactions and relationships are considered extremely complex and many other variables are affecting their impact. Up to today's knowledge a simple integrating detector for a specific compound, reporting it in a metrics that can show its impact on a human being(e.g. compounds described in toluene equivalents), is the best option for a simple VOC metric.

2.2.7 Radon

Radon (Rn) is a decay product of radium (witch is a decay product of uranium), an element found in the environment, particularly in soil. Radon, as well as radium, is radioactive. Rn is colorless and odourless. It is emitted everywhere on earth, but concentration in a given region depends on local soil properties and porosity.(Lippmann 2008)
Radon decays and produces other isotopes that are quickly bounding with smoke or dust particles. Elements created as a result of decaying process of Rn are listed in table 2.3. When radon decays to Polonium (Po 218) it emits alpha particles, that travel only short distances before disintegration. Human skin is a barrier for alpha particles, however, when inhaled they can do severe damage in the body. Radon enters the buildings with ventilating and infiltrating air. Indoor concentrations can be 10 to 100 times higher than outdoors if the ventilation of the space is not sufficient. (Neher 1994)

Name	Isotope	Half life	Decay process
Radon	Rn 222	3.8 day	alpha
Polonium	Po 218	3 min	alpha
Lead	Pb 214	27 min	beta
Bismuth	Bi 214	20 min	beta
Polonium	Po 214	164 μs	alpha

Table 2.3: Decay chain of radon (Rn 222), (source: Neher (1994)).

Radon metrics

Concentration of radon in the air is typically measured and assessed in units of becquerel per m^3 (Bq/m^3). Number of 1 Bq/m^3 represents 1 disintegration per 1 s per 1 m^3 of air, and it describes the activity of the radioactive elements. Even one alpha particle within the body can cause a lot of damage to the tissues, it is possible that negative impact can occur at any level of exposure to Rn. In this case there is no threshold below which health risk is not present. Worldwide average radon level in indoor air was estimated as 39 Bq/m^3. (WHO 2009)
Limits of Rn concentration in indoor air are provided in CEN (2014a), exact values are presented in figure 2.16. Assessment based on this limits is done on annual average values of concentration.

Figure 2.16: IAQ assessment based on Rn concentration in indoor air (source: CEN (2014a)).

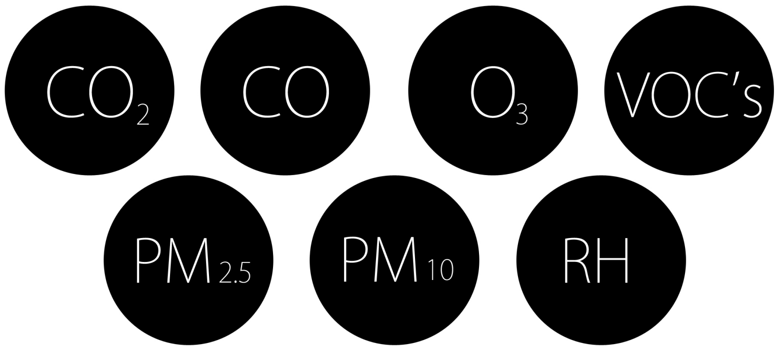
Radon impact

Most of the Rn that is inhaled with air does not stay in the lungs but is exhaled directly, but its decay products such as Po 218 and Po 214 are very likely to release alpha particles, that can cause damage of tissues inside the body. These isotopes are potentially causing lung cancer among exposed individuals, especially is people in question are smokers. However, researchers state that it is typically not possible to determine if the lung cancer was a result of radon exposure only, or smoking only or both elements together (Neher 1994). It was estimated that Rn causes between 4 and 14 % of all lung cancers, depending on country, and it is the second most important cause of this disease after smoking.(WHO 2009)
Correlation between Rn exposure and other diseases was studied by various researchers. Some of the studies confirmed the relationship between the occurrence of radon and leukemia, and sclerosis. However, it was stated by WHO (2009) that more work is required to validate these outcomes.

Radon is a dangerous pollutant that requires monitoring especially in spaces with natural ventilation. Health implications connected to exposure to Rn even in small doses are serious and might lead even to development of lung cancer. It cannon be stated at the time if any correlations between comfort and performance of people and amount of Rn in inhaled air exist.

2.2.8 Chosen indicators

The literature review conducted in the field of air pollutants was intended to yield a list of the most important, and prevailing agents. However, it was discovered that almost all of known to us air pollutants have strong negative effects on human health. It was therefore concluded that the more parameters would be examined in the space the higher the probability that there are no hazards in the indoor air. In the authors' opinion, all of the parameters described in this section should be included in the IEQ evaluation. Parameters included in the method, presented below, were chosen with regards to the current state of development in the field of cheap sensing technology.
Relative humidity is included in this comfort category (as well as in the thermal comfort), due to its' implications on susceptibility to viruses and bacteria, that were mentioned in section 2.1.



2.3 Acoustic comfort

As the urban areas constantly grow and become denser, securing the proper acoustic quality of indoor spaces becomes more important and complicated task. According to the number of studies, permanent exposure to the poor acoustic conditions severely affects occupants comfort, health, and productivity at work. Although its negative impact depends strongly on the subject, exposure time, level and context, general conclusions can be drawn and used as a premise to care about the quality of the acoustic environment. Most of the research are focusing on office environment, but there is a growing need of addressing the comfort and health impact of acoustical IEQ on occupants in residential buildings. Nevertheless, the office-based studies could be interpreted in the broader context to provide guidelines suitable for residential spaces.

The purpose of this sections is to point out the most influential factors regarding occupants health, work performance and the overall sensation of comfort. Therefore, underlying physical, quantitative parameters can be utilized as the indicators of the acoustical environment quality in buildings.

Basic Concepts

Sound could be defined as a pressure variation that can be detected by the human ear. The number of such pressure variations per second is called the **frequency** of sound, and is measured in hertz (Hz). The **audible** sound frequency spectrum for a healthy young person ranges from approximately 20 Hz to 20.000 Hz (or 20 kHz). As people respond logarithmically to stimuli (according to *Springer Handbook of Acoustics*, p. 586), it is more practical to express sound pressure level (SPL) in decibels (dB) rather than in Pascals (Pa) which would lead to the use of very large numbers. Decibels represent the logarithmic ratio between two quantities (i.e. pressures, powers, voltages). Formula 2.1 is the representation of sound power (as a square of sound pressure) in decibels.

$$dB = 10 \times log_{10}(\frac{p_m^2}{p_{ref}^2}) \tag{2.1}$$

where:

p_m	measured sound pressure [Pa]
p_{ref}	reference pressure of 20 μPa

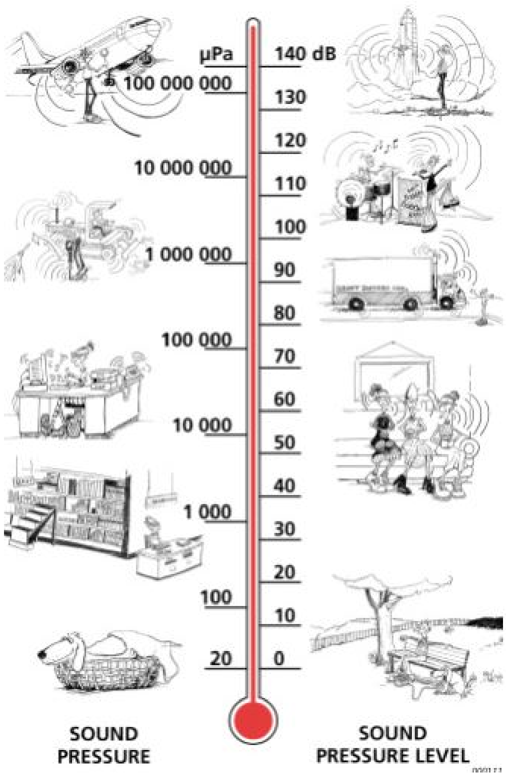


Figure 2.17: Common sound sources and its intensity (source: Brüel & Kjær (2001))

Audible sounds ranges from the threshold of hearing at 0 dB (or 20 μPa) to the **pain threshold** starting approximately around 130 dB (or 100 Pa). To put it in perspective, the doubling of sound source power (i.e. loudspeaker) gives only 3 dB increase in pressure. An increase of around 8 dB to 10 dB is required before the sound subjectively appears to be significantly louder (doubled), see Sone-Phone scale.

2.3.1 Background Noise

Background noise is an indoor environmental indicator used to describe an overall acoustic condition in the examined space. As a psychoacoustic factor, noise is rather perceivable than a measurable quantity. It can be generally described as an uncomfortable feeling of a person exposed to the sound of excessive loudness. The range of the loudness acceptability varies for different people, depending on a vast number of factors like: gender, age, hearing abilities, context, time exposure, the frequency of sound etc. Nevertheless, there is a measure that is often used to describe the perceived loudness of a sound, which is a Phon. "The phon is a unit that is related to dB by the psychophysically measured frequency response of the ear. At 1 kHz, readings in phons and dB are, by definition, the same. For all other frequencies, the phon scale is determined by the results of experiments in which volunteers were asked to adjust the loudness of a signal at a given frequency until they judged its loudness to equal that of a 1 kHz signal. To convert from dB to phons, you need a graph of such results. Such a graph depends on the sound level: it becomes flatter at high sound levels." (web: *School of Physics, UNSW*).

It is worth mentioning that dB-phone relation is valid only for the so called "pure tones" - sounds of one specific frequency i.e. 1 kHz*. Real world sounds consists of multiple frequencies whose contribution vary in time and with position in relation to sound source.*

The following figures 2.18 and 2.19 presents the relation between perceived sound loudness (expressed in Phons) and actual sound pressure level (in dB) of the pure tone sounds, according to different studies. According to *ISO 226:2003 - Acoustics - normal equal-level loudness contour* the "equal-loudness-level contours represents the average judgment of otologically normal (healthy) persons within the age limits from 18 years to 25 years inclusive". However, as it can be seen in the following figures the prediction of human response to the emitted sounds was evolving throughout decades of investigation. Outcomes of the conducted studies were gathered in the paper McMinn (2013) and are presented in the figure 2.23.

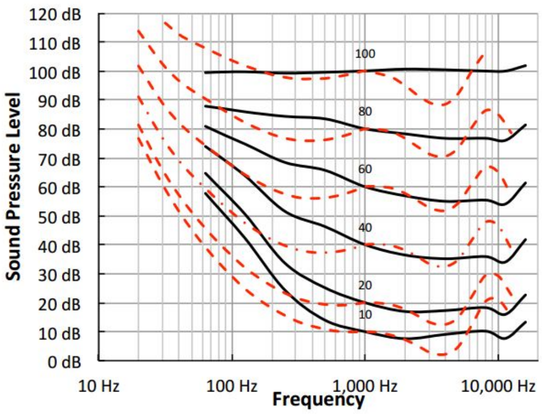


Figure 2.18: Original Fletcher-Munson equal level contours (black) and revised contours adopted in early versions of ISO226 Standard (Fletcher and Munson 1933)

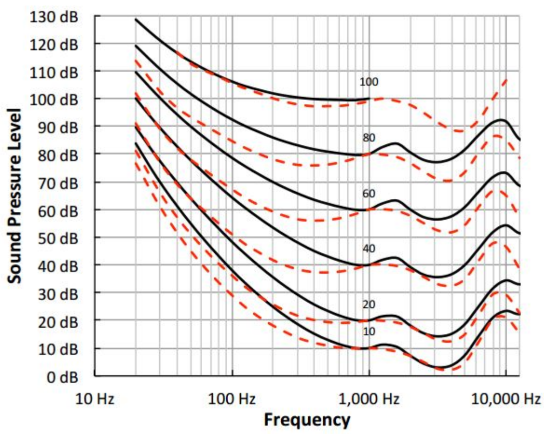


Figure 2.19: Comparison between equal level contours from withdrawn ISO226:1987 (dashed red) and up to date ISO226:2003 (black).

Loudness subjectivity

Clearly, perceived loudness is a matter of extended studies, and so far no uniform model is provided in standards that resolves most of the issues. In fact, acoustics is a very complex matter and despite many years of studies, there are still no tools that will take into account all phenomena that accompany sound wave interpretation by human hearing. Perceived loudness of specific sound event depends not only on the subject capabilities but also on the indoor environment attributes such as geometry, sound source location, the presence of absorptive materials etc. Figure 2.20 presents the physical length of the sound wave depending on its frequency. That helps to understand which objects can interfere with certain frequencies. For instance, long waves of very low frequencies interact with objects in the bigger scale, therefore they are not significantly distorted by a small size objects present in the space. Similarly, shorter waves of higher frequencies will be deflected by same objects complicated geometry very easily, therefore will spread in space more uniformly.

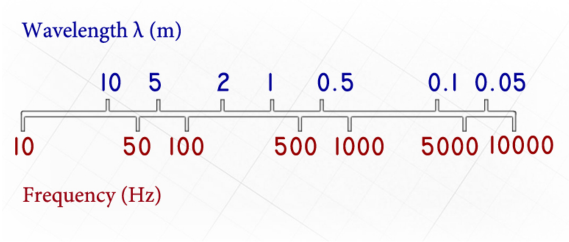


Figure 2.20: Sound wave length in relation to its frequency

That being said, it is understandable that depending on the location in the room, sounds of a specific frequency will be amplified and in others attenuated, creating a pattern that is shown in the figure 2.21. That leads to taking measurements in several spots in the examined space and averaging the outcomes in order to increase measurement reliability.

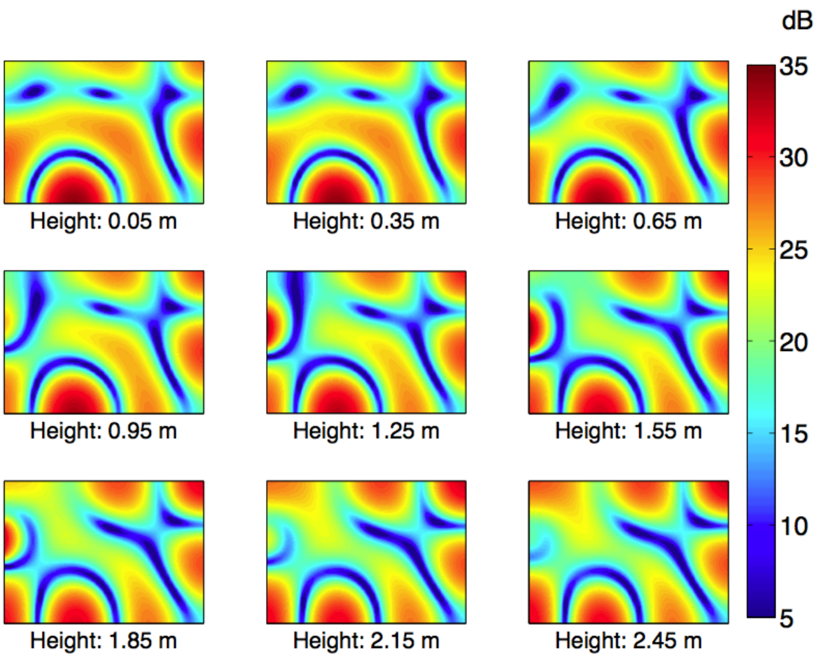


Figure 2.21: Example of simulated sound distribution in a room, at different plane heights. The sound was a low frequency 112 Hz pure tone. (source: Møller, Pedersen, and Staunstrup (2012))

Low-frequency sound leads to a number of issues, ranging from annoyance to more serious health issues. Although this thesis only introduces the matter, there are a lot of studies that focuses only on detection and elimination of a low-frequency noise problems that could be examined further.

More to that there is also an advanced concept of Head-Related Transfer Function (HRTF) that have important implications in relation to perceived sound loudness. Figure 2.22 below presents the human ear geometry impact on the sound pressure distribution, as well as spatial sound wave intensity simulation.

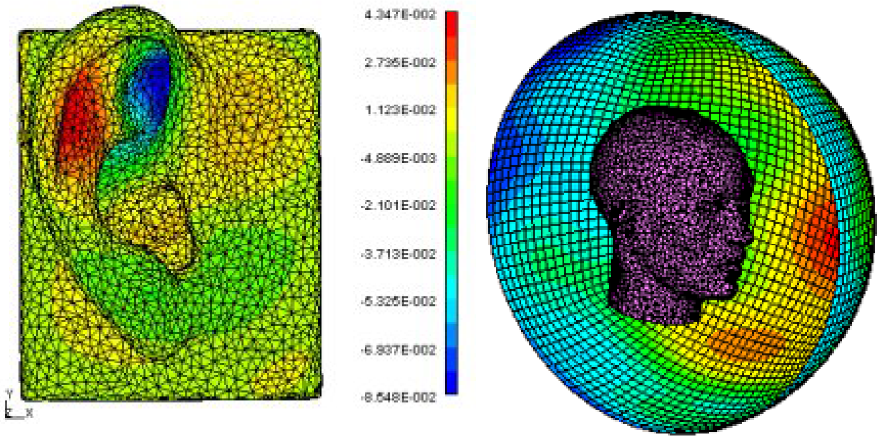


Figure 2.22: Simulation of sound wave pressure distribution around the ear and subject head (source: *Virtual Acoustics and Audio Engineering, UoS*)

Background noise metrics

A number of metrics are commonly used to quantify noise. Most of them are based on the **A-weighted sound pressure level** that allows correlating measurable quantity of dB(A) with human perception of loudness. It adopted the 40-decibel loudness level from the Fletcher and Munson (1933) research. Since then, it was the basis for predicting the human perception of the noise of different levels and frequencies. Over time, several attempts were made to revise the curve, aiming to find the most unified and reliable prediction of the human perception in the broader possible range of sound level and frequency. However, none of them was adopted in measuring procedures so far. All of the standards and design guidelines to date refer to values and levels obtained by A-weighting method. Figure 2.23 presents discrepancies between different methods used to approximate people sound perception depending on its frequency. The dBA curve (black), to some extent, reflects the inverse of the equal loudness curve for 40 Phons provided by the current revision of *ISO 226:2003 - Acoustics - normal equal-level loudness contour* (green).

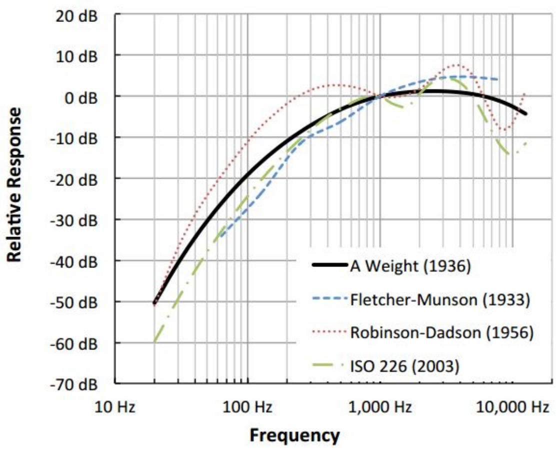


Figure 2.23: 40 Phons-based curves reported by the consecutive studies (source: McMinn (2013))

Note that chart in figure 2.23 has inversed Y-axis meaning that certain low frequencies (20 Hz÷1 kHz) *are attenuated by human hearing while other are amplified. All of the curves could be potentially applied in the sound assessment devices, however all current standards provide noise guidelines limits in* dBA.

According to the Brüel & Kjær (2001), sound level difference of 1 dB is just noticeable for most people. Nevertheless in practice difference level of 3 dB is commonly used to describe the noticeable difference in sound level for the majority of people.

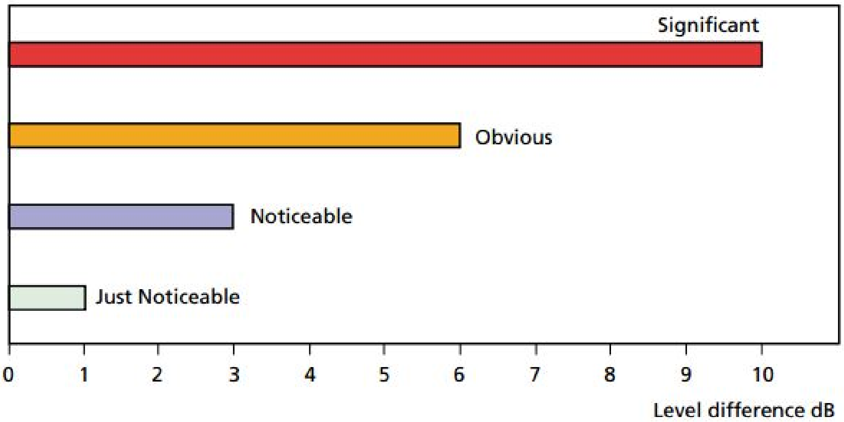


Figure 2.24: Perception of variation in sound loudness (source:Brüel&Kjær handbook)

If one would select 3 dB difference between the curves (in the figure 2.23) as an acceptable discrepancy, then current ISO standard fits the A-weighting curve in the considerable frequency range. Even though the discrepancies, between outdated dBA curve and more up to date ones, might be acceptable for some application, there are plenty of other limitations of the A-weighting metric. The summary of its advantages and drawbacks is provided in the summary section of this chapter.

Despite the pattern differences of human hearing response presented before, studies generally agree that people are less sensitive to sound frequencies at both ends of a spectrum. Nevertheless, our sensitivity to specific frequencies decreases with increasing loudness of the sound (see a flattening of the response as perceived loudness increases in the figure 2.18). That is often explained with the hearing system's profound ability of adaptation to the sound of different loudness and frequency. The flexibility of human hearing makes it difficult to mimic with one robust model under a wide range of conditions. This is the reason why there is no versatile method that will address all the possible situations, and thus there are several models with rather limited application.

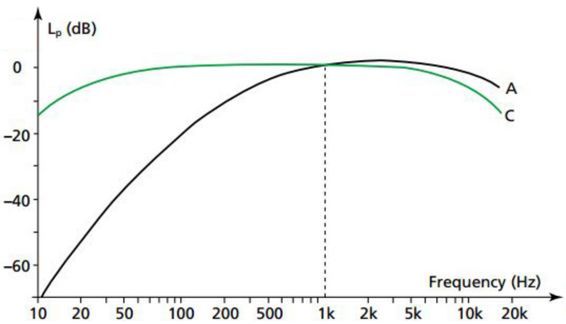


Figure 2.25: A-weighting and C-weighting curves (source: Brüel & Kjær (2001))

As people have a profound ability to adapt to the acoustic environment, different weighting curves should be used to approximate hearing response properly at different sound levels. A-weighting is used for low to moderate sound levels, while C-weighting is used to assess loud environments.

The common method for assessing low-frequency sounds is the so-called **C-weighting method**. It is based on the 100 Phon equal level curve from Fletcher and Munson (1933). Therefore, it suffers from the similar issues as the A-weighting method when it comes to approximating people response. It performs better for very loud environments, or low-frequency sounds, but fails in a wide frequency range due to its flattened characteristics. Even though people perceive the low and high frequencies as being equally loud at high sound levels, a lot of the low-frequency part is filtered out by the ear, making it less likely to cause damage. Since the ear's loudness sensitivity for tonal components is of a less importance than the hearing impairment risk due to noise, the C-weighting is not a broadly applied method.

Having in mind that neither A nor C-weighting is sufficient to predict human response to the complicated real-world acoustic environments, more advanced algorithms should be introduced. Dealing with complex sounds at the extremes of the frequency spectra involves the use of octave band analysis or Fast Fourier Transform (FFT) to detect tonal components or provide more insight into the acoustic environment being investigated.

Low or high frequency sounds usually originate outside the building, especially when it is located in the vicinity of railways, plants, industrial buildings or airports. Moreover, it could be also generated by the temporal events such as heavy equipment on the construction site nearby, passing airplane, road traffic etc. However, sometimes the building systems such as plumbing or HVAC can emit rather annoying tonal sounds. Figure 2.26 provides sounds classification according to its frequency range, generated by the HVAC-related appliances.

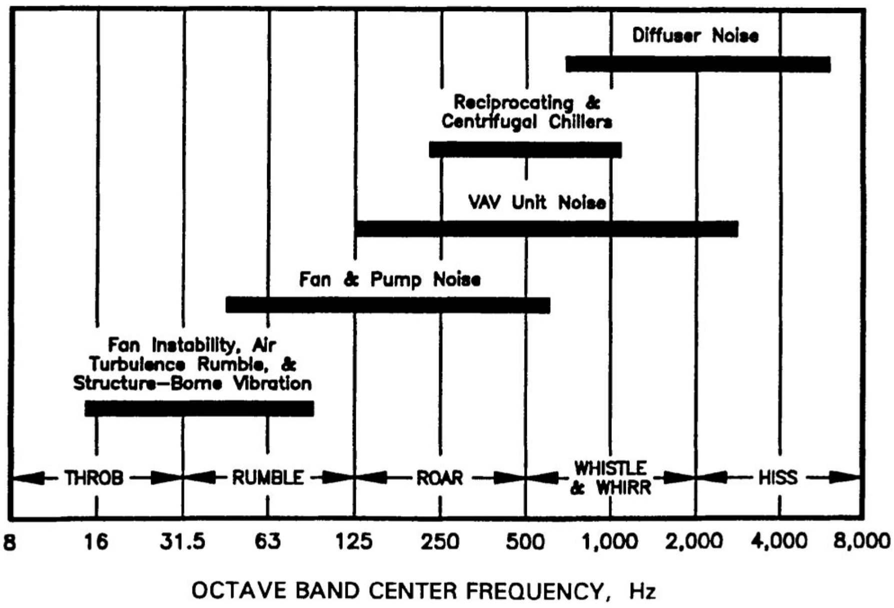


Figure 2.26: Sound spectra of mechanical equipment in buildings (source: Schaffer (2005)).

In contrast to the A-weighted sound pressure level, which does not take into account sound quality, but only relative loudness, there are several more advanced criteria to assess acoustic landscape acceptability. They were first introduced by the American National Standard Institute (ANSI) and described in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbooks (see: *Springer Handbook of Acoustics*, page 419).

Method	Overview	Considers Speech Interference Effects	Evaluates Sound Quality
dB(A) (1930's)	No quality assessment Frequently used for outdoor noise ordinances	Yes	No
NC (1950's)	Can rate components Limited quality assessment Does not evaluate low-frequency	Yes	Somewhat
RC Mark II (1997)	Used to evaluate systems Should not be used to evaluate components Evaluates sound quality Provides improved diagnostic capability	Yes	Yes
NCB (1989)	Can rate components Some quality assessment	Yes	Somewhat
RNC (2000)	Some quality assessment Attempts to quantify fluctuations	Yes	Somewhat

Table 2.4: Existing criteria for noise evaluation (source: *2009 ASHRAE Handbook: Fundamentals*)

All of the rating methods listed in table above usually consist of two distinct parts: a number of criterion curves and a rating procedure taking into account measured sound data in relation to the curves and with regards to the sound quality. As it is summarized in the table 2.4, most of the indices provide a limited sound quality assessment. Some of them have been developed for a rating of the ventilation system components acoustic performance. Figure 2.27 presents the **Room Criteria (RC)** chart, with a number of RC quality curves. The sound in the region labeled with *A* can cause perceptible noise-induced vibration such as rattling of doors, windows, or fixtures. The sound in the region labeled *B* may generate lower levels of these noise-induced vibrations. Three regions at the bottom of the chart stand for, respectively: LF - low frequency (rumble), MF - medium frequency (roar), HF - high frequency (hiss). The detailed description of all indices is provided in ASHRAE (2009, chapter 8). **Room Noise Criteria (RNC)** method attempts to consolidate NCB and RC curves under one indicator. Evaluation and comparison of the methods were conducted by Tocci (2000), also methods limitations were pointed out. Although all above-mentioned noise criteria attempted to provide a consolidated measure to assess acoustic quality it is not very well recognized outside the US.

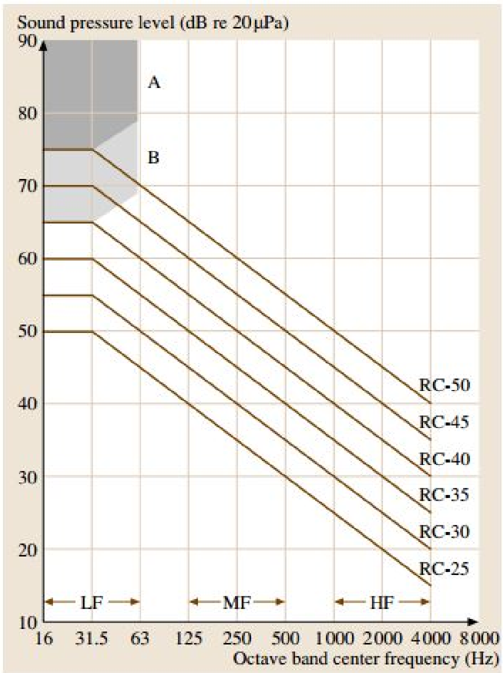


Figure 2.27: Noise criteria - Room Criteria index (source: *Springer Handbook of Acoustics*)

Even though no uniform method of assessing space acoustic performance exist, both American and European standardization committees seem not to differ much when it comes to design targets for occupied spaces (both residential and office). Table 2.5 presents acceptable noise limits according to the method used.

Space		ASHRAE		EN15251
Building	**Room**	**Noise Criteria (NC/RC)**	**dB(A) sound level**	**dB(A) Sound Level**
Residential	Living areas	30 (±5dB)	35 (±5dB)	25÷40
	Bedrooms	X	X	25÷35
Office	Private offices	30 (±5dB)	35 (±5dB)	30÷40
	Open-plan offices	40 (±5dB)	45 (±5dB)	35÷45
Other	Auditorium	30 (±5dB)	35 (±5dB)	30÷35

Table 2.5: Current noise limits for different zones according to US and EU standards

The design limits for indoor spaces regarding A-weighted sound pressure level in a number of EU countries are presented in the figure 2.28.

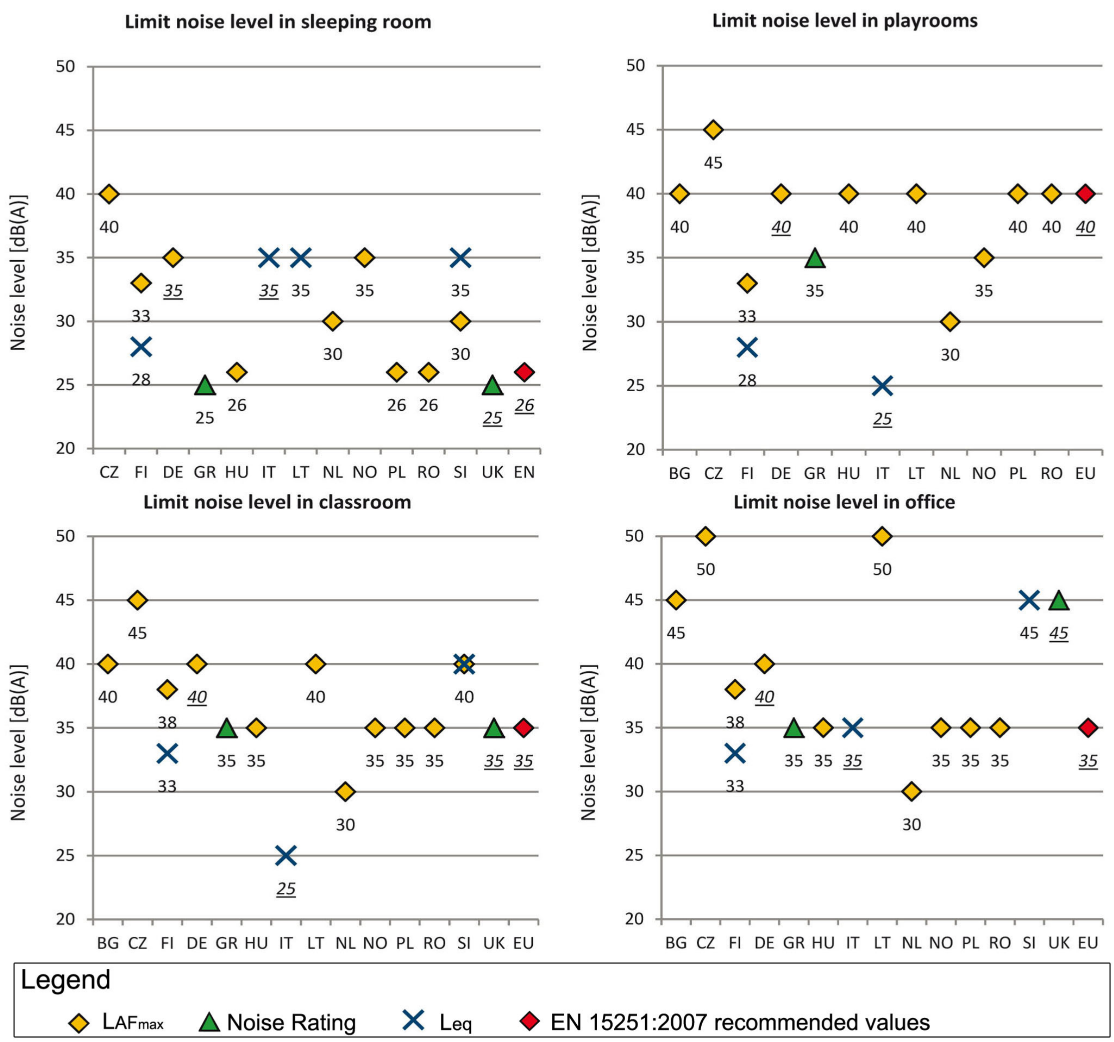


Figure 2.28: Acoustic requirements for various spaces in EU countries (source: Brelih (2013)). Colors indicate different method that was used to establish the limit, red indicates EU limit suggested by standard EN 15251.

The most common way of expressing instantaneous sound level is to use dB(A). For long-term measurements, these readings are expressed by the equivalent continuous sound level L_{eq}. Usually, its subscripts, for instance, $L_{AF,8h}$, defines measurements details, where A or C stands for used weighting, F or S indicate device integration time (fast or slow) and last number specifies the total measurement length.
Figure 2.29 shows the division to different acceptability classes according to the measured background noise level throughout a number of studies. Numbers in brackets, next to each bar, refer to the original studies that the review Heinzerling et al. (2013) was examining. Bar colors indicate room acoustic quality starting from the best - green for lower dB(A) values on the horizontal scale, to the worst - purple, according to the occupants' responses. It is clear that different studies' outcomes differ since neither a number of classes nor their ranges match.

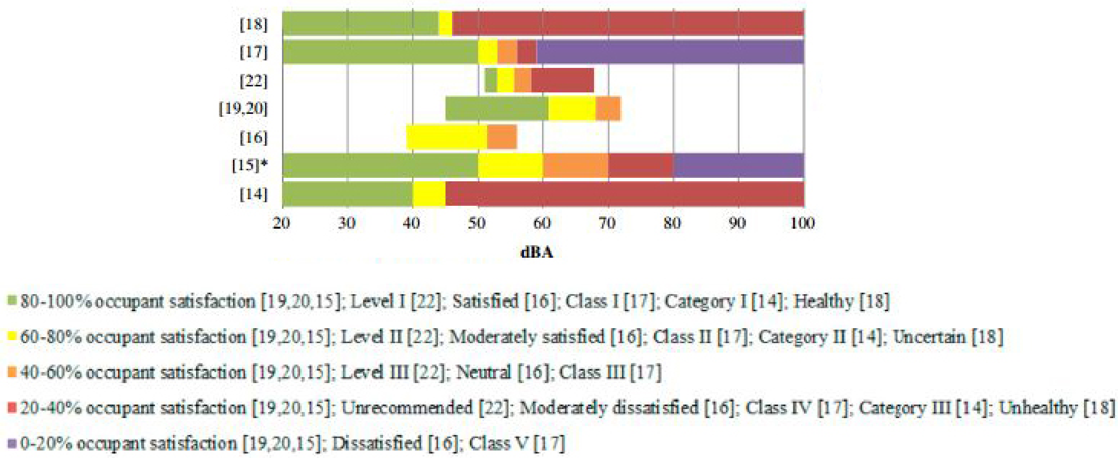


Figure 2.29: Comparison of background noise level assessment according to several studies examined in Heinzerling et al. (2013)

The literature review done by Heinzerling et al. (2013) clearly shows that there is no consensus among researchers on the qualitative assessment of acoustic environments. The substantial disagreement between studies is observed not only with suggested ranges of certain quality class (green, yellow, orange etc.) but also with the number of classes itself. Some studies used only two quality classes i.e. [16] while other suggest five (see [15], [17]). Therefore, Heinzerling attempted to gather all the separate paper outcomes with different quality classes and limits under one color-scheme to visualize them altogether. More details on methods used to determine quality classes for certain studies can be found in Heinzerling et al. (2013). Assumed level of noise floor (minimum sound level measured) for all studies was 40 dBA.

2.3.2 Speech Intelligibility

Speech Intelligibility (SI) is a term used to describe the proportion of understood speech under-examined acoustical conditions. There are several single number quantities that aim to provide the objective measure of SI for specific applications. Where in some spaces such as auditorium, lecture rooms, theaters; high speech intelligibility is desirable, in other it might be an issue. It was found, that unattended speech has a negative impact on people cognitive tasks at the workplace, depending on its intelligibility. As open plan offices are still very common in architectural design there is a growing need for measuring the acoustical performance of such spaces. Also, together with other acoustical parameters mentioned in this section, it gives the objective measure of the acoustical conditions in the room. Knowing the SI impact on human comfort and performance, the assessment framework could be created to evaluate different spaces according to their function.

The most commonly utilized index for assessing SI is **Speech Transmission Index (STI)**. For evaluation of speech intelligibility in open plan offices, standard *DS/EN3382-3:2012 – Measurement of room acoustic parameters – Part 3 : Open plan offices* suggest supplementing the measurement with other single number quantities such as distraction distance, the spatial decay rate of speech, background noise and A-weighted sound pressure level of speech from distance. The STI is an objective measure ranging from $STI = 0$ for not intelligible to $STI = 1$ for perfectly intelligible. Since measuring procedure of STI is rather complex it is not introduced here. However, in general, the STI index depends on room acoustic absorption, distance to the sound source and background noise. It is said that certain level of background noise might have a positive, masking effect on speech, decreasing its disturbing impact. Nevertheless, in most cases, occupants are disturbed by the intermittent speech events occurring in their direct surrounding and therefore impossible to mask in a reasonable way. The following figure 2.30, shows the impact of speech intelligibility assessed with STI method on the cognitive task performance of the subjects. Despite the fact that it is applied in International Standard ISO 3382, originally developed by Hongisto (2005), the numerical values that define the curve shape are being questioned by more up to date studies. However, in residential buildings, where a certain level of speech intelligibility is desirable, the performance or annoyance based models are losing their relevance.

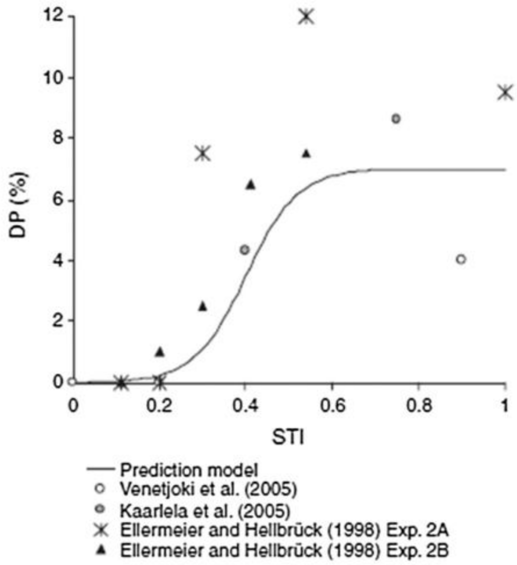


Figure 2.30: Decrease in performance as a function of STI as proposed by Hongisto (2005), together with four other studies data. Only the overall trend should be regarded as validated, not magnitude.

The procedure of measuring STI value in accordance with the current standard (*IEC 60268-16:2011 - Sound System equipment, Part 16: Objective rating of speech intelligibility by speech transmission index*) involves measurements in furnished but unoccupied rooms with standardized sound signals. Furthermore, the Speech Transmission Index is very local, alters depending on the mutual distance of a speaker and subject, which result in an infinite number of STI within a single room.

2.3.3 Reverberation time

Another characteristic of a room acoustics is a reverberation time. It tells what is the room ability (response time) to decrease noise signal by 60 dB. In practice, it is usually evaluated on a limited interval of the decay curve, see 2.31, i.e. T_{30}. Slope is calculated starting from −5 dB up to −35 dB below the initial value, and based on that 60 dB drop time is derived. Instead of RT_{60} which require considerable dynamic range to be derived directly (low noise floor and high signal to noise ratio), two metrics are commonly used, RT_{20} and RT_{30}.

$$T = 60dB \frac{(t_{(-35)} - t_{(-5)})}{(-5dB) - (-35dB)} \tag{2.2}$$

where:

t_{-n} | stands for the time when the decay curve reached certain limit values [s]

Reverberation time impact

Reverberation time strongly depends on the room geometry (bedroom, open plan office, auditorium) and materials used in the building construction and furnishing. However, reverberation time is normally measured in not furnished rooms to allow an objective comparison between various spaces. Full measuring and calculation procedure in accordance with current standards is provided in *DS/EN3382-2:2008 - Acoustics – Measurement of room acoustic parameters*.

As a general rule, the higher the reverberation time, the longer sound is circulating inside the room before it dissipates.

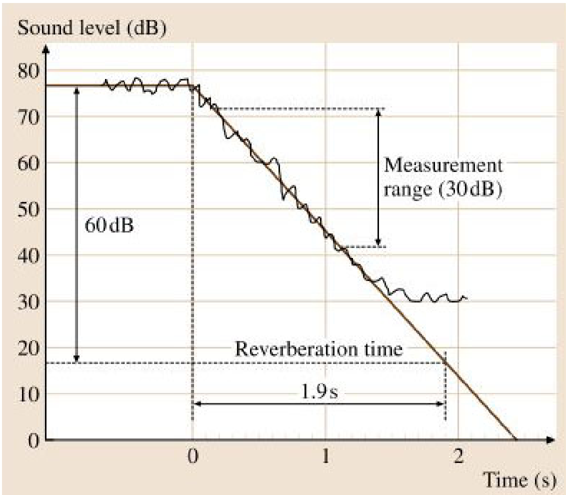


Figure 2.31: Reverberation time decay curve

Performance areas, such as offices or classrooms, should be designed in a way to avoid excessive sound propagation and amplification to reduce echoes and limit noise. Target values of reverberation time for such spaces are provided in *DS/EN 3033:2011 Indoor Environment - Classification of the indoor environment in buildings — Office buildings, schools, kindergartens and residential buildings*. As a rule of a thumb performance areas and general purpose rooms should have a rather short reverberation time, ranging from 0.4 s up to around 0.7 s (see "Reverberation time in class rooms – Comparison of regulations and classification criteria in the Nordic countries"). Reverberation time is often measured in octave bands from 125 Hz÷4000 Hz, and taken either as an average value from all bands or as single octave band value, usually 500 Hz, which should be clearly stated. Nonetheless, no target values for dwellings are given in the standard. Different studies suggest, that contrary to what is believed reverberation time cannot be directly linked with occupants or lecturer dissatisfaction of the room acoustic performance as other parameters such as background noise, room size etc. shows greater impact (see: Brunskog et al. (2009)). Other spaces, such as theaters, concert halls, opera houses etc. should have relatively long reverberation time to add fullness to the music and amplify it, in most cases values above 1.5 s are desirable.

2.3.4 Summary

Noise Effects on Humans

There is a number of studies that have been trying to find a link between background noise levels and occupants comfort or work performance. Nevertheless, many research was unable to support their claims with sufficient certainty or their conclusions were mutually inconsistent. One has to be aware that there are various other factors - unrelated to the acoustic comfort, that cannot be ruled out during experiments and still greatly affect test group responses. Study Szalma and Hancock (2011) examined many studies that developed psychological models aiming to determine effect of certain sound events on people cognition. Only the proven effects are were included in the list below. Taking possible uncertainties into consideration, statements below are mostly based on the studies that provided well-recognized effects of overexposure to noise (see section 2.5). Study Mehta, Zhu, and Cheema (2012) is included as the single one presenting any positive impact of background noise on occupants performance in certain circumstances.

It was found that moderate background noise may increase workers creativity by introducing slight disruption to their current cognitive process, allowing more abstract thinking. In other words, certain limit of background noise might enhance the ability to put things in wider perspective when task does not require much focus.

Long exposure to the noise levels of 85 dBA and higher is proven to be harmful for subjects hearing.
According to WHO even low sound level of around 33 dBA (inside) 55 dBA (outside) during night may lead to sleep disturbances and corresponding health effects.
Chronic exposure to the excessive noise impairs cognitive functions, causes annoyance, induces stress, therefore leads to increased risk of severe non-auditory health effects such as hypertension or stroke.
It was proven that intermittent noise, in particular speech is the most disruptive noise event, causing annoyance among workers. Subjects adapt easier to moderate, continuous background noise.
Moderate and high background noise level has detrimental effect on work, especially for resource-demanding cognitive tasks. Szalma and Hancock (2011)

Selected parameters

From aforementioned indices, only a few parameters are chosen for implementation into the Manikin measuring unit. Main factors that played role in the selection were:

- Recognized impact of the parameters on occupants and its relevance in overall IEQ assessment scheme.
- Ease of implementation - some parameters required additional equipment or more advanced procedures that will increase significantly both cost and complexity of measuring unit.
- Complexity level of measuring procedure and required post-processing.

Therefore the following parameters will be included in the IEQ assessment tool. A-weighted, equivalent continuous sound level $L_{eq,A}$ & Reverberation Time.

Pros and cons of using aforementioned parameters:

[dB(A)]
Is widely known and utilized to measure environmental related perceived sound level
All current standards provide limit values using dB(A) index, what makes it applicable and understandable among building industry
[RT]
It gives insight into the room acoustical performance, could indicate problems with sound waves propagation within the space

[dB(A)]
Is valid only for low to moderate sound levels (up to 60 dB) McMinn (2013)
As derived from subjects response to pure tones, it should not be utilized for complex tone noise assessment
Tends to underestimate the effect of low frequency (20 Hz÷150 Hz noise on the occupants (Jakobsen 2003)
It also underestimates annoyance caused by sounds with tonal components (see figure 2.26) (Salomons and Janssen 2011)
[RT]
Measurement procedure provided in EU standards is very strict and rather complex and as such cannot be easily implemented into the maintenance free, stand-alone device like a manikin

2.4 Visual comfort

2.4.1 Introduction

Evaluation of overall visual comfort, assessing all of the aspects of visual comfort characterizing the relationship between the light environment and human needs, has no general agreement or methodology established. Perception of lighting quality by humans is influenced by many physical and physiological factors. By that means, lighting quality can not be expressed by only photometric measure, it can be judged according to the visual comfort and performance needed for the given working task. Visual comfort perceived by humans can be also interpreted as the quality of the visual environment and its adaptation related to the performed task. This metrics is difficult to quantify and it is a psychological aspect. Extensive literature and standards analysis was conducted, looking for the most suitable visual metrics and determining the advantages or limitations associated with their application. Overall any changes in luminance are affecting the person's evaluation of the lighting, and dependence on the preferred conditions may change the mood. Changes in mood may affect feelings of **health**, **well-being** and motivation to do the task, hence affect **performance**. Effects of lighting are instantaneous when it comes to performing a visual task. However, effects on the circadian rhythm and its shift takes a few days of inappropriate lighting conditions.(R. P. Boyce 2014). These biological effects are called the non-visual, non-image forming effects of light and are related to human photoreception of light. Sources: (C. G. Brainard et al. 2001) and (Cajochen et al. 2011).

Long term measurements done by manikin are beneficial for further research in lighting quality and human response. It is important to state that luminance is perceived through the eyes, but all the information is processed by the brain, hence the environment is judged by subjective expectations and preferences.

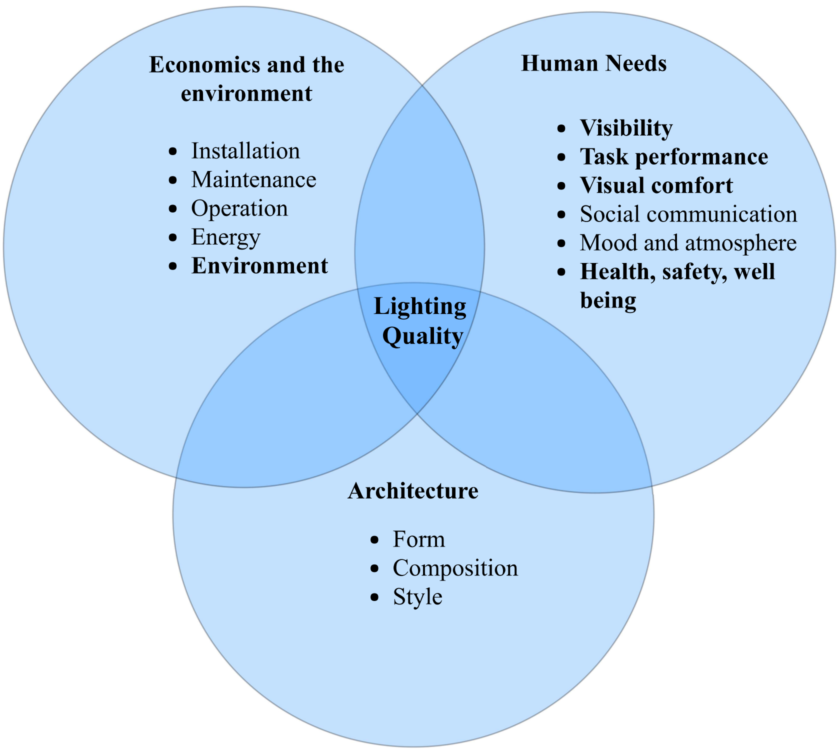


Figure 2.32: Diagram of lighting quality aspects, source: (Veitch 1998).

In general, the aspect of the lighting practice is to design adequate lighting for a specific task carried out by humans. With an aim to increase the speed and accuracy of performing a visual task. Visual performance due to increased light levels improves, but only to a certain level (this phenomenon is described further in this thesis). To a certain level of illuminance the productivity increases, however, research shows that after reaching a certain illumination the productivity does not increase further. On the other side, unacceptable lighting conditions may impact on visual task performance and decrease productivity through motivation (R. P. Boyce 2014). Due to lack of research, the biological effects of light on human performance is yet not very well known. There is an insufficient understanding of the interaction between different aspects of lighting on visual tasks and neurological responses.

In this thesis, the emphasis will be put on evaluating the lighting quality while performing visual tasks and overall visual comfort of the occupant in a given space. Figure 2.32 displays all the variables affecting lighting quality, where most of them even with the newest possibilities are very difficult to evaluate through an automatized manikin. The highlighted indicators are possible to evaluate with an artificial perception.

Evaluation of the following **comfort and health-based** visual aspects is presented: ***quantity of light, distribution of light and glare***.

2.4.2 Quantity of light

Relevant indicators describing the quantity of light used in the methodology are briefly described in this section. All of the indicators are using instantaneous illuminance values at a given point for the evaluation. The adaptation capability of the human eye leads to big thresholds throughout different scientific papers on the insufficient or excessive quantity of light. Results obtained from the indices are highly correlated with the other aspects of daylight, mainly glare problems when excessive illuminance levels are calculated.

Illuminance

Illuminance of a surface at a given point is a physical quantity, measured in lux $[lm/m^2]$ and defined as total incident luminous flux per unit area. Supplementing equation is described in 'Appendix A:Theory'. Illumination affects the psychological well-being of a person depending on the daylight and luminance of the luminaire. Illumination of a workspace should be sufficient to carry out work tasks, to create positive mood or atmosphere and to motivate. Improper illuminance level can cause eye strain, leading to safety threats and irreversible eye damage in a long term.

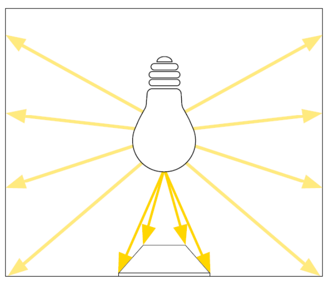


Figure 2.33: Illuminance

Illuminance is independent on the type and feature of the light source, it is used to construct a short-term and a local metric assessing the quantity of light. The reference values of illuminance intensity vary depending on the type of the building. Referring to the European standard EN 12464-1 and most literature review a suggested value of 500 lx on the work-plane is recommended. An example of a task area calculation is shown in figure 2.34.

Measurement is done by a luxmeter, allowing simple and instantaneous illuminance interpretation. The mean illuminance is the arithmetic brilliance level measured by luxmeter in a defined grid, under precisely defined conditions. According to **EN 12464** the measuring grid for workplaces is 0.75 m(lux meters are placed on a grid of $0,75\,x\,0,75[m]$. Limitations of the given approach are:

- each measurement is valid only for the given moment,
- variation over time is not accounted,
- luxmeter only covers a specific area which is also affected by its orientation,
- the nature of light is not distinguished,
- measured value is independent of the human perception.

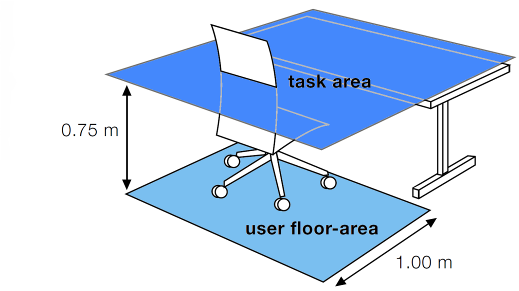


Figure 2.34: Work-plane defined in EN 12 464

Illuminance itself cannot quantify any discomfort such as glare. Measurements done by luxmeters can be used to compare the outcome of CMOS (digital) cameras and possibly improve their calibration.

Useful Daylight Illuminance

Useful Daylight Illuminance (UDI) paradigm is defined as an annual occurrence of illuminance at a given point which falls in a given range of "useful daylight". The analysed period is divided into 3 groups: (1) oversupply of daylight leading to visual discomfort, (2) appropriate illuminance level, (3) too little daylight. Each group represents a percentage of time when the specified illuminances occur.

UDI is a local quantity measurement restricted by upper and lower boundaries of natural light. Long-term measurement informs not only about useful daylight illuminance, but also on the frequency of occurrence of either insufficient or excessive levels of daylight.

The limitations of such paradigm are the variance of illuminance limit values based on different publication, UDI provides 3 values for each measurement. The proposed ranges from different sources are summarized in table 2.6

Source	Lower illuminance limit [lux]	Upper illuminance limit [lux]
(Nabil and Mardaljevic 2006)	100	2000
(Mardaljevic, Heschong, and Lee 2009)	100	2500
(Olbina and Beliveau 2009)	500	2000
(David 2011)	300	8000

Table 2.6: Illuminance limit values

It is assumed that if average illuminance is between the limits of two boundary values, then visual comfort is secured only by daylight. The equation to calculate the frequency of useful visual comfort is the UDI_{useful} range shown in 8.2. Values chosen for the boundaries based on literature review (Sicurella, Evola, and Wurtz 2012) are: $E_{lowerlimit} = 150lx$ and $E_{upperlimit} = 750lx$. This narrowed range guarantees to avoid too high or too low values.

Intensity of Visual Discomfort

The intensity of Visual Discomfort (IVD) is defined as the time integral of the difference between the spatial average of actual daylight illuminance and the upper limit of visual comfort. The range of the illuminance boundaries is: $E_{over} = 750lx$ for the upper limit and $E_{under} = 150$ for the lower limit. As the above-mentioned indicators IVD_{over} and IVD_{under} get higher, the visual discomfort for excessive or insufficient daylight has higher importance.

When the boundary conditions are not met, an acceptability threshold should be introduced, since even if $IVD_{over} > 0$ (excessive illuminance) it does not necessarily mean an unacceptable situation and the overall visual comfort should put more weight on glare evaluation, because if $IVD_{over} > 0$ (excessive illuminance) occurs than excessive daylight mostly relates to glare problems. According to (Sicurella, Evola, and Wurtz 2012) illuminance indicator limits can be overcome by not more than 30% of their value.

2.4.3 Distribution of light

Visual comfort is affected not only by sufficient daylight availability in a working space but also by its distribution. Spatial distribution is a variability of luminance (or illuminance) across a surface. Multi-point measurements are required to determine spatial light distribution.

Drawback is the large number of measurements in a grid pattern. The simplest way is to evaluate the maximum, minimum and average luminance values in the whole scene or field of view. Due to spatial variations locating the maximum and minimum values is not straightforward, and picture analysis might yield more accurate results.

Uniformity affects our perception of space and navigation in it. Evenly distributed lighting creates a visually continuous environment with breaks created by lighting level drops 2.35. Based on **EN 12646** standard illuminance level of at least 30 lx on ceilings and 50 lx on walls is recommended, since unlit ceilings and walls create an unpleasant room impression.

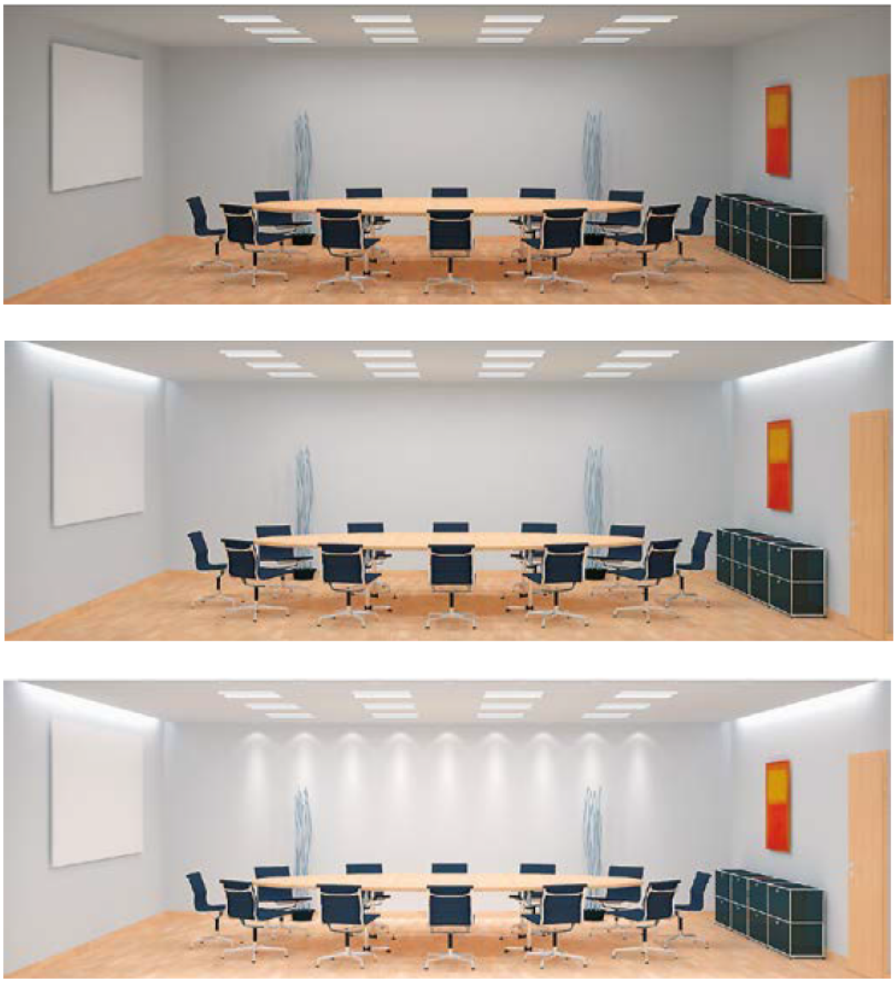


Figure 2.35: Different light distributions, showing dynamism and EN 12 464 requirements (ceiling and wall minimal illumination), source: (Zumtobel 2013)

Illuminance Uniformity

The distribution of daylight can be expressed as a ratio of minimum illuminance (E_{min}) to an average illuminance ($E_{average}$) value on a given plane in a given moment. In some cases it is beneficial to use a ratio of maximum (E_{max}) and minimum illuminance on a given plane. U_o is a local short-term assessment of light uniformity. Different standards recommend some uniformity ratios, which are described in 2.7

Source	Illuminance uniformity
As 1680	$U_{O,average} > 0,67$
DIN 5035	$U_{O,average} > 0,67$
NSVV	$U_{O,average} > 0,70$
CIBSE	$U_{O,average} > 0,80$
BS 8206-1	$U_{O,average} > 0,80$
	$U_{O,max} > 0,70$
CIE 29.2	$U_{O,average} > 0,80$

Table 2.7: Illuminance uniformity standard recommendations

With a high uniformity comes also a perception of boredom to the space, as the lighting itself lacks any contrast and dynamism. The limitation of the uniformity calculation is that it does not account surroundings and background only the workspace illuminance uniformity.

2.4.4 Luminance uniformity

Luminance is the luminous intensity of light emitted from a surface per unit area in a given direction. The equation is described in the appendix 8.5.

According to (Suk, Schiler, and Kensek 2013) the acceptable absolute L_{gamma} value of glare source (as diverged to the luminance ratio of the source and relative background) is the most significant value when attempting to define an upper limit of the glare indicator for a specific case. Literature review shows no agreement on such values. Based on different authors the range varies from 2000 nit to 10 000 nit or even greater in (Büllow-Hübe 2008). Therefore these values will be evaluated further in this work.

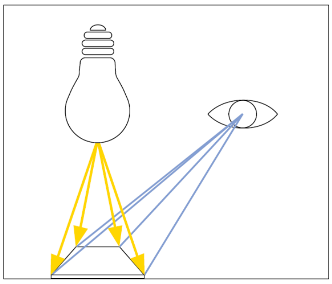


Figure 2.36: Luminance

Luminance ratio (Contrast Ratio) is used for glare thresholds by the contrast ratio between background and glare source (or the task area). Recommended ratio, less than 1:3 (task area to surroundings) is defined in the guidelines by Illuminating Engineering Society of North America (IESNA) and NUTEK guidelines. Different researchers are not consistent with the contrasts regarding visual comfort. Most of the conducted studies were based on different luminous environments such as small windows, incandescent sources, and artificially lit spaces.

The differences of a few researches:

- luminance ratios smaller than 1:5 are desirable for humans according to Lukiesh
- luminance anywhere within the field of view should not exceed 1:40 ratio by Egan 1983
- luminance greater than 1:10 should be avoided and 1:100 is not tolerable Wymelenberg 2012; Osterhaus 2003
- visual comfort is maintained if the ratio of 3:1 is between task and adjacent darker surfaces and 10:1 between task and remote darker surroundings by Egan 1983
- 1:10 contrast ratio between background and visual display terminal is the limit of acceptable glare threshold by Wienold and Christoffersen 2005
- 1:3:10 between visual task, immediate surroundings and near surfaces by Osterhaus 2009

According to (Linney 2008) the current luminance thresholds and ratios might be too low for daylit interior environments. It is also suggested to determine what proper absolute luminance values are in interior and exterior environments for glare assessment.

2.4.5 Glare

Glare is a visual discomfort caused by high luminance contrast of objects present in the visual field or by excessive and uncontrolled brightness. In most cases glare causes discomfort or disability to complete a work task. Glare reducing the visibility in the field of view is called disability glare. The main concern regarding the case of indoors, lighting or performing a visual task indoor is the discomfort glare. In the presence of bright light sources, luminaries, windows or other bright surfaces visual discomfort can be perceived.

However, the physiological or the perceptual mechanism for discomfort glare is not established yet. In essence it is the contrast between the luminance of the glare source, the source angular size seen from the observer and the background luminance as seen from the position of the observer.

General combination of these factors can be expressed as:

$$G = \left(\frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(P)} \right) \tag{2.3}$$

where:

L_s is the luminance of the glare source, in a case of a window it is the luminance of the sky,
ω_s is the solid angle subtended by the source with respect to observer's eye, in a case of a window it is the apparent size of visible sky seen by the observer (the brighter the sky, the higher the index),
L_b is the background luminance (the average background luminance with the glare source removed) controlling the adaptation of the observer,
P is the position index or angular displacement of the source from the observer's line of sight (the further from the center line of sight, the smaller the index),
e, f, g are exponents for suitable weighting, according to the specific glare formulae.

Glare is a **complex phenomena** with several approaches depending on the complexity of the calculation have been introduced for predicting discomfort events. Glare can be also named as "borderline case of contrast". These events cause:

- Unpleasant sensation,
- Temporary vision blurring,
- Feeling of ocular fatigue,
- Loss of lighting efficiency,
- Productivity loss.

The simplest and most direct is an evaluation based on measuring or calculating the luminance of a given glare source seen from a specific observation point. In most of the indexes, a logarithm is used since our eyes respond logarithmically to light. Further expanding relates the glare risk to the luminance contrast in the field of view of an observer. Different metrics fit the above mentioned approach and equation 2.3 :

- (BGI) British Glare Index
- (DGI) Daylight Glare Index
- (CGI) CIE Glare Index
- (UGR) CIE Unified Glare Index

For these indexes and the used equation, these assumptions arise:

The higher the illuminance and the size of the source is, the higher the glare risk is. Brighter background luminance is decreasing the glare risk. The observer's disturbance is decreasing the further the source is from the center of the view.

The most recent research showed that combining the modified glare index and a vertical eye illuminance evaluated in the same point yields strong correlation with user's responses regarding glare discomfort (Wienold and Christoffersen 2006). According to (Jakubiec and Reinhart 2011) in exceedingly bright scenes, discomfort can be predicted even without significant visual contrast.

This section describes the glare indices as they were introduced and modified. Even the most recent approaches are derived from the basic glare formulas an explanation of the indices improvement over time is necessary.

British Glare Index

British Glare Index (equation: 8.6) is based on the glare equation developed at the Building Research Station by (Petherbridge and Hopkinson 1950).

BGI is the least accurate index when using a large area light source (Center 2014) and it does not consider the human adaptation. Accurate calculation is only for small light sources with a solid angle lower or equal to 0.027 sr within the field of view. Also more weight is on the background luminance than in other indices.

CIE Glare Index

(Center 2014) presented a new index improving the mathematically BGI for multiple glare sources, which was accepted by International Commission on Illumination (CIE).

For the glare assessment using this index a direct and diffuse light is evaluated on a horizontal plane passing through observer's eyes. The formula is split into two main part, first describing the room's luminous properties and the second combining the luminance, location and the size of the glare source

Discomfort Glare Index

Discomfort Glare Index (DGI)is derived from CGI and aims to predict glare from a large area source of luminance, such as a window. The improved equation is defined in 8.8.

Although DGI was mathematically developed for large luminance sources, it only refers to sources with uniform light distribution, which in general means removing direct sunlight.

However, human perception of glare is more significant if the light source is non-uniform and if the source is located perpendicularly to the center line of the field of view. The equation 8.8 is not accurate when the window area covers most of the field of view and the window luminance equals to the background luminance.Limitations of the DGI were improved by (Nazzal 2005). The most important change of the equations is including the effect of observer's position and the influence of the surroundings to discomfort glare 8.9.

Unified Glare Rating

Developed by CIE and has an equation 2.4. This index is used as reference values for different visual tasks in **EN 12464-1**. UGR is based on a glare formula that accounts all the luminaires in the system which contribute to the sensation of glare. Reference values for activities and visual tasks are specified in **12464** standard, relevant ones for the purpose of this work are listed in the table 2.8.

Type of task or activity	UGR
Writing, typing, reading, data processing	≤ 19
Day room	≤ 22
Filing, copying, etc	≤ 19

Table 2.8: Reference values of UGR for visual tasks based on EN 12464

The new European standard sets $UGR = 19$ as the maximum permissible value for offices, which is equivalent for offices and $UGR = 22$ can be used for day rooms in dwellings.

$$UGR = 8log_{10}\left[\frac{0,25}{L_b}\sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}\right)\right]; \qquad \omega_s \in \left\langle 3\cdot 10^{-4}, 10^{-1}\right\rangle sr \tag{2.4}$$

where:

ω_s is the solid angle between the source i from the position of the observer

P is the Guth position index depending on the position of the source i compared to the observer and expressing the perception of glare

L_{si} is the luminance in the direction connecting the observer with each source

L_b is the background luminance (for windows is the averaged luminance of the wall except the window)

The UGR index simplifies CIE Glare Index and provides easier calculation process, where the glare source contributes to the adaptation of the observer. The direct illuminance at the eye has been neglected. Another assumption is the fact, that glare sources are omitted and only the background luminance is accounted for the luminous environment component of the formula. CIE document states: "for practical purposes, this has little effect when the formula is applied to rooms having illuminances within the usual range recommended for working interiors".

Since the basic UGR index is the accuracy only for small glare sources 2.37 with a solid angle between the boundaries specified in equation 2.4. It is more suitable to glare assessment from smaller light sources (artificial) and since the position index is defined for glare prediction from above the observer's horizontal plane of sight any glare prediction from below the plane of sight could not be valid. CIE advises to use Great-room Glare Rating (GGR) for light sources with an area above 1.5 m^2. This equation is derived from CIE glare index and CIE unified

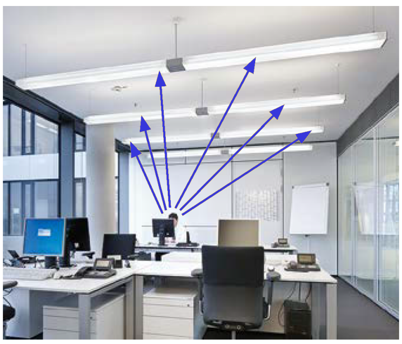


Figure 2.37: UGR limitation of not accounting glare sources

glare rating.

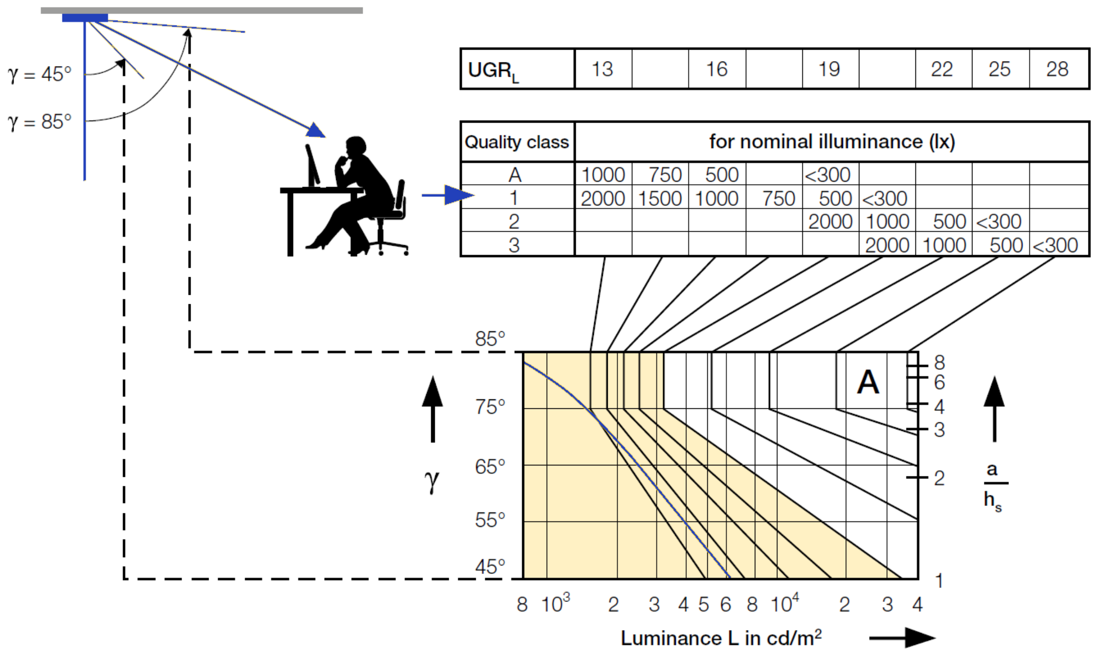


Figure 2.38: UGR quality classes (Zumtobel 2013)

The above mentioned indices can be compared in a general nine-point glare sensation scale from (Mardaljevic 2013).

Degree of glare sensation	BGI	CGI	DGI	UGR
Intolerable	31	34	30	34
Just intolerable	28	31	28	31
Uncomfortable	25	28	26	28
Just uncomfortable	22	25	24	25
Unacceptable	19	22	22	22
Just acceptable	16	19	20	19
Perceptible	13	16	18	16
Just perceptible	10	13	16	13
Imperceptible	7	10	14	10

Table 2.9: Nine-point glare sensation scale

Previously described glare indices only take into account ratios between the background average illuminance and glare source luminance. Illuminance perceived by the observer (vertical plane at observer's eye height) is not considered. Strong correlation between the vertical eye illuminance and contrast ratios is described in (Wienold and Christoffersen 2005) regarding the glare perception by the observer. Therefore DGP index is introduced.

Discomfort Glare Probability

Discomfort glare probability (DGP) was introduced by (Wienold and Christoffersen 2005) and later the formula was validated in (Wienold and Christoffersen 2006).

$$DGP = 5,87 \cdot 10^{-5} E_v + 0,0918 \cdot log_{10} \left[1 + \sum_{i=1}^{n} \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1,87} \cdot P_i^2} \right) \right] + 0,16 \tag{2.5}$$

E_v vertical eye illuminance $[lx]$
L_s Source luminance $[cd/m^2]$
P position index based on azimuth and elevation of the source's angular displacement from the observer's plane of sight

Limitation regarding the validity of the equations are: DGP has to yield values between $\langle 0,2; 0,8 \rangle$ and vertical eye illuminance E_v above 380 lux.

According to (Suk, Schiler, and Kensek 2013) DGP is the most appropriate metrics to use for absolute glare issues. DGP glare index requires few steps to get an accurate result:

- first the main occupants viewpoint(s) need to be chosen,
- renderings in *Radiance* or HDR pictures with scientific grade CCD cameras are created,
- glare evaluation based on *Evalglare* specially developed to detect glare sources on 180^o fish-eye scenes.

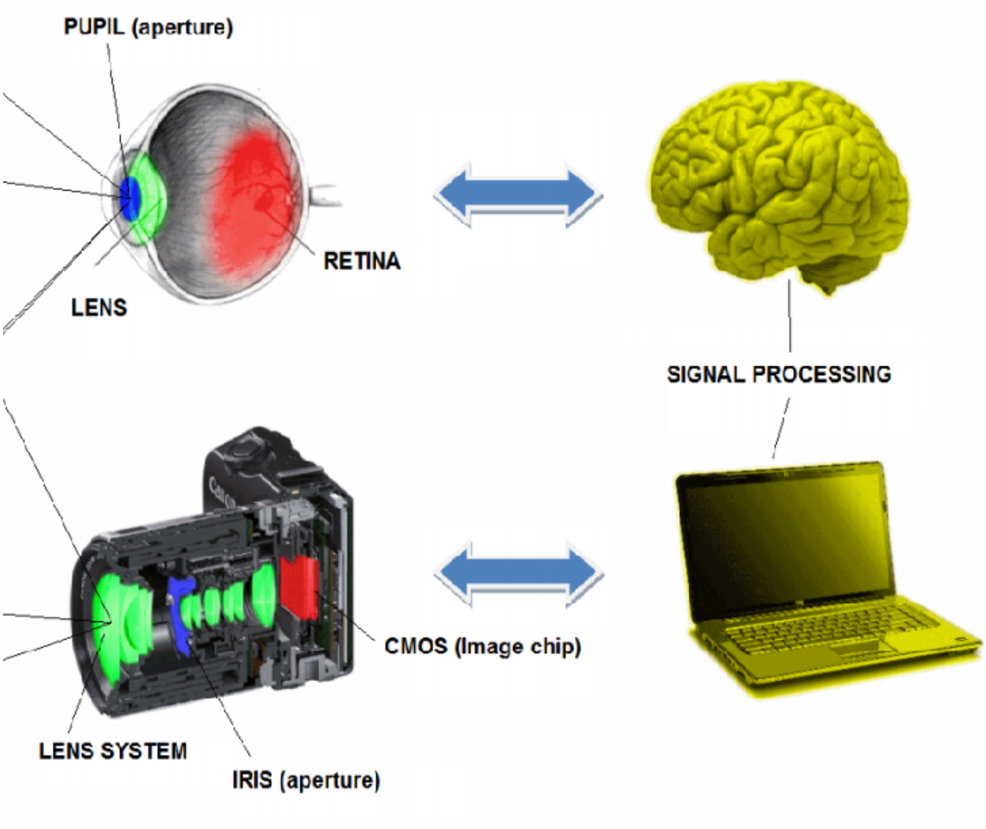


Figure 2.39: Approximation of the visual perception, by a camera and computer processing, source: (Center 2014)

The limitation of the procedure is the involvement of high computational time and user input in comparison to the analytic calculations (most of the above-mentioned glare indices).

Simplification by (Wienold 2007) to reduce the computational effort is based on, "the correlation between the linear function of vertical eye illuminance and the probability of disturbed persons was stronger than all other tested functions" (Wienold and Christoffersen 2006).

The limitation of the evaluation is its location in space and scene importance, which makes it hard to generalize. The logarithmic term depending on the luminance and solid angle of the source seen by the observant is neglected in equation: 8.11.

The DGPs is supposed to remove the high computational effort (generating pictures for every time step of the calculation process) by neglecting the peak glare sources in the field of view of the observer. If a direct view of glare sources is within the field of view of the observer, than simplified DGP for absolute glare condition evaluation cannot be used.

$$DGPs|_{Hviid} = 5,87 \cdot 10^{-5} \cdot E_v + 0,16 \quad (2.6)$$

(Hviid and Nielsen 2008) proposed to only use and linearly depend on the vertical illuminance at eye level. Considering the similarity with Wienold's version the predicted glare probability is lower by 2-3 %, where the same limitations apply. Respecting the simplicity of DGP where direct sunlight cannot be neglected a governing equation was proposed and validated by Wienold (Wienold 2009) based on 2 full-year hourly datasets, resulting into 8.10.

The computed local quantities are just the main glare sources, not the exact luminance distribution, time reduction in computational effort arises from indirect ambient reflections. Compared to DGP reasonable results are achieved (Wienold 2009). (Jakubiec and Reinhart 2012) proposed a comparison matrix for different glare indices on a four-point glare sensation scale.

Degree of glare sensation	DGP	CGI	DGI	UGR
Intolerable	>0,45	>28	>31	>28
Disturbing	0,35-0,40	22-28	24-31	22-28
Perceptible	0,30-0,35	13-22	18-24	13-22
Imperceptible	<0,30	<13	<18	<13

Table 2.10: Four-point glare sensation scale comparing different indices, source:(85)

The **Daylight Glare Probability(DGP)** deals with absolute glare issues. DGP is well correlated with user's response to glare perception(Wienold and Christoffersen 2005), global brightness of the scene is accounted also (vertical eye illuminance), it accounts for occupant's discomfort, it evaluates glare as a percentage of observers considering current luminous conditions as uncomfortable.

The following table presents the recommendations from different standards all over the world. The recommended values are within thresholds found during the literature review for each of the countries. The estimation of visual comfort its evaluation is in its essence the same in the whole world with not significant differences either in methods or values recommended.

Summary of lighting recommendations

Country	Parameters	Requierements
China		level 1 / level 2
	Illuminance (horizontal) task area	500 lx / 300 lx
	Illuminance of immediate surroundings	300 lx / 200 lx
	Luminance ratio on task area	1:3 near work place
	Unifortmity task	>0,7
	Uniformity surroundings	>0,5
	Discomfort glare	UGR < 19
Japan	Illuminance (horizontal) task area	750 lx < x < 1500 lx
	Illuminance of immediate surroundings	200 lx
	Luminance ratio on task area	0,5
	Unifortmity task	>0,6
	Uniformity surroundings	-
	Discomfort glare	-
EU	Illuminance (horizontal) task area	>500 lx
	Illuminance of immediate surroundings	Ambient light >300 lx
	Luminance ratio on task area	1:3 near work place
	Unifortmity task	>0,7
	Uniformity surroundings	>0,5
	Discomfort glare	UGR < 19
Brazil	Illuminance (horizontal) task area	500 lx
	Illuminance of immediate surroundings	300 lx
	Luminance ratio on task area	-
	Unifortmity task	0,7
	Uniformity surroundings	0,5
	Discomfort glare	UGR < 19
Russia	Illuminance (horizontal) task area	General lighting 300 lx, supplemented lighting: supplementary 400 lx & general 200 lx
	Illuminance of immediate surroundings	300 lx
	Luminance ratio on task area	-
	Unifortmity task	<1,5 or 2 (for max to min illuminance ratio)
	Uniformity surroundings	-
	Discomfort glare	-
Australia	Illuminance (horizontal) task area	320 lx
	Illuminance of immediate surroundings	240 lx
	Luminance ratio on task area	2:1 (task:background)
	Unifortmity task	>0,7
	Uniformity surroundings	-
	Discomfort glare	UGR < 19

Figure 2.40: Different standard requirements

2.4.6 Lighting effects on productivity and health

The luminous environment actuates a chain of biological mechanisms on human physiological and psychological factors, which influences productivity and performance. All the factors on either the environment or human side were described by (Gligor 2004). Several researches have been conducted in the $1920's$ on the effects of lighting conditions on productivity and indicated that adequately illuminated environment can improve performance.

Later studies are showing rather contradictory results, for example according to (Hughes 1978) an illuminance increase from 500 lx to 1500 lx in office could increase office work by 9 %. Whereas an another study by (Gligor 2004) on lower illuminance levels 150 lx tended to improve performance of a complex word categorization compared to higher illumination levels 1500 lx.

(Hughes 1978) conducted direct measurements of productivity increase in industrial environment in a range from 0 % to 7.7 % due to different lighting levels.

Numerous literature sources showed null results in the experiments carried out. There are no clear-cut effects on illuminance on a given task performance, over a wide range of lighting levels and for a variety of either complex or simple tasks in an office (Gligor 2004).

The already know fact is that unacceptable lighting conditions may impact on visual task performance and decrease overall motivation while performing the task (R. Boyce and Cuttile 2003). The discovery of the *ipRGC* photoreceptor in 2002, raised awareness of the lighting research and circadian biology connection. It is the main photoreceptor responsible for the humans to perceive light/dark cycle next to other biological effects. Light is the external input for the human's endogenous clock.

The human biological clock is responsible for the following processes summarized by (Dacey, Liao, and Peterson 2005):

- sleep and wake rhythm,
- body core temperature,
- hormone secretion including melatonin, serotonin, and the stress hormone cortisol,
- pupillary reflex,
- alertness,
- mood,
- **human performance**.

Research conducted by (G. Brainard et al. 2001) in 2006 showed that short-wavelength light is the most effective in coordinating the endogenous clock, therefore the most recent research is currently investigating the possibility of the blue-enriched light to affect human response like alertness and mood (Gooley et al. 2001). Mechanism of the alertness modulation by light has been examined, but the observed reaction is still **unclear** to a certain degree. In 2009 experiments indicated, that the human circadian system can be reactive to dim levels of light (e.g. candlelight) (Duffy and Czeisler 2009).

The maximum phase shift of the circadian rhythm is obtained with a 9100 lux stimulus, whereas to reach the 50 % magnitude of the biggest shift only 100 lux light level(less than $\sim$ 1 %) is needed. If humans are exposed to very dim light pulses ($\sim$ 100 lux) for several hours a significant phase-shifting (melatonin suppression) effect in humans occurs.

This was validated and explained in 2016 by (Gabel 2016) how the effect of light is not proportional to its intensity. The effects on melatonin suppression and alertness are the same at 9000 lx as for 3000 lx. To reach 50 % of the effect of 9000 lx exposure to 100 lx is enough. The threshold to notice changes either on the physiological or behavioral level is between 50 lx to 100 lx. For example, the natural daylight around noon can reach up to 100 000 lx, which implies to the fact, that the sunlight is the most effective modulator of the internal clock.

Conclusion Light's health impact on human beings are:

- the human circadian rhythm is responsive to short and dim light pulses,
- daylight has a significant influence on hormonal secretion and day-night time,
- modern humans are getting relatively little bright light, however, they are exposed to indoor lighting and its intensity for a long period of time,
- very little is known about the circadian sensitivity to light, nor is the overall "biological clock's" behaviour.

Therefore the conclusion of the health benefits or hazards are **not yet quantifiable**.

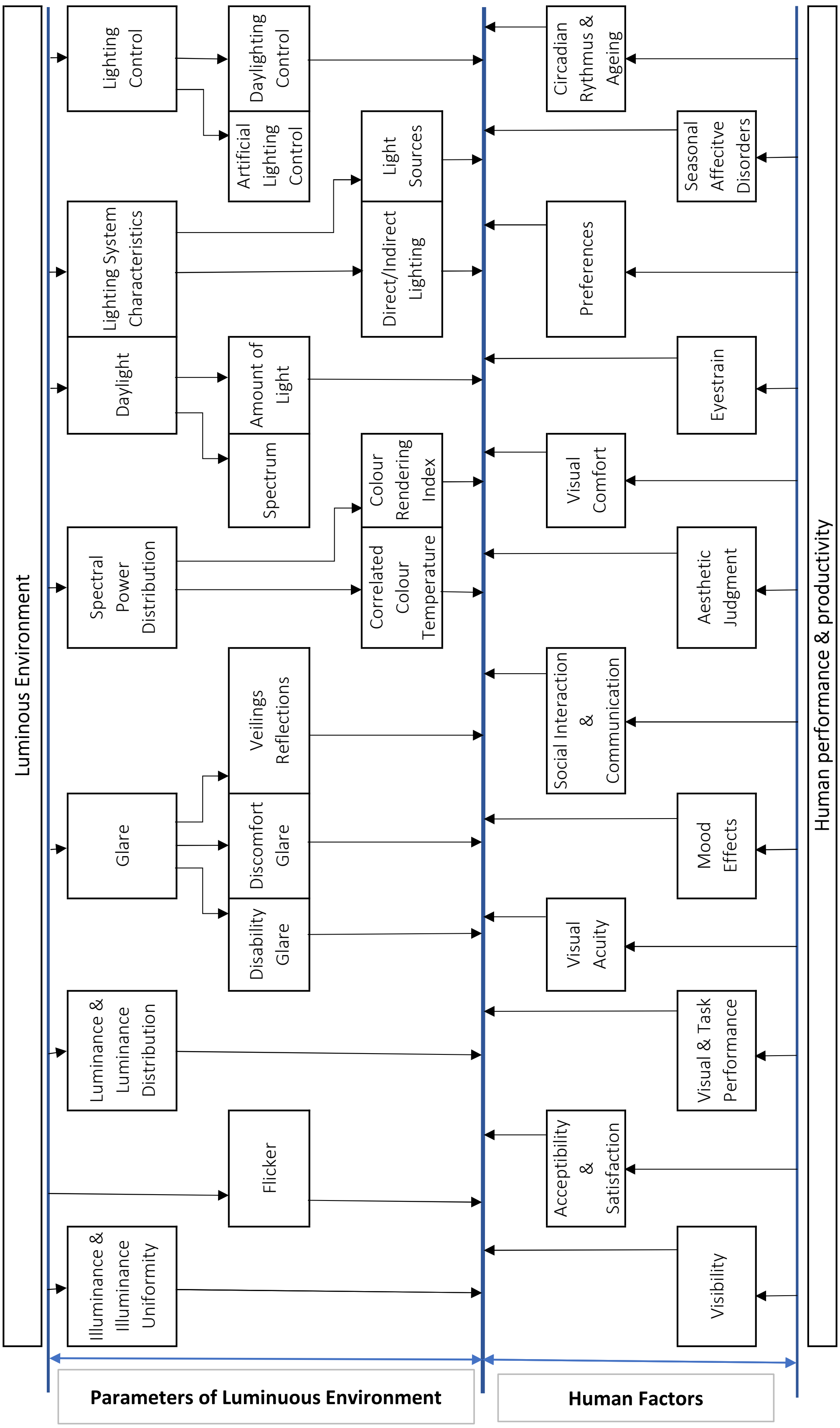


Figure 2.41: Luminous environment and human performance (Gligor 2004)

2.4.7 Summary

Based on the literature review and the most suitable metrics to use a manikin are:

- **Illuminance** is measured by two luminosity sensors located on the back of the hand, simple measurement giving instantaneous light quantity values,
- **Luminance uniformity** is evaluated by picture analysis based on HDR photos, despite the aforementioned drawbacks, it is a simple evaluation and with more testing, it can be further calibrated,
- **Glare** is evaluated by luminance levels based on HDR photos,
- **DGP** is a supplementing measure for the glare phenomena, it is beneficial to use DGP in comparison with luminance mapping. The eye-height illuminance is measured by a luminosity sensor located in the right eye of the manikin.

Basics of the measured data - illuminance

Performance and health indicators show the best illuminance range for a regular visual office work between 500 lux to 750 lux is the **most suitable**. Increased illuminance shows higher performance, but at the same time, health-related indicators show negative effects on a human being. The matter of performance and health indicators was described in the visual comfort chapter. The discrimination thresholds of a difference noticed by the observer is a based on **Weber and Fechners law**. It's based on a human study responding to a physical stimulus in a quantitative way. This law represents a general relationship between a quantity or intensity of either the visual stimuli and how much more needs to be added (or subtracted) for the observer to be able to notice the difference.

The figure 2.42 indicates the human visual sensation between two extremes - dark light and fully saturated retinal illumination. Also confirms the Weber's law valid boundaries. Later research conducted by Fechner showed that the discrimination threshold increases for an increasing stimulus. See graph 2.43. Fechner's law predicts that two different illuminances are only discriminable by a human eye if they generate a constant amount of response:

$$k = \frac{\delta I}{I} \tag{2.7}$$

δI is the difference threshold
I represents the initial stimulus intensity
k is the Weber constant

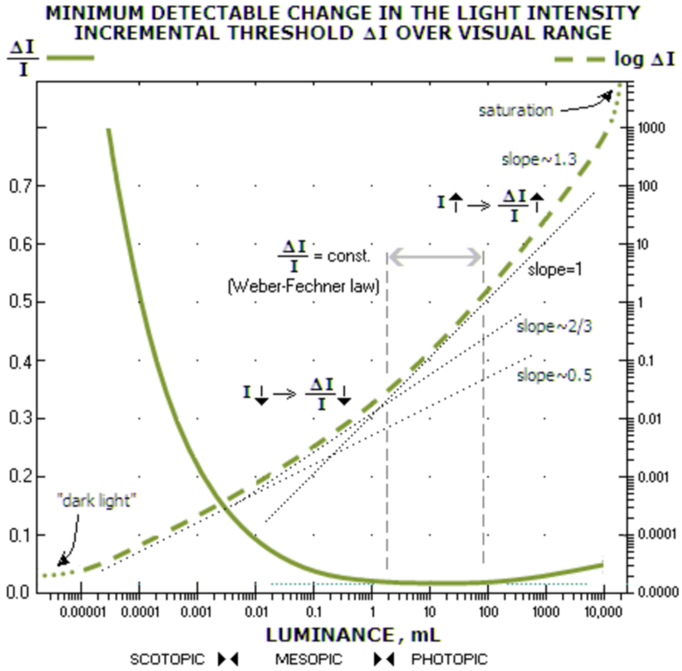


Figure 2.42: Brightness response summary of researches (Selig Hecht 1924)

For visual stimulus an **average** value of 8 % is a noticed in terms of illuminance intensity, but only for **low** luminance values, this value increases significantly above 100 cd/m^2
The overall perception of luminance mimics a logarithmic function and is a subject to recent research in **cognition modelling**, therefore we assume that a logarithmically **spaced vector** between two luminance values can create accurate thresholds for assigning the scoring boundaries a human vision can distinguish.

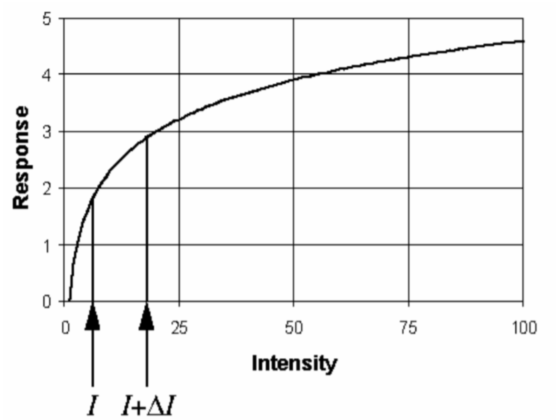


Figure 2.43: Weber's law modified by Fechner

To obtain the threshold values the rules of logarithms are applied for the range of insufficient illuminance which is below 500 lux and excessive illuminance over 750 lux. Threshold values are then allowing to link a **score** to an actual value of illuminance. The following values are calculated and later used for scoring by the developed Matlab function.

The scoring scheme is created for both cases: **Insufficient illuminance** (below the optimal threshold) and **excessive illuminance** (above the optimal threshold). The limiting values are based on the literature review summarized in table 2.6. Values shown in the table have a big discrepancy

Score	Insufficient Illuminance
A	500 - 750 [lux]
B	500 - 292 [lux]
C	292 - 171 [lux]
D	171 - 100 [lux]
E	< 100 [lux]

Table 2.11: Illuminance thresholds

Score	Excessive Illuminance
A	500 - 750 [lux]
B	750 - 1041 [lux]
C	1041 - 1443 [lux]
D	1443 - 2000 [lux]
E	> 2000 [lux]

Table 2.12: Illuminance thresholds

and therefore together with the performance and health-related studies the bounding limits were chosen to be: **minimum illuminance** 100 lux and **maximum illuminance** 2000 lux.

Basics of the measured data - luminance uniformity

HDR

The difference in luminance (or color) makes an object distinguishable. In terms of visual perception, it is a brightness difference of the object within the same field of view or wider field of view. Development of a tool which is processing pictures as the human eye's field of view 2.44 was during its creation simplified to rectangles, with a prepared coordinate system for further development and polynomial boundary approximation.

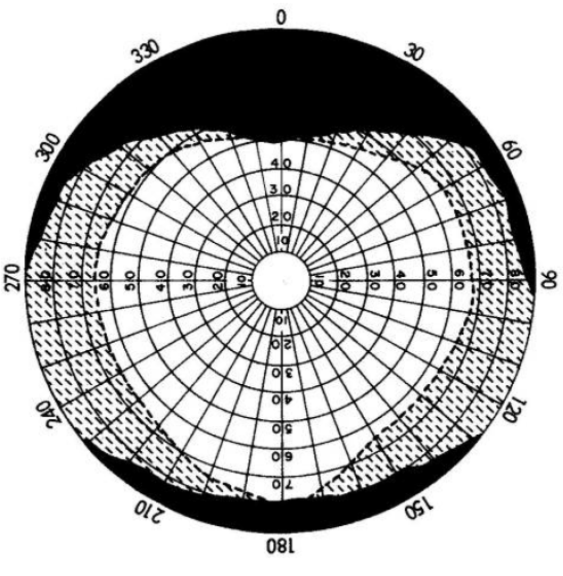


Figure 2.44: Human eye's field of view. Source: Parker and West 1973

An **assumption** of a similar material reflectance distribution within the field of view is applied. Enabling to estimate the illuminance uniformity without recalculating luminance values and their corresponding reflectance obtained from the hdr picture. Contrast is defined in many ways, but the most used one is the **luminance contrast** introduced by Weber. Another widely used rule of a thumb contrast ratio is an indicator of the overall contrast between the ambient luminance, wider field of view luminance and field of view luminance. Luminance **contrast ratio** of 10:3:1 roughly indicates an optimal contrast ratio and further examination is required to obtain a score. For performing a visual desk work, the field of view and wider field of view is important, while a human being is focusing on a task it is **ignoring** most of visual stimuli except **excessive glare** from outside the wider field of view.

$$k = \frac{I - I_b}{I_b} \tag{2.8}$$

I_b luminance of the wider field of view
I luminance of the field of view

The above mentioned fraction is also called as the **Weber fraction**, it is commonly used and suitable for cases where the average luminance is equal to background or wider field of view luminance. It provides a **simple local** evaluation providing a value on how the light is distributed and if the contrast is within the ranges for **human visual comfort**.

Score	Contrast ratio
A	0.65 - 0.70
B	0.65 - 0.35
C	0.35 - 0.19
D	0.19 - 0.10
E	-

Table 2.13: Higher contrast

Score	Contrast ratio
A	0.65 - 0.70
B	0.70 - 0.79
C	0.79 - 0.88
D	0.88 - 0.99
E	-

Table 2.14: Lower Contrast

The thresholds of a noticeable difference, in contrast, are divided into 2 categories. Firstly the dynamic (higher contrast) ratio (from 0.7 down to 0.1) which indicates dynamic task environment and provides enough contrast to distinguish objects and produce visual task without causing excessive eye strain. Secondly, the lower contrast means evenly distributed luminance between the field of view and wider field of view creating a working environment duller, leading to performance decrease and if a difficult visual task is conducted, eye strain appears sooner.

Basics of glare evaluation software

HDR

The development of software used for evaluating **glare** originating from daylight use several techniques for glare detection which can be:

- threshold luminance value (fixed)
- luminance value x-times higher than average field of view luminance or entire picture
- the direction, solid angle and average luminance of glare sources
- indirect (background) illuminance level to compute glare index

These approaches were created from the existing glare analysis formulas: VCP and CGI. Most used software as Findglare, Evalglare, Per-pixel Lighting Data Analysis and include analysis based on indices such as DGI, UGR, VCP and CGI with all their **limitations** mentioned above. Radiance and Evalglare are used via DOS Windows and are difficult to operate for a regular user. Therefore most computer-based daylight simulation software (Daysim, Diva, HDRscope, and Ecotect) utilized Evalglare codes.

To get as close to human vision perception the **High Dynamic Range** (HDR) images taken through a fish-eye lens are chosen. For the calculation process, a code in Matlab was developed.

HDR photos and Matlab glare evaluation basics

Conventional digital images are low dynamic range photographs(LDR), however, HDR images store a large range of luminance information.

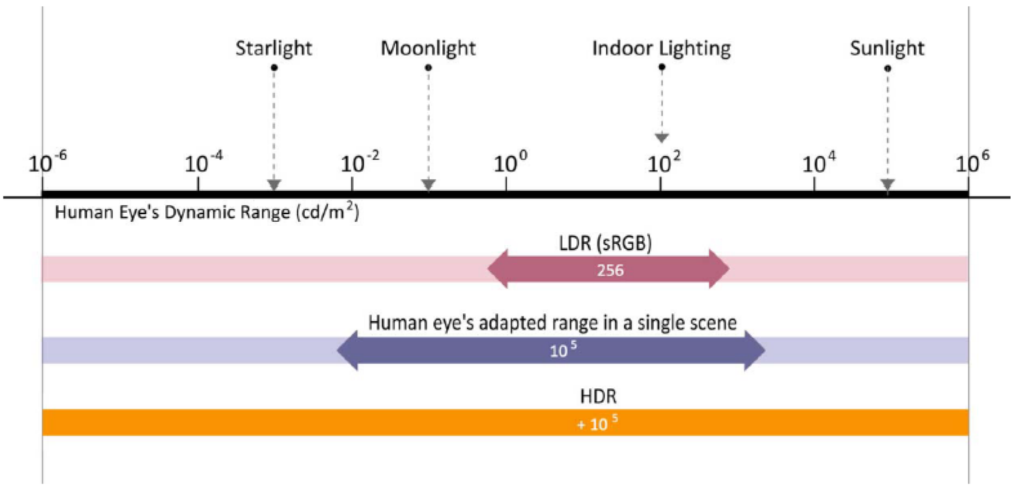


Figure 2.45: Luminance ranges. Source: Suk and Schiler 2013

To create an HDR image there are two ways: using ray tracing and radiosity in a 3D graphic-aided computer or captured from real scenes through photography. According to (Jakubiec and Reinhart 2011) conventional digital cameras are **inexpensive** to create HDR images. Limitation of a digital image sensor is the impossibility to capture a full dynamic range of a scene with a single exposure photo. **Multiple sequences** of a static scene can be taken with a different exposure value (shutter speed control) will properly expose some parts of the image while other parts will be under and overexposed. The idea behind combining the images is to find the relationship of the different pixel luminances and to determine the most accurate luminances.

Luminance mapping with a conventional digital photography is still not the most adequate measuring technology, but even the use of a traditional luminance meters is time consuming, prone to error and the measurements too coarse to determine light variation and distribution.

Summed up by Imanici in 2004: "There is a need for a tool that can capture the luminance values within a large field of view at high resolution, in a quick and inexpensive manner."

Figure 2.46: 16 exposures used for creating the Debevec and Malik HDR approach in 1997. Source: Debevec and Malik 1997

To create an HDR image from multiple LDR images 2.46 a specific software or a package needs to be used. The **limitation** of this approach is that the camera has to stay at the exact same place. HDR has a **great potential** in daylight and daylight glare analysis with an accurate luminance level readings compared to earlier luminance mapping tools.

The need for multiple LDR exposures to create a single HDR image comes to the camera response curve, showing the relationship between the incident light and pixel value of a camera. No camera has a linear response curve, however, it is possible to normalize each function with related exposure times to achieve a smooth and monotonic curve. Obtaining this function creates a valid HDR photo with a **full luminance range**. This approach was developed in 1997 by Debevec and Malik and since then implemented into every HDR software, the function is shown in figure 2.47.

$$L = 0.2126 \cdot R + 0.7152 \cdot G + 0.0722 \cdot B \tag{2.9}$$

L is luminance $[cd/m^2]$

After the creation of an HDR picture a luminance matrix is created, recalculating the value of red, green and blue channels to a single luminance value of each pixel by using the luminance equation 4.7. From there the values are a subject to mathematical treatment.

The thresholds used for glare evaluation

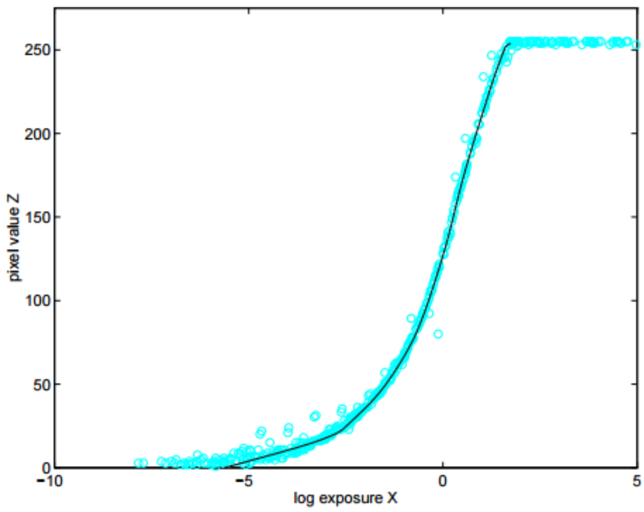


Figure 2.47: Camera response function: red, green and blue channels merged

A detailed experiment about HDR image analysis and human responses to glare was performed by Jae Yong Suk 2014. Questionnaires were compared to actual HDR glare measurements and summarized by the following results:

- 1. When a task is not performed, the
  - a. imperceptible glare luminance range at 2752 cd/m^2
  - b. perceptible glare luminance range is from 2752 cd/m^2 to 7000 cd/m^2
  - c. disturbing glare luminance range is from 7000 cd/m^2 to 12522 cd/m^2
  - d. intolerable glare luminance range extends beyond 12522 cd/m^2
- 2. When a computer-based typing task is performed, the
  - a. imperceptible glare luminance range at 1920 cd/m^2
  - b. perceptible glare luminance range from 1920 cd/m^2 to 5014 cd/m^2
  - c. disturbing glare range from 5014 cd/m^2 to 11718 cd/m^2
- 3. When a paper-based focused writing task is performed, the
  - a. imperceptible glare luminance range at 1696 cd/m^2
  - b. perceptible glare luminance range from 1696 cd/m^2 to 5263 cd/m^2
  - c. disturbing/intolerable glare range beyond 5263 cd/m^2

Based on the **evaluated** thresholds any person performing a visual task has a lower tolerance to glare. The following steps were conducted to obtain the exact threshold values:

- Users marked on pictures where they perceive glare,
- Only these areas were evaluated to obtain the most relevant luminance values from HDR images.

From the **experiments** the visual task luminance range is significantly lower than no task thresholds. Considering the most tasks performed nowadays in offices and dwellings are computer (visual) based the 2. category from the result above was chosen for evaluation and scoring. Interesting is that direct sunlight illuminated onto white papers on a desk even with having relatively lower luminance levels is causing intolerable glare.

Score	Luminance threshold $[cd/m^2]$
A (Imperceptible)	0 - 1920
B (Perceptible)	1920 - 5014
C (Just acceptable)	5014 - 8366
D (Disturbing)	8366 - 11 718
E (Intolerable)	> 11 718

Table 2.15: Glare score

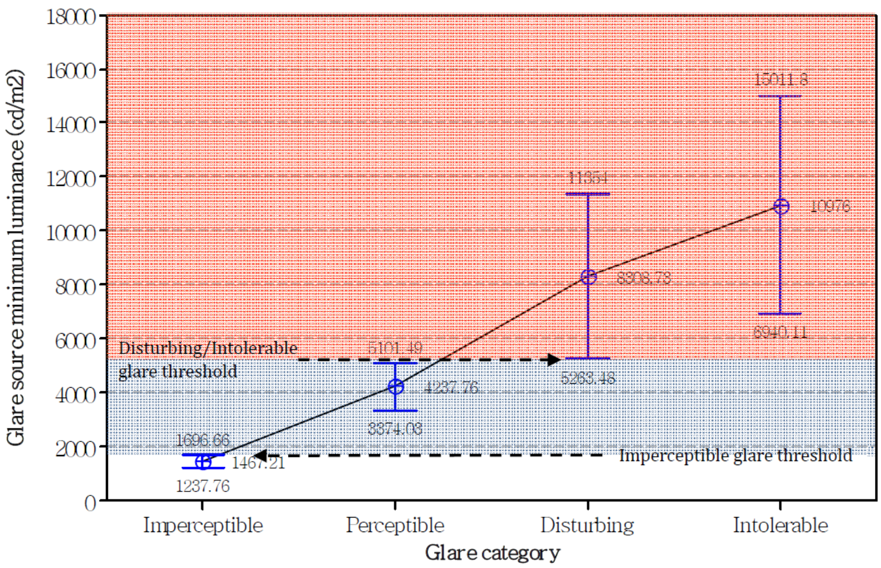


Figure 2.48: Observed glare thresholds

2.5 Relevant correlations

This section provides a summary of the literature review conducted by the authors. There is a number of significant research and papers on the IEQ, but it can sometimes be hard to reveal. Therefore, important references concerning investigated IEQ parameters were gathered in a tabular form, with the division to health/comfort/performance implications. Numbers represent specific sources where information on the topic can be found. Together with the table a list of references in provided.

Category	No.	Assessed Parameter	Health Impact	Productivity Impact	Comfort/Annoyance Impact
Indoor Air Quality	1.	**CO_2**	1i, 2i, 3i, 4i	2i, 5i, 6i	2i, 5i, 7i, 8i
	2.	**CO**	1i, 9i, 10i, 11i	11i	11i
	3.	**Ozone**	1i, 12i, 13i, 14i, 15i	16i, 17i, 18i	14i, 16i
	4.	**VOC's**	1i, 9i, 12i, 19i		
	5.	**Particles**	9i, 19i, 20i, 21i, 22i	16i, 23i	
	6.	**NO_2**	1i, 12i, 22i, 24i		
	7.	**Radon**	1i, 9i, 25i, 26i		
Thermal	8.	**Temperature**	1t, 2t, 3t, 4t, 5t	6t, 7t, 8t, 9t , 10t	11t, 12t
	9.	**Relative Humidity**	13t		13t
Visual	10.	**Illuminance**	4v, 5v, 6v	1v, 2v, 3v	2v, 8v, 14v
	11.	**Luminance uniformity**		7v, 8v, 9v,	8v, 9v
	12.	**Glare**		10v, 11v, 12v, 13v, 14v	9v, 10v, 14v
Acoustics	13.	**Background Noise ($L_{eq,A}$)**	1a, 2a, 3a, 4a, 5a	6a	7a, 8a, 9a, 10a
	14.	**Reverberation Time**		11a	12a
	15.	**Speech Transmission Index**		13a	13a, 14a

Figure 2.49: Table with investigated IEQ parameters and references related to their health/comfort/performance implications.

In order to introduce a degree of scientific research for each parameter, colors were introduced in the table. Each comfort category has its' own representative color. Blocks marked with the same color as its' category means that the correlation in question is well-established. If the block is gray, then there is some research on the topic but the correlation is unsure and requires more data. Empty blocks represent the correlations were research was not found by the authors or was regarded as not reliable.

The purpose behind the creation of such summarizing table was to link directly these research that is considered the most relevant and to present it in a structured way. What is more, this table contains references found and evaluated by a small group of people. What would be beneficial for further usage of such 'literature summary' is feedback and input of other people working in the field of IEQ. If the table would be improved in the future, it could be a place for researchers, designers, academics, and students to look for specific information regarding IEQ parameters and this way shortening the time required for individual research.

List of references:

IAQ:

[1i] - *Sittig's Handbook of Toxic and Hazardous Chemicals and Carcinogens, 6th Edition*
[2i] - "Human responses to carbon dioxide, a follow-up study at recommended exposure limits in non-industrial environments."
[3i] - "Indoor air quality and personal factors related to the sick building syndrome."
[4i] - "Monitoring Indoor Air Quality for Enhanced Occupational Health."
[5i] - *rehva 06: Indoor climate and productivity in offices*
[6i] - "Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration."
[7i] - "Sensory pollution sources in buildings."
[8i] - "Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance."
[9i] - "Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project)."
[10i] - *Carbon Monoxide and Human Lethality: Fire and Non-Fire Studies*
[11i] - "Effects on health of prolonged exposure to low concentrations of carbon monoxide"
[12i] - *Air quality guidelines for Europe.*
[13i] - "Air Quality Guidelines - Second Edition"
[14i] - "Use of Ozone Generating Devices to Improve Indoor Air Quality"
[15i] - *Susceptibility to Inhaled Pollutants*
[16i] - "Valuing the Impacts of Air Quality on Productivity (Final report)"
[17i] - "Ambient Air Pollution and Human Performance: Contemporaneous and Acclimatization Effects of Ozone Exposure on Athletic Performance"
[18i] - "The Impact of Pollution on Worker Productivity"
[19i] - *Environmental Toxicants: Human Exposures and Their Health Effects*
[20i] - "The Air We Breathe: An international comparison of air quality statndards and guidelines"
[21i] - *Environmental Health*
[22i] - *Air quality in Europe — 2016 report*
[23i] - "Particulate Pollution and the Productivity of Pear Packers"
[24i] - "Air pollution and population health: a global challenge"
[25i] - *Who Handbook on Indoor Radon - A Public Health Perspective*
[26i] - "Radon Monitor"

Thermal:

[1t] - “Building and occupant energetics: a physiological hypothesis.”
[2t] - “Could increased time spent in a thermal comfort zone contribute to population increases in obesity?”
[3t] - “Historic variations in winter indoor domestic temperatures and potential implications for body weight gain.”
[4t] - “Human health and thermal comfort of office workers in Singapore.”
[5t] - “Indoor environmental comfort in Malaysian urban housing.”
[6t] - “Thermal comfort and productivity in offices under mandatory electricity savings after the Great East Japan earthquake.”
[7t] - “Indoor temperature, productivity and fatigue in office tasks.”
[8t] - “Influence of dynamic environment with different airflows on human performance.”
[9t] - “Influence on occupant responses of behavioral modification of clothing insulation in non-steady thermal environments.”
[10t] - “Influence of indoor air temperature variation on office work performance.”
[11t] - “A global database of thermal comfort field experiments.”
[12t] - “Calculation of thermal comfort: introduction of a basic comfort equation.”
[13t] - “Humidity and its Impact on Human Comfort and Wellbeing in Occupied Buildings.”

Visual:

[1v] - “Lighting, productivity and the work environment.”
[2v] - “Lighting, Productivity and Preferred Illuminances – Field Studies in the Industrial Environment.”
[3v] - “Luminous Environment and Productivity at Workplaces.”
[4v] - “Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor.”
[5v] - “A broad role for melanopsin in nonvisual photoreception.”
[6v] - *Non-visual Effects of Light on Human Circadian Physiology and Neurobehavioral Performance.*
[7v] - *Concepts in Architectural lighting.*
[8v] - “Evaluating Human Visual Preference and Performance in an Office Environment Using Luminance-Based Metrics.”
[9v] - “Towards an assessment method for visual comfort in daylit offices.”
[10v] - “Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras.”
[11v] - “Luminous Environment and Productivity at Workplaces.”
[12v] - “Lighting, productivity and the work environment.”
[13v] - “Towards a new daylight glare rating.”
[14v] - *Maximum Luminances and Luminance Ratios and Their Impact on Users’ Discomfort Glare Perception and Productivity.*

Acoustic:

[1a] - *Springer Handbook of Acoustics*, pages 1041-1043
[2a] - “Assessment of noise exposure and associated health risk in school environment”
[3a] - “Auditory and non-auditory effects of noise on health”
[4a] - *DS/ISO 1999:2014 - Acoustics – Estimation of noise-induced hearing loss*
[5a] - “Is Noise Always Bad? Exploring the Effects of Ambient Noise on Creative Cognition”
[6a] - “Noise effects on human performance: a meta-analytic synthesis.”

[7a] - *Springer Handbook of Acoustics*, pages 1043-1046
[8a] - “Low frequency noise and annoyance”
[9a] - “A Review of Published Research on Low Frequency Noise and its Effects”
[10a] - “The Effects of Noise from Building Mechanical Systems with Tonal Components on Human Performance and Perception”
[11a] - “Effects of reverberation time on the cognitive load in speech communication : Theoretical considerations”
[12a] - “Reverberation time in class rooms – Comparison of regulations and classification criteria in the Nordic countries”
[13a] - “A model predicting the effect of speech of varying intelligibility on work performance”
[14a] - “Use of the Speech Transmission Index for the assessment of sound annoyance in open-plan offices”

II

Manikin prototyping

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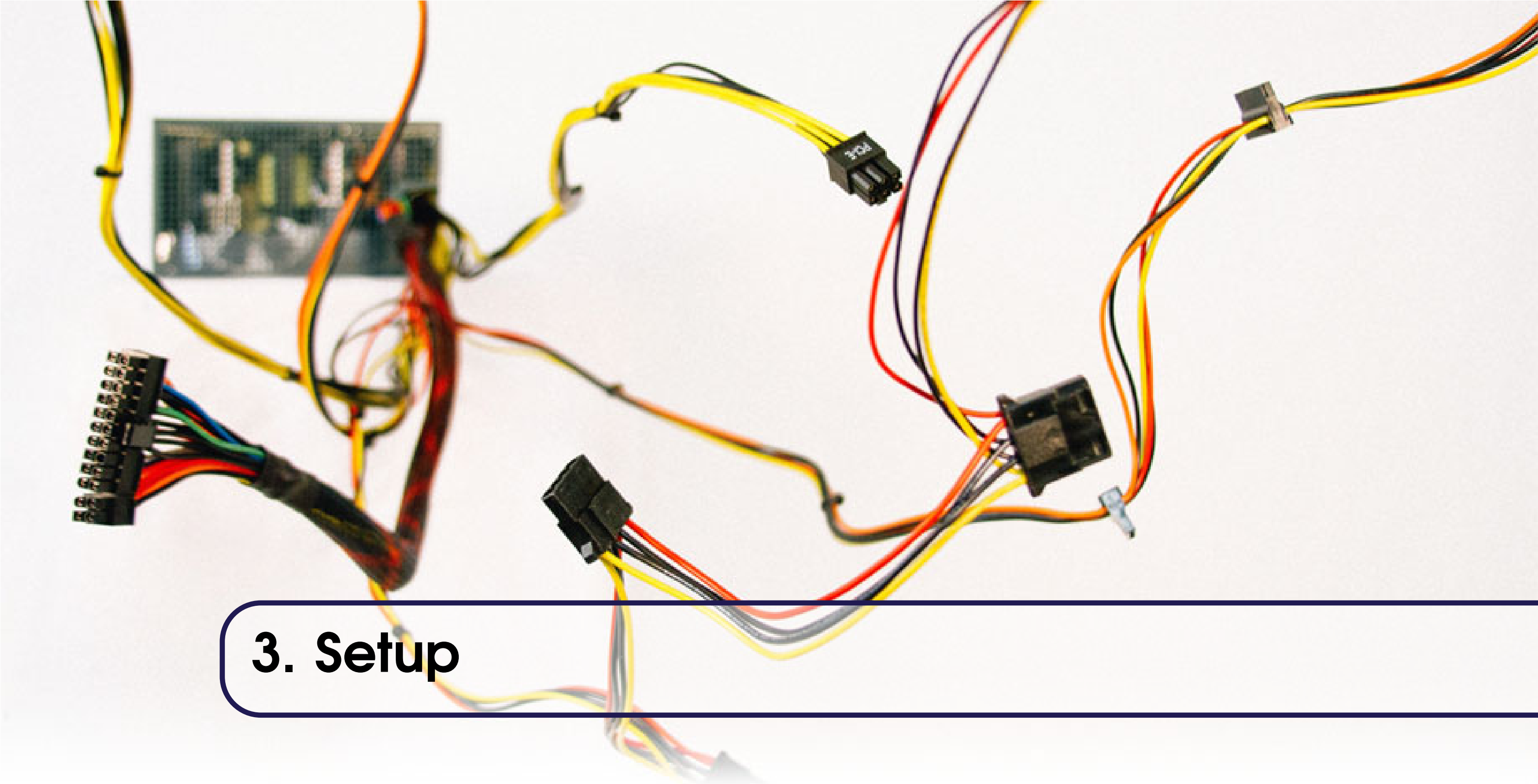


3. Setup

Concept

The idea behind this project was to develop cheap and robust measuring unit that will sense and assess most of the important IEQ parameters in a way occupants perceive the environment. It will address the need for 'unbiased' sensation of the indoor environment and provide an objective evaluation of examined space. Provided that Manikin will mimic human perception of the environment to the reasonable degree, it can substitute occupants for an unrestricted amount of time and withstand a wide range of test conditions ruling out the psychological factor from the evaluation. Another advantage of a Manikin utilized for IEQ assessment is the ability to detect small deficiencies of the environment that are usually overlooked by or unknown to the real occupants. Such undetected deficiencies may lead to discomfort or adverse health effects that were not previously linked with the adequate cause. For instance, occupants might not be aware that recurring headaches, fatigue or other symptoms are caused by the long-term exposure to harmful noise levels or by poor air quality at their workplace. However it is challenging to substitute human being with the measuring device, it is even more challenging to do it in a simple and inexpensive manner, utilizing widely accessible technology. Use of such inexpensive, newly developed electronics allows to compare its performance and accuracy to the scientific-precision equipment commonly used by professionals during commercial tests or post occupancy evaluations. Further advantages and shortcomings of adopted solutions are discussed in chapter 4 - Measuring Principle.

3.1 Sensing Unit

Term "sensing unit" is used to describe the following components combined together. It can be regarded as the Manikin:

- ’Body’ - human-alike dummy made of fiberglass that creates a framework for sensor distribution
- ’Senses’ - set of sensors grouped together under separate modules each imitating different human sense
- ’Brain’ - CPU and programmed architecture that receives, propagates and interprets information

Figure 3.1: Main areas of focus for indoor environmental quality assessment scheme

Communication between interconnected systems should be developed in order to assure their compatibility and efficient data flow. The following main parts of the architecture can be distinguished:

1. Sensors - basic setup unit that records a selected indoor environmental parameter
2. Central Processing Unit (CPU) - manages data acquisition and flow, sending sensor readings through built-in WiFi to the cloud server
3. Cloud Server - stores all sensor raw values organized within one database
4. Processing scripts - access database and performs operations on portion of data, assess the raw values and output the score
5. End user mobile application - provides user with the qualitative information about the examined space

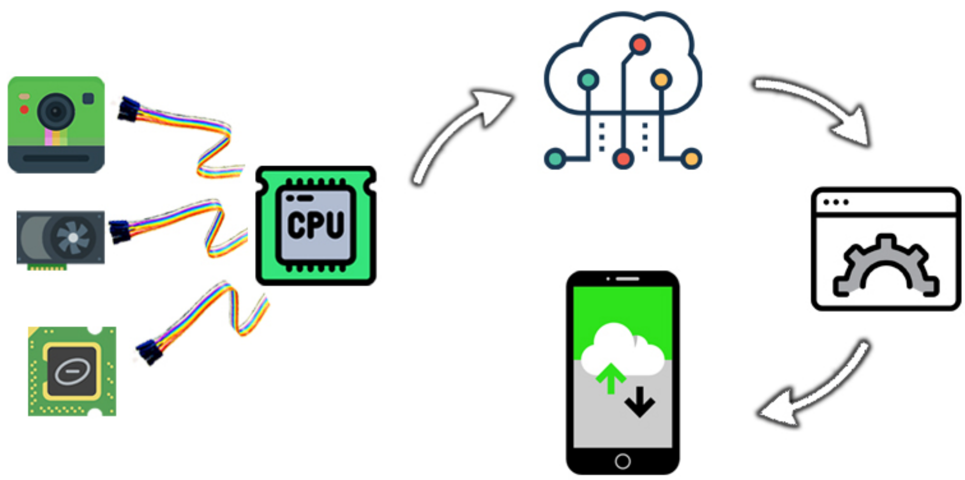


Figure 3.2: Data propagation from sensors up to end user display

As the entire architecture is a product of a collaboration between Indoor Environmental and Energy Engineering and Computer Science departments, only parts 1. and 4. are covered in this thesis, as the most relevant for the subject of studies. Section 5.1 describes in detail the developed assessment method that was implemented in the processing scripts.

3.2 Sensors

Term "sensor" is used to describe a Printed Circuit Board (PCB) together with all installed electric components such as transistors, resistors, capacitors, potentiometers etc. It is often referred to as a "breakout boards" that is ready for implementation under a number of open-hardware, programmable, microcontroller platforms such as Arduino, Intel Edison, Raspberry Pi or similar. More on that is provided in section 3.3.

Sensors are the basic components of the sensing unit. Their main task is to measure/quantify specific parameter of the examined space and pass that information further to the data logger avoiding any signal loss or distortion. Sensors that were used in this project generally consist of:

- transducer - main part that transforms one form of the energy into another, usually space's physical parameter of interest (i.e. CO_2, sound wave pressure etc.) into the voltage fluctuations
- printed circuit board (PCB) - electrical circuit that provides power supply for circuit components and allows communication between sensor and micro controller
- connection - usually pins/signal wires, number of which depends on the sensor interface protocol

Taking as an example Carbon Monoxide (CO) sensor, some of the basic features are introduced that one has to understand in order to use such equipment.

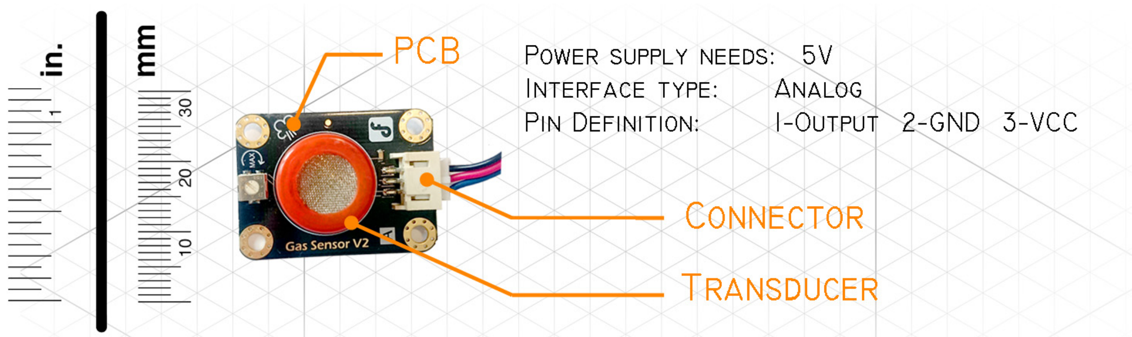


Figure 3.3: Example of the sensor used for measurements

In order to select sensors that are compatible with the specific platform, it has to support proper communication interface. The following introduction of various existing interface protocols is provided only as an introduction of a complex matter and not a thorough description of such. It is made from a perspective of practical application features, as it presents implications of using sensors with a certain interface. The reader might find it helpful to get familiar with some basic abbreviations/terms that are commonly used in the realm of computer science.

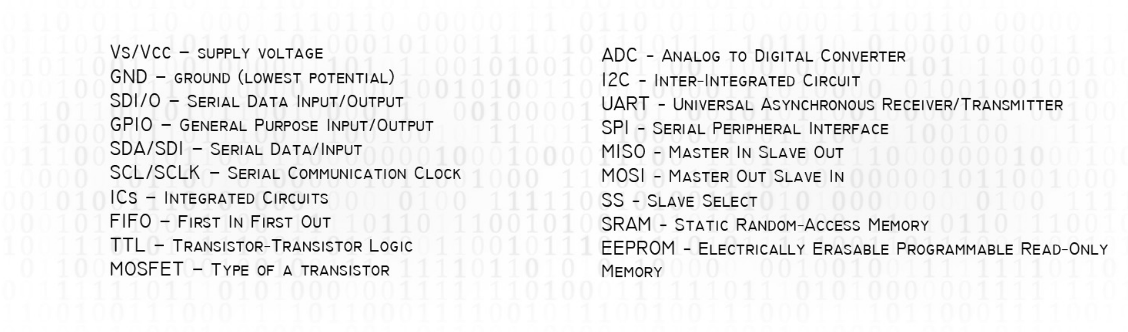


Figure 3.4: Basic terms that are used throughout the subject literature

The following interfaces were encountered during sensors/platforms selection in the process.

Analog interface

It is the most basic, though not simple, interface that translates the continuous real-time signal into its digital representation. This process takes place thanks to the built-in Analog to Digital Converter (ADC) and is known as quantization.

Analog devices are usually much more susceptible to noise - undesired variations in voltage. Even small changes in the voltage level of an analog signal may produce significant errors when being processed. Assuming the noise problem is minimized in the system there are plenty of different factors that have an impact on signal logging accuracy. How precisely real-time signal will be represented depends on the platform ADC clock speed and bit resolution, in other words, how much information of an original signal and how fast can be obtained. It is important especially for continuous audio or video recordings as a huge amount of data is needed in order to reconstitute the original signal. Fast data acquisition, storage, and streaming is a complex task and could be especially challenging for inexperienced users working with open-hardware platforms. Data size issue of raw audio/video files is often resolved with different compression techniques, nevertheless covering all the data acquisition nuances is out of the scope of this thesis. More practical insight of how specific problems encountered during this project was resolved can be found in section 4.3 that refers to the audio data acquisition.

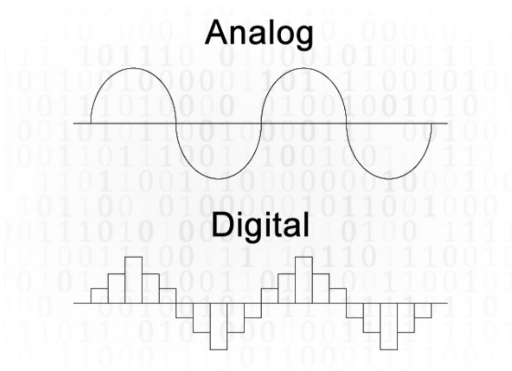


Figure 3.5: Real-time analog signal and its digital representation

Digital Interfaces Digital interfaces main purpose is to make it easier for a developer to add more devices into the project to increase its capabilities and complexity. The following interfaces are most commonly encountered:

- UART
- SPI
- I^2C

Among all differences that discriminate one interface from the other, possibly the most practical, is the number of wires required to allow communication between CPU and sensors. Although UART requires only 2 wires for receiving and transmitting the signal, the data is transferred without support from an external clock signal. Because of that more effort is necessary to appropriately acquire data through such interface. The trade-off between ease of data transfer and number of required wires is introduced with the SPI or I^2C protocols. The following figures 3.7 and 3.6 present the difference between architectures built using these two interfaces.

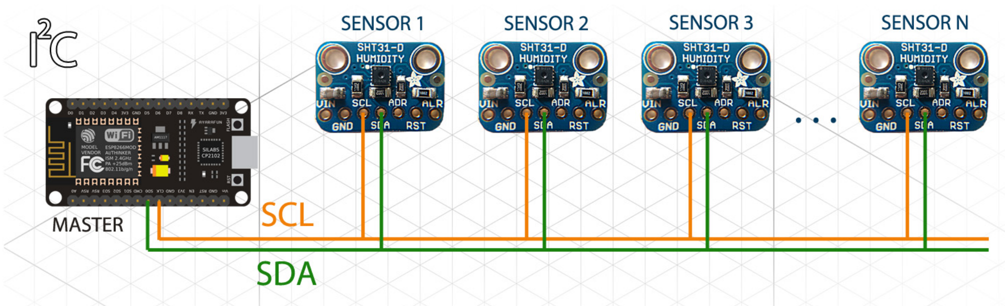


Figure 3.6: Architecture based on Inter-Integrated Circuit interface

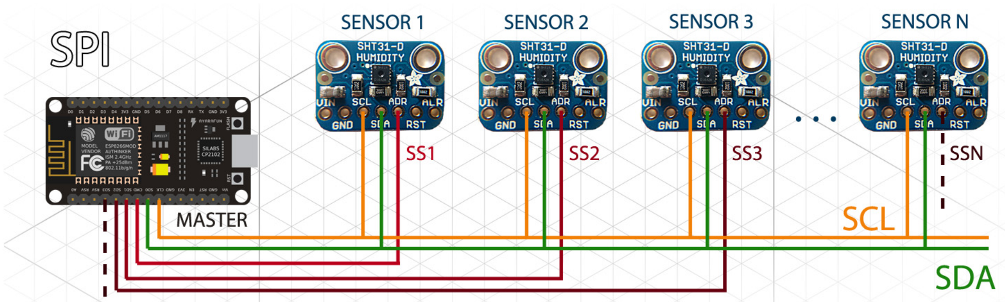


Figure 3.7: Architecture based on Serial Peripheral interface

Most of the analog sensors utilize older transducers and are, in general, harder to implement than digital ones. There is also a limited number of pins, depending on the platform, that allows analog sensor reading. More to that, more care should be taken to stabilize voltage and eliminate all possible sources of noise - voltage fluctuations. Therefore, with further development of embedded devices technology, it is expected that the market will be taken over by the digital microelectronics and it will become more accessible to the layman user. Although software implementation skills for a regular person might be still a limiting factor, this field also heads towards straightforward graphical environments. There are also more and more open hardware solutions that become user-friendly, opening access to the embedded electronics world to the wider public.

The complete sensor list that this project aimed to implement can be found in the Appendix, together with their short specifications.

3.3 Central Processing Unit

As it was already mentioned, various platforms can be utilized as the CPU for such projects. These platforms allow implementation of various sensors, breakout boards and low-power (5V or 3,3V) electronic devices depending on the project purposes. They can work as a data logger, microcontroller, portable computer or anything else that one can imagine and is capable of programming. It is very important to pick an appropriate platform for specific project application as it may bring more possibilities or severely limit them. The summary presented below is made based on the subjective experiences from the current project and can be used as a thumb rule for platform selection:

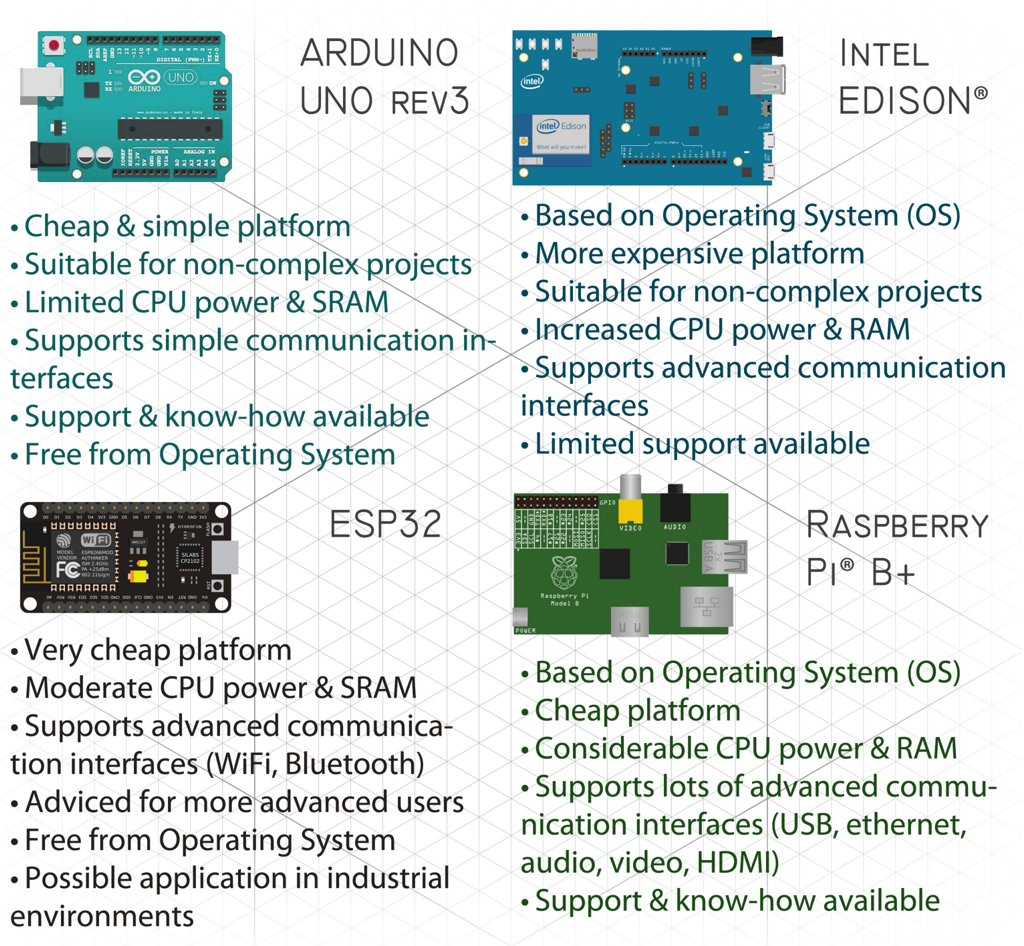


Figure 3.8: Summary of the most popular microprocessor based platforms

As this brief summary may be used for rough comparison of the main platform features, each has its own advantages and disadvantages that have to be considered individually. For instance, for some purposes having an operating system to communicate with the platform may be a benefit, as it serves to ease the platform access for the user, when for other it might be a drawback. Especially when dealing with an analog signal that has to be sampled with considerable frequency (i.e. audio sampling with the frequency of 44 100 Hz).

It is not a trivial task to select the suitable platform for such variety of monitored parameters as in the scope of this project. Not only it has to support certain interfaces, but also proper power supply, reading frequency, sufficient storage capabilities and the possibility of streaming the recorded data OUT of the system. The process of platform selection and all the factors that played a role in the final decision are described in the chapter 6.

3.4 Manikin

A lot of projects are dedicated to implementing the similar idea of IEQ assessment but in many different forms. Some projects turn towards a compact size IEQ assessing stations/boxes with which user can interact, indicating his satisfaction with the current conditions. Others are creating movable trolleys equipped with various full-size devices. However, in this project, human shape manikin was chosen as the setup framework.

It is worth mentioning why it is beneficial to use human shape manikin as a sensing unit shell. First and most obvious is a psychological factor. People seem to be less disturbed with a presence of a familiar looking device - the manikin, in contrast to the aforementioned measuring carts or standard measuring equipment that requires a lot of space. Secondly, manikin shape in some measure forces proper sensor distribution without bothering with precise dimensioning. It also leaves the door open to further expansion with new features such as advanced thermal module with constant skin temperature, human alike respiratory system, motion capabilities etc.

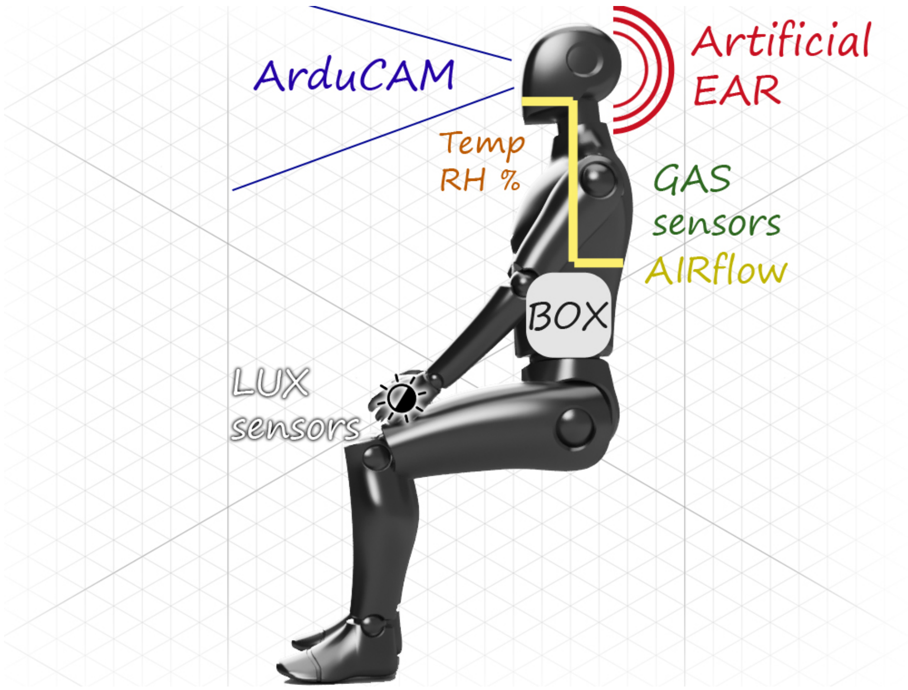
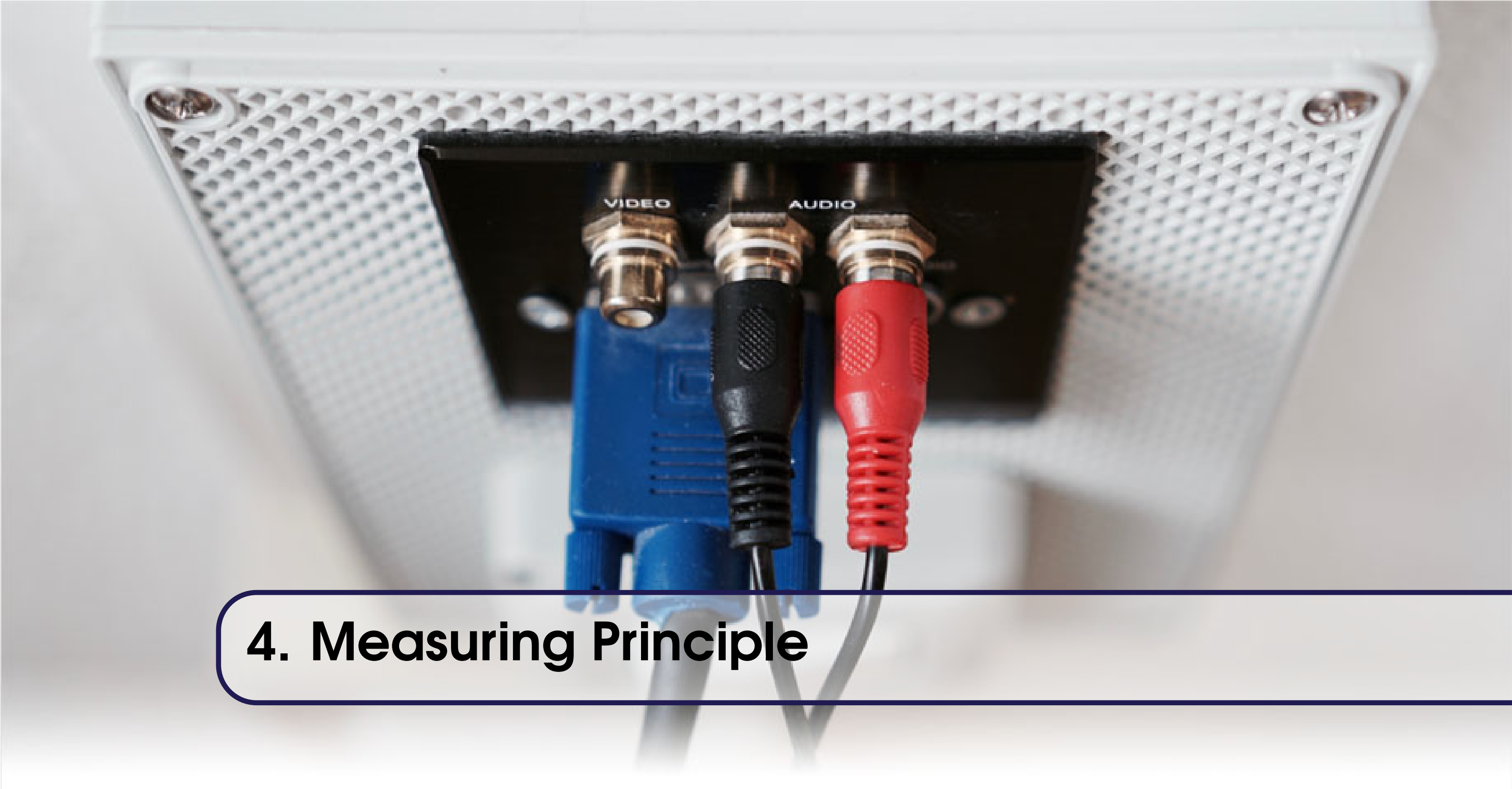


Figure 3.9: Initial concept of manikin features and sensors distribution throughout the manikin body

The main drawback of utilizing full-scale manikin is the amount of physical work required to plan, design and prepare all the necessary openings, supports, connections, and fittings, most of which has to be tailor-made to fit the irregular shapes. More description of the manikin prototyping and documentation of the process is provided in the chapter 6.



4. Measuring Principle

This chapter contains information about four measuring modules designed for the prototype. Description of each module, includes equipment that builds it, the principle of operation, and idea for post-processing of obtained data. Limits established for the resulting indicators are also presented.

4.1 Thermal module

Thermal module is a part of the sensing unit that measures and evaluates parameters related to the thermal sensation of a person. Thermal comfort is analyzed based on four parameters: air temperature, mean radiant air temperature, relative humidity, and air velocity. Sensors used for this purpose are presented in figure 4.1.

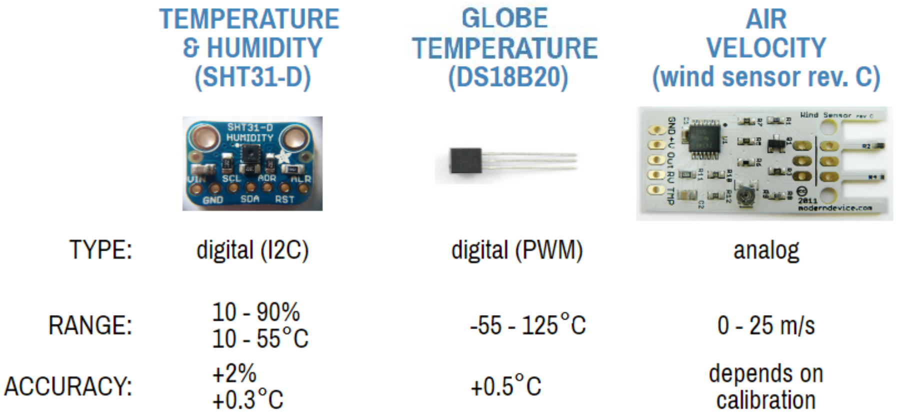


Figure 4.1: Specification of sensors for thermal comfort measurements.

4.1.1 Principle

Temperature & Humidity sensor is located in the manikin's airways (elastic tube) as it is presented in figure 4.2. This location is important so that the ambient temperature measurement is not affected by the sensors in the 'air box', which are heating up ('air box' sensors are described in section 4.2). What is more, this sensor requires constant air flow of 1 m/s on the sensing element, what is generated by the fan in the 'air box'. Accuracy given in figure 4.1 is an effect of factory calibration, and guaranteed in the range of air temperature from 10 to 55 °C. The selected sensor is also equipped with a compensation function pre-programmed into the breakout board. Thus, SHT31-D should be insensitive to voltage fluctuations. More on the sensor's operational method is written in section 4.2.

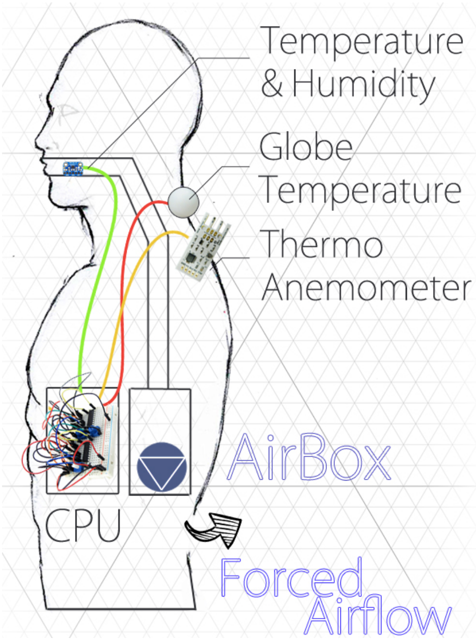
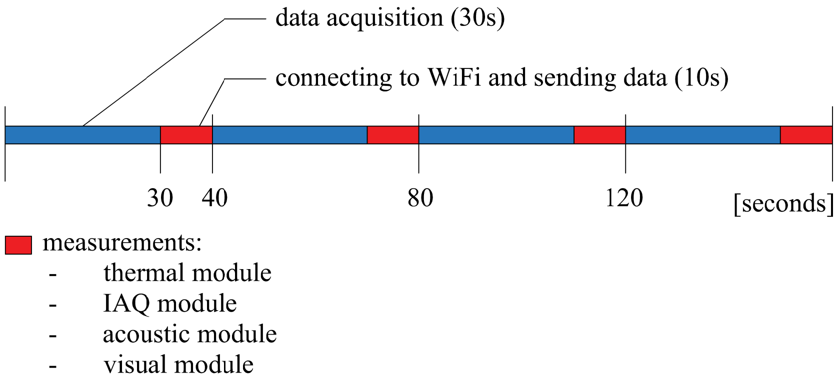


Figure 4.2: Schematic representation of the thermal module prototype.

The thermometer used for measuring globe temperature is placed on the manikin's shoulder, and it is covered with a gray globe with a diameter equal to 40 mm. This thermometer should detect temperature with a given accuracy in the range from -10 to 85 °C. The resolution of measurements can be adjusted (by changing the number of written bits). Depending on project requirements detectable temperature changes can be: 0.5, 0.25, 0.125, or 0.0625 °C.
Air velocity sensor uses hot wire method, which is based on measuring the heat loss of an electrically heated component to the ambient air. The resulting voltage is measured and compared to the reference value. Since the heat loss might occur due to other factors than airspeed, such as air temperature, the sensor is equipped also with a temperature sensor. The correction for air temperature is pre-programmed in the sensor. It is mounted on the manikin's neck, at the same height as the globe temperature sensor. This sensor has no stated accuracy of measurement and requires calibration in order to establish signal/air velocity correlation.

Ranges of measurement and accuracy discussed here are taken from the equipment data sheets. After performing tests they might be found vary from numbers shown in figure 4.1. More information regarding the sensors is provided in Appendix 8.4 and in documents provided as an attachment to this work ("Spec").



Measurement of all parameters is done in a specific order, which is presented in the figure above. Measurements related to thermal comfort start after the sound data acquisition. Sensors are activated and collect data in a measuring window equal to 30s. Samples gathered in one measuring window are averaged, and one value is generated from each sensor. These values are sent to the server through the WiFi connection established by the CPU. There they are processed into a final score. Details on electric circuit and time frame of single measurements and data sending can be found in *Improving Indoor Environments through Embedded Systems and Cloud-based Analysis*.

ASHRAE 55-2010: "Measurements shall be made in occupied zones at locations where the occupants are known to or are expected to spend their time."

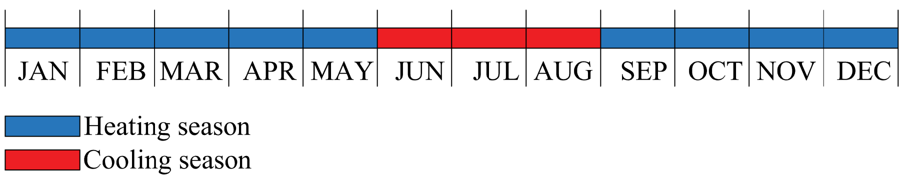
- *number of locations chosen for measurements should be a representative sample of the entire space,*
- *air temperature and velocity should be measured at heights:* 0.1, 0.6, *and* 1.1 m *for comfort evaluation of sedentary occupants,*
- *humidity can be measured at any level within the occupied zone,*
- *average airspeed requires gathering data for at least* 3 min.

Using manikin for measuring thermal comfort parameters will lead to a bit different temporal and spatial resolution than the one required by ASHRAE 55-2010. Measurements will be done in spots of interest, exact locations will be chosen by the users. However, in each space all most occupied locations should be evaluated, most occupied meaning: occupied for more than 1 h a day. Measurements have to be done at least for 3 days in a year: the coldest day, the hottest day, and a day during the transitional season.
Since thermal module developed for the first manikin prototype is the simplified one, it should be improved on. This version should be used only for a preliminary assessment. A number of nodes measuring air temperature and velocity should be increased to mimic the reaction of human body to thermal conditions accordingly (see examples of complex models in Fiala et al. (2012), S. Tanabe et al. (1994)).

4.1.2 Post-processing

The values obtained by the thermal module are processed by the script created primarily in MATLAB. This code utilizes the simple comfort model based on the $PMV - PPD$ calculation from ISO 7730. Inputs to the code contain measured data and the current date. The date is used to establish the season of the year, based on which specific criteria for evaluation are chosen. The equations used for calculations can be found in CEN (2005b) or in attached MATLAB code ("Thermal module"). Here only simplified relationships between calculated parameters are described.

(1) Determine the season from the date;



(2) Choose the clothing constants appropriate for the season;
Heating season: 1.0 clo
Cooling season: 0.5 clo

(3) Calculate draught rating (DR) - estimation of local discomfort due to high air velocity;

$$DR = f(T_a, v_a, T_u) \quad (4.1)$$

DR	- draught rating	[%]
T_a	- air temperature	[°C]
v_a	- air velocity	[m/s]
T_u	- turbulence intensity	[%]

(4) Calculate the mean radiant temperature;

$$M_{RT} = f(T_g, v_a, \varepsilon, D, T_a) \quad (4.2)$$

M_{RT}	- mean radiant temperature	[°C]
T_g	- globe temperature	[°C]
ε	- globe emissivity	
D	- globe diameter	[m]

(5) Determine the heat transfer coefficient by forced convection (H_{CF}) - depending on air velocity;

(6) Iteratively find surface temperature of clothing (T_{CL}) and heat transfer coefficient by natural convection (H_{CN}) - depending on temperature difference between air and surface of the clothing;

(7) Calculate heat loss components:

HL_1	- through skin	[W/m^2]
HL_2	- by sweating	[W/m^2]
$HL_{3,4}$	- through respiration (latent and dry)	[W/m^2]
HL_5	- by radiation	[W/m^2]
HL_6	- by convection	[W/m^2]

(8) Calculate PMV and PPD from thermal balance of the body;

$$T_S = f(M) \quad (4.3)$$

$$PMV = f(T_S, M, HL_{1-6}) \quad (4.4)$$

$$PPD = f(PMV) \quad (4.5)$$

T_S	- thermal sensation coefficient	[m^2/W]
PMV	- predicted mean vote	
PPD	- predicted percentage dissatisfied	
M	- metabolic rate	[W/m^2]
HL_{1-6}	- heat loss components	[W/m^2]

(9) Give a score for obtained results: $PMV - PPD$ and DR.

Parameter score	*PMV* limits	corresponding *PPD*	$T_a \leq 25\,^{\circ}\mathrm{C}$ *DR* limits	$T_a > 25\,^{\circ}\mathrm{C}$ *DR* limits
A	$\pm\,0.5$	$\leq 10\,\%$	$\leq 5\,\%$	$\leq 10\,\%$
B	$\pm\,1.0$	$\leq 22\,\%$	$\leq 10\,\%$	$\leq 20\,\%$
C	$\pm\,1.5$	$\leq 50\,\%$	$\leq 15\,\%$	$\leq 30\,\%$
D	$\pm\,2.0$	$\leq 75\,\%$	$\leq 20\,\%$	$\leq 40\,\%$
E	non-compliance with preceding thresholds			

4.1.3 Discussion

Thermal module introduced in this chapter is assessing comfort with the use of a *PMV* − *PPD* model and draught rating. This method, even though they are fairly simple computation-wise, give good predictions of thermal sensation perceived by humans (discussed broadly in section 2.1). The module requires expanding into a more complex module by increasing number of 'sensing' nodes. Existing thermal manikins could be used for inspiration in this matter (see also: Tamura (2006), Foda and Sirén (2012), Ružić and Bikić (2014)). Moreover, the globe used with the digital thermometer for globe temperature measurement should be changed for a bigger (15 cm) and preferably black one, with known emissivity coefficient.
MATLAB script that is used for evaluation includes some simplifications that could be improved on:

- The season could be substituted with wireless measurement of outdoor air temperature or obtaining the value for a given location from the closest weather station. Limits used by the script would be then better representing the actual occupant perception.
- Draught rating limits could be calculated based on measured air temperature or the apparent temperature (index quantifying the impact of air temperature and humidity on thermal sensation).
- Metabolic rate, as well as clothing insulation, could be treated as a user input. This way the prediction would be personalized and representing real preferences of occupants.

The equipment described in this chapter requires calibration and testing. After these procedures performance of the assessment, the script has to be validated. More detailed view on this in presented in part III.

4.2 IAQ module

IAQ module is responsible for measuring and assessing air quality in a given space. The score is given on a basis of parameters concentrations sensed in the air. The overall well-being of occupants is used for establishing limits for scoring, taking into account not only comfort but also potential negative effects of pollutants.

4.2.1 Principle

Sensors used for detecting air pollutants are presented in figure 4.3. More details on the used equipment can be found in Appendix B. Chosen equipment can be divided into 4 categories in relation to their method of operation. The majority of the sensors (CO, O_3, and VOC) are metal oxide sensors, CO_2 sensor is an infrared device, the sensor used for detection of PM is an optical one, and the element sensing relative humidity is polymer based. Used operation principles are described below in regards to the specific purpose of each sensor, and outline benefits of such choices and possible issues.

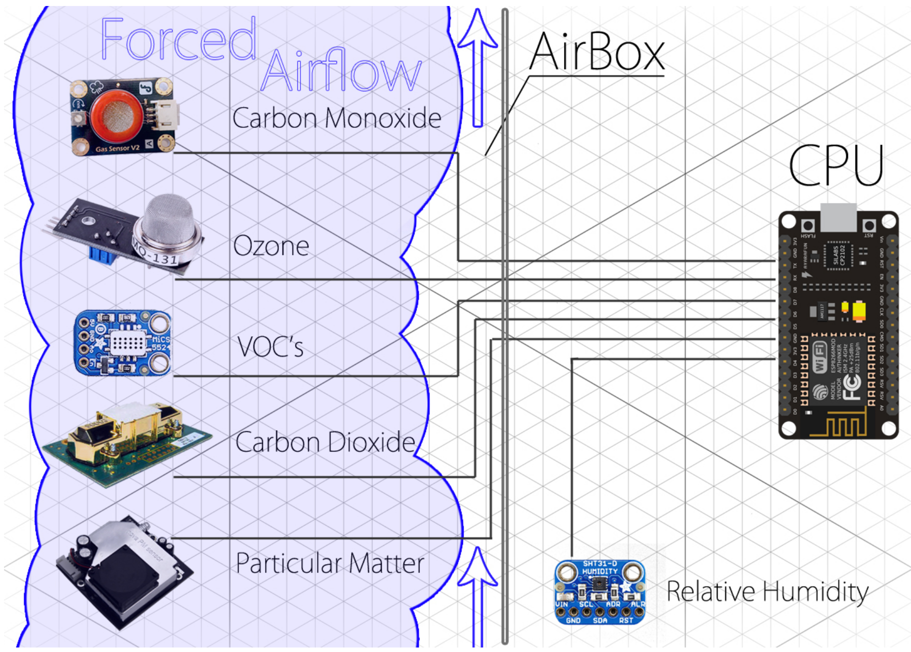
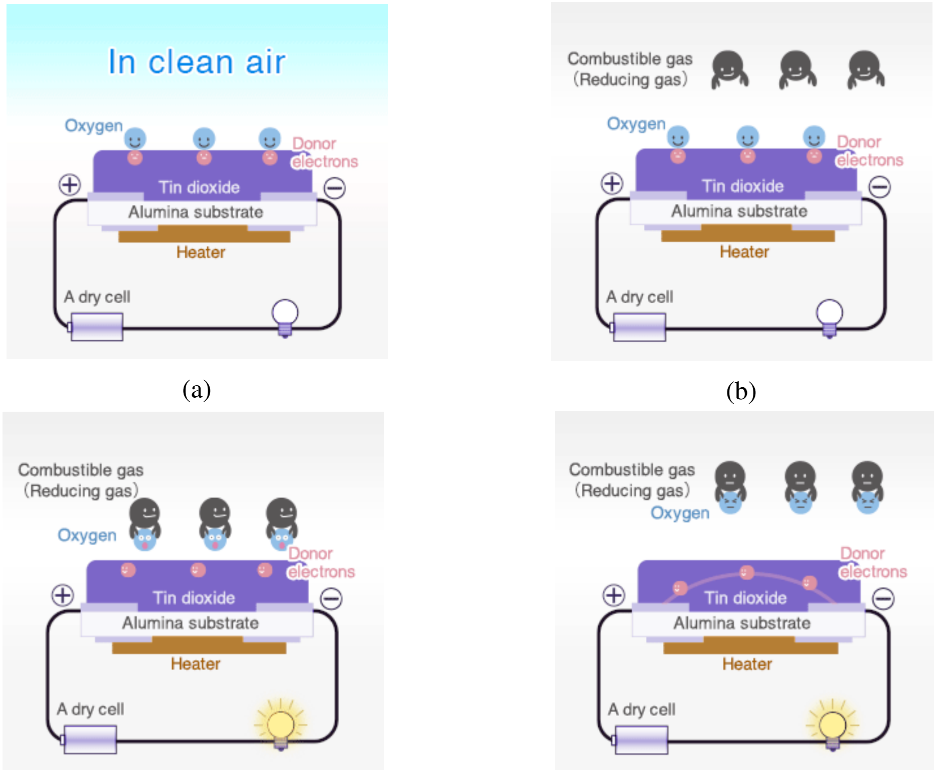


Figure 4.3: Schematic representation of IAQ module prototype.

Metal oxide semiconductor (MOS) sensors

MOS gas sensors are using electrical conductivity of their sensing layers to detect gases concentration. The sensing layer is made out of a metal oxide and it reacts when comes in contact with a so-called 'reducing gas', what changes its resistance. This process is well shown in figure 4.4. It can be seen in picture 4.4a that oxygen from the air is absorbed by the free electrons flowing through the sensing layer, and preventing further flow of current (increasing layer's resistance). When the reducing gas occurs in the air around the sensing layer (figure 4.4b), it reacts with the oxygen adsorbed by the sensor (figure 4.4c and 4.4d) and decreasing the resistance of the layer as a result. The higher the concentration of the reducing gas the more oxygen it will bound and the more current will flow through the sensing layer.
Depending on the material used for the sensing layer and gases that should be detected, the appropriate heating temperature is used for the sensor. In the case of older sensors typically a long preheating period is required in order to obtain accurate and stable readings (24-48 h). Newer elements, with very thin layers of metal oxides, can heat up to the required state in manner of few

seconds or minutes.



(a) (b) (c) (d)

Figure 4.4: Operation principle of MOS gas sensors (source: FIGARO Engineering Inc. (2017)).

MOS type sensors used for IAQ module are:

- **MQ-7:** Carbon monoxide sensor that works in a cycle that allows for taking measurements after each 2.5 min. Requires long preheating time before measurements. The element heats up to about 100 °C.
- **MQ-131:** Ozone sensor, that is highly sensitive to O_3 but it also reacts to NO_2 and chlorine. Therefore all three substances should be included for establishing limits for measurement assessment. Similarly to MQ-7, reaches stability after long preheating to 100 °C.
- **MiCS-5524:** here referred to as 'VOC sensor', is a probe sensitive to many substances, for example, VOC such as hydrocarbons, alcohols, terpenes, glycols, aldehydes, esters, and acids. It requires calibration with the use of desired gases and creating a function of their concentration and sensor's resistance. Accordingly, the limits for evaluation should be established.

Infrared gas sensors

Sensor used for CO_2 detection uses a non-dispersive infrared (NDIR) principle. This method can be understood based on particles found in the air and their characteristic absorption of light. Air is a mixture of different gas particles. Light has a complex character but it can be described as beans with different wavelengths, depending on the range of light in question (visible, infrared, ultraviolet, etc.). Light wavelength and its frequency are correlated as in equation 4.6. The speed of light is a known and constant value, what leaves each wavelength with just one frequency of oscillation.

$$\text{Wavelength} = \frac{\text{Speed of light}}{\text{Frequency}} \tag{4.6}$$

A number of different wavelengths (from infrared range) is used in infrared sensors. Light is absorbed by gas components, amounts absorbed by different particles is presented in figure 4.5. The transmittance value shown on the vertical axis represents the amount of light that passed through the gas sample, 0 % indicating that the gas absorbed entire beam of a certain frequency.
MH-Z14 contains two chambers with the same light sources. One of them is called the reference chamber filled with air with known CO_2 concentration. The second chamber is a measuring chamber, where the sample of air enters and the CO_2 concentration is detected. This sensor is equipped also with internal temperature sensor, what allows for temperature compensation of the results.

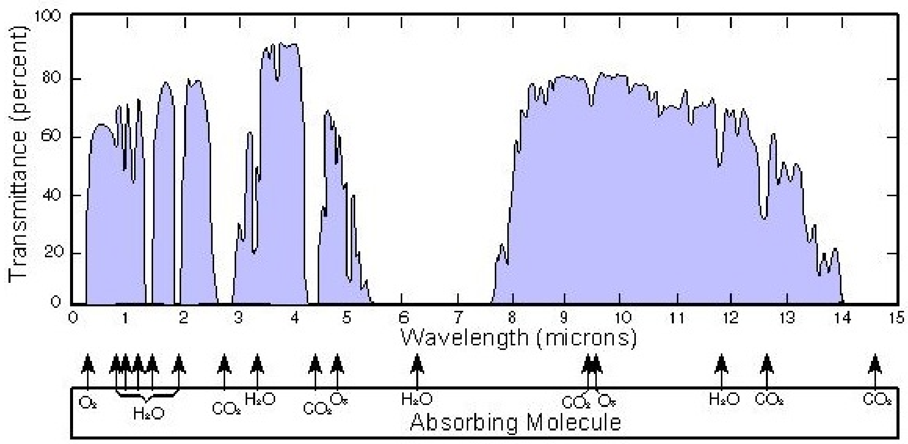


Figure 4.5: A diagram showing the wavelength at which different atmospheric gases absorb infrared radiation (source: Auble, D. and Meyers, T. (2017)).

Optical particle sensors (OPS)

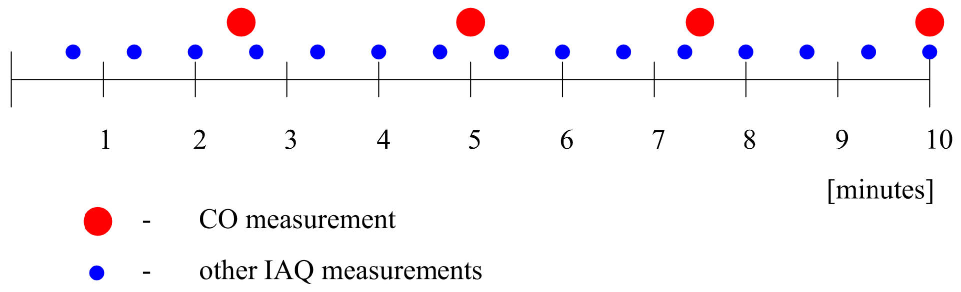
OPS are sensing units that utilize the fact that when a particle goes through a beam of light, some of it is being scattered. The number of particles is measured based on the number of pulses of scattered light sensed by a photodetector. Also, the intensity of scattered light is related to the size of the particle, allowing for gathering more information on particles found in a sampled gas.
SDS011 dust sensor is able to measure both number and size of the particles. The minimum particle diameter that can be detected is 0.3 μm. It is pre-calibrated to output two values of PM concentration, one for $PM_{2,5}$ and one for PM_{10} what was desired for this project.

Polymer humidity sensors

Relative humidity is measured by the same sensor as the air temperature (mentioned in section 4.1). It is located in the tube connecting manikin's mouth with the 'air box'. The air box is placed inside the manikin's body and contains all other sensors showed in the scheme. Air flow through the tube and box is generated by the fan connected to the box. More details on 'air box' and its operation are provided in chapter 6.
The element that is responsible for sensing RH is based on a varying capacitance of the polymeric layer. Humidity sensor used in SHT31-D has a layer of polymer located in between two electrodes. The polymer is a dielectric material, what means that it conducts the current very poorly. They have no free electrons that may drift through the material, so in presence of electric field, they get

polarized. In absence of water vapor, the capacitance of the polymer is the lowest, the higher the amount of water vapor in the air the higher gets the capacitance.

Technical parameters of before-mentioned sensors are gathered in Appendix 8.4. Accuracies presented there are only preliminary values, stated by the manufacturers. All sensors require proper testing and calibration in order to establish realistic ranges and accuracies. Requirements for preheating time have to be met while programming and implementing the sensors into the IAQ module. Details on this process can be found in Computer Science student group: sw805e17 (2017) and chapter 6 of this report.
Measurements are supposed to be taken inside the 'measuring windows' introduced before. First measuring window starts just after the initialization of IEQ assessment system and lasts for around 30 s. Time step between proceeding measuring windows is exactly 10 s. Considering the operation of the sensors, all of them except for MQ-7 (measuring CO) are capable to fit into this time frame. CO sensor gives new measurement after 2.5 min, what is a significant delay to other sensors. Exact moments of measurements ready for sending by IAQ module can be depicted in such way:



As it can be seen, in a period of 10 min, CO sensor measures 4 times, while other sensors are resulting in 15 data points. The reading of the sensors have to be adjusted while programming data acquisition in order to avoid mistakes connected to the lack of synchronization. The empty spaces in CO sensor output have to be filled with numeric data due to server configuration. The most obvious way to deal with this issue is to use previously measured value until the new measurement is done. However, this also requires to use the shift in time between the sensors, since the distance between the measuring windows and a new measurement done by CO sensor is changing.

4.2.2 Post-processing

Measured values of concentration are processed by a MATLAB script ("IAQ module"). The code uses the limits established for the sensed parameters and assigns a score to each of them. Measurements are also stored and scanned to check whether concentrations are stable, increasing or decreasing, and send proper information to the user if needed.
The average values of concentrations are also evaluated after specific time intervals (for example for CO it is 15 min, 30 min, and 1 h). This check allows detecting exact times when the concentrations are elevated and for how long they remain high. This function is implemented to allow communication of the IEQ assessment system with the occupants in the room. If any unwanted or dangerous concentrations are sensed the message would be given to a user, containing possible actions he/she can carry to improve air quality.

Parameter score	CO_2 [ppm]	CO [ppm]	O_3 [ppb]	VOC [ppb]	$PM_{2,5}$ [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	RH [%]
A	≤ 800	≤ 3	≤ 30	≤ 3	≤ 18	≤ 60	45-55
B	≤ 1000	≤ 7	≤ 60	≤ 10	≤ 36	≤ 120	40-60
C	≤ 1200	≤ 11	≤ 90	≤ 17	≤ 54	≤ 180	35-65
D	≤ 1400	≤ 15	≤ 120	≤ 24	≤ 70	≤ 240	30-70
E	non-compliance with preceding thresholds						

4.2.3 Discussion

IAQ module described in this section is supposed to measure and assess a number of parameters. Depending on calibration and tests of the sensors the final number will be established. The majority of the most influential factors are measured by sensors implemented into the module. If the assembling and programming of measuring procedure will be accomplished the module should run as a complex air quality monitor.

In order to make the assessment even more thorough, more sensors could be implemented (for example NO_2, SO_2, specific VOC). The script used for evaluation could be easily expanded with new parameters.

Some of the correlations between parameters of interest and comfort/health/performance impacts are not well established at the time. Whenever new evidence is provided by the researchers, the limits and functions should be adjusted to reflect the newly found relationships.

Scripts could be also improved by using a kind of 'history' of measurements in order to establish patterns for specific concentrations. This way predictions could be made about the state of IAQ and actions could be required ahead of time.

4.3 Acoustic module

The acoustic module is responsible for sound data acquisition and processing. It consists of several parts which mutual communication and compatibility have to be secured in order to provide proper working conditions. Each part is assigned to a different task which prepares input signal to the digital processing. The sound module is the only one involving the use of professional, expensive equipment. However, there is a possibility of simplifying measuring procedure and rely on cheaper and less complex electronics.

4.3.1 Measuring principle

Figure 4.6 shows the entire acoustic module setup (up to the CPU unit) and data flow between interconnected parts is described further on.

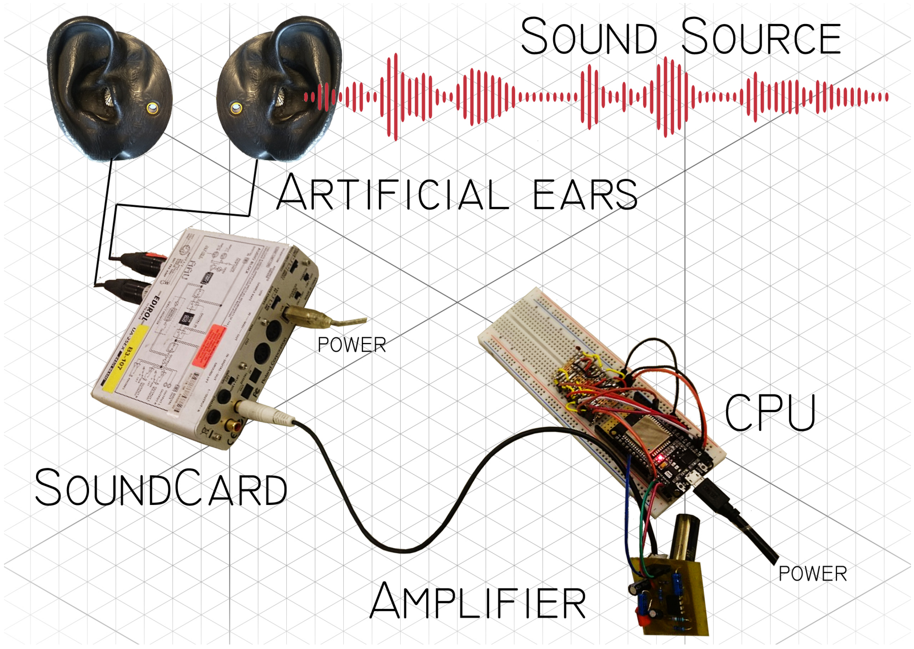


Figure 4.6: Scheme representing acoustic module setup

The sound is recorded continuously for the period of 30 s, then the recording is streamed to the server, through the built-in WiFi module, where post-processing takes place. Another sample is being recorded after 10 s, so all the other sensors could be read and stream data without interference with sound measurement. Break between the recordings is necessary in the current setup in order to avoid CPU's internal voltage fluctuations that introduce substantial noise to the recording. Therefore full measurement of duration for instance 8 h, could be break down into 30 s samples with 10 s breaks in between (see fig. 4.7). It gives rather representative data set for entire measurement period to be considered as a continuous monitoring.

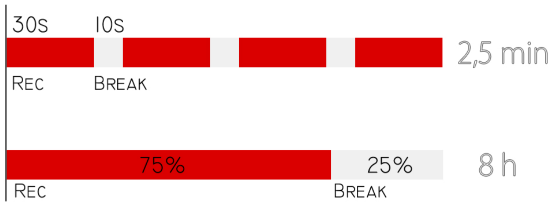


Figure 4.7: Duration of actual sound recording in measurement time span.

Acoustic setup consists of the **microphones**, placed inside of the **artificial ears** which are mounted on the **manikin's head**. External **soundcard** (EDIROL) that provides phantom power supply of 48 V to the microphones, and merges two signals into MONO.

Although such STEREO-MONO conversion does not allow full binaural measurement and extraction of more complex information (i.e. sound directivity etc.), it allows a single 'sound level index' to be calculated based on the output signal. Such solution was a result of the hardware and software issues that emerged during the prototyping process. In reality, interpretation of the electric signals that comes out from each of human ears is done inside the brain and is a far more advanced process.

How the signals are summed together can be found in the sound card manual (see: Appendix). Later, the signal from soundcard is amplified, with a custom-made PCB amplifier, and logged by the central processing unit with a frequency of 44 100 Hz. Such a high sampling rate, taking measurement 44100 times per second, or (in the time domain) every 22.67 μs requires fast enough logging unit with equally fast internal memory to succeed. Because of the human hearing frequency spectrum of 20 Hz-20 000 Hz, at least doubled sampling frequency and a low-pass filter are required to avoid signal distortion or aliasing (see: *Nyquist-Shannon Sampling Theorem*). After passing the CPU's ADC (Analog to Digital Converter), data is transferred in digital form, and stored as a 30 s chunk of raw data in internal memory of the central unit. Then, it is being sent and stored in a cloud server database. Finally, each recording is being post-processed with a Matlab-based script and is given a score according to the adopted scoring method. More about the scoring system can be found in chapter 5 - where adopted Scoring System is described.

4.3.2 Setup components

Microphones

Microphones are the essential component of the acoustic module. They are responsible for transforming a pressure change, induced by a sound wave, to the electric signal that can be picked up and later analyzed. There are a lot of parameters that had to be taken into account while picking appropriate microphone for the project purpose, among which the most important seemed to be:

- Analog vs Digital - this is the very first choice that defines the 'realm' in which microphone operates
- Frequency range [Hz] - in which microphone has a 'flat' response (see figure 4.8)
- Dynamic range [dB(SPL)] - defined by the minimum and maximum sound pressure level that microphone can support
- Sensitivity [mv/Pa]- defined by the microphone voltage response to the 1 kHz sound wave of 94 dB(SPL)

It is often desired to use microphones which provide flat frequency response in the broad frequency spectrum to increase measurement accuracy. It is advised to repeat calibration periodically as microphone's sensitivity decreases with time. Figure 4.8 shows the selected microphone freq. response declared by the manufacturer for the pressure field.

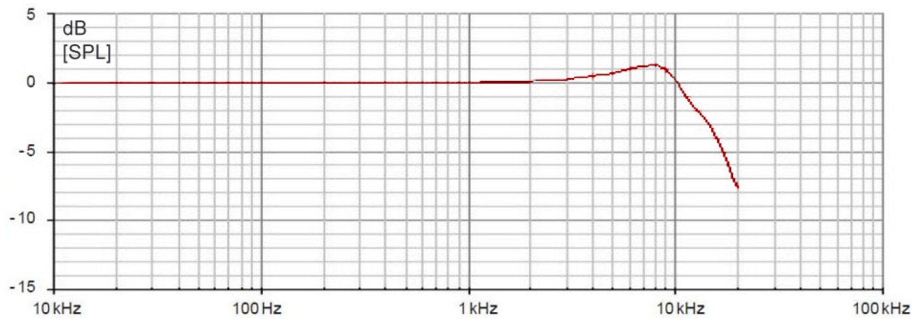


Figure 4.8: G.R.A.S. 40 AD1/2" microphone typical frequency response

However, one has to be aware that microphones have specified frequency response only in the sound fields in which they are calibrated to operate. Figure 4.9 show how frequency response may differ depending on the acoustic field in which microphone operates. Therefore, inappropriately chosen microphone - sound field relation will result in a considerable discrepancy of sound level readings from desired. Sound direction often plays a role unless the microphone is omnidirectional - indifferent to the sound wave incidence angle.

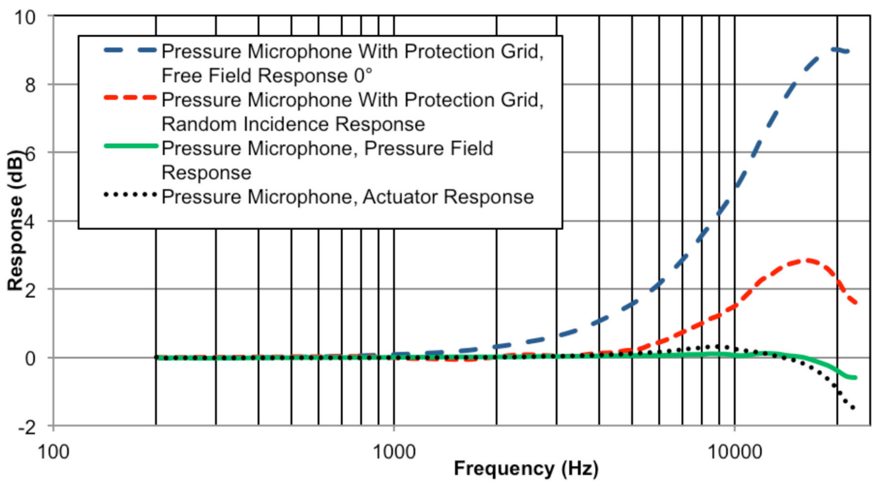


Figure 4.9: Microphone frequency response in relation to the sound field (source: "Acoustic Methods Of Microphone Calibration")

Dynamic range tells how wide is the sound level range in which microphone can operate stably. Usually, it depends on the microphone physical components used in its production. Nonetheless, most of the currently manufactured microphones have the suitable dynamic range for the purposes of measuring sound level. Microphone sensitivity is a more complicated parameter that deserves more attention. It defines how low level or distant sounds will be picked up by the microphone. Before deciding on microphone sensitivity one should consider the environment in which it will operate. However, a good trade-off can be achieved with moderate sensitivity microphone and appropriate amplifier setting in the acoustic setup. More information about microphone main characteristics can be found in Lewis (2011).

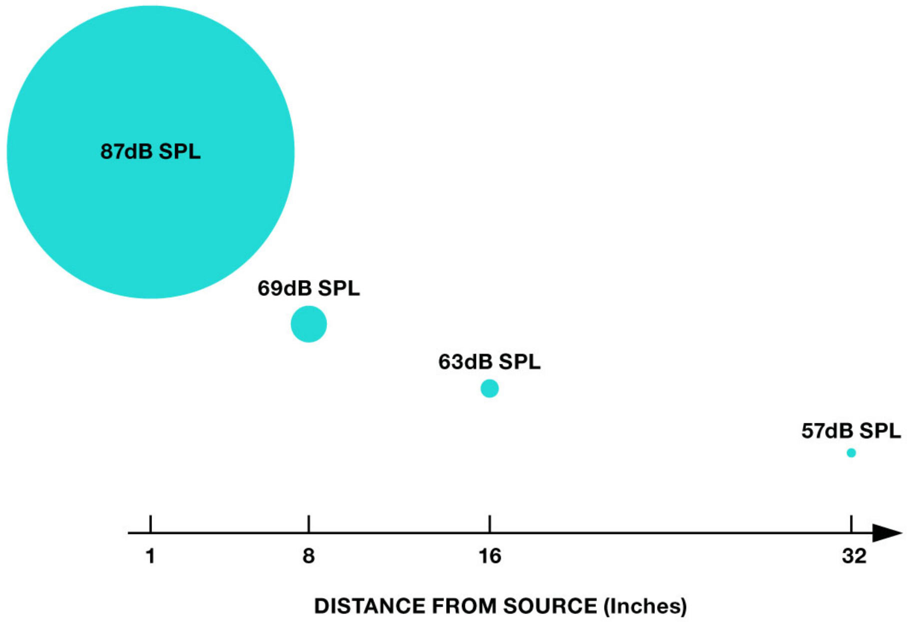


Figure 4.10: Measured sound level respectively to the source distance (source: *Understanding Microphone Sensitivity*)

As a rule of thumb, for purposes of assessing sound level in indoor environment, one should select the microphone with the following features:

- omnidirectionality - to secure uniform response regardless of the sound direction
- high dynamic range - to record sounds with wide span of intensity
- high sensitivity - to pick up sounds that are audible but distant

Microphones used in this project meets only the last two criteria. Moreover, due to the fact that every microphone used in the project has a bit different characteristics, it is expected that some discrepancies between their indications will occur.

Amplifier

Although implemented sound card, provided all the necessary circuits for signal processing and amplification, it has not been utilized. The main reason for that is the fact that such devices are not suitable for platforms without an operating system (see fig 3.8), thus it was impossible to benefit from all its features. To solve this issue, a computer science student group designed an amplifier on a custom-made PCB. However, its operation and characteristics are beyond the scope of this thesis and can be found in their semester report (see: *Improving Indoor Environments through Embedded Systems and Cloud-based Analysis*).

4.3.3 Data post-processing

Matlab scripts run according to the same general principle, regardless of the selected module (Acoustic, Visual, Thermal, IAQ). Raw sensor data is an input that is being analyzed and assessed 'live', and the resulting scoring matrix is created with each measuring loop completed by the unit. Sound Level Meter script was developed based on the "EN 253: Matlab Exercise #3 Design of a Sound Level Meter", adjusted to the specific project purpose and expanded with simplified reverberation time estimation. The following 'pseudo-code' presents entire processing algorithm implemented for acoustic module.

Acoustic Module Post-processing algorithm:

1. Import 30 sec '.WAV' file "BLOCK" -> create raw data matrix [x];
Raw data matrix should consist of $30 * 44100$instantaneous amplitude values.

2. Removing DC offset -> [DC=mean(x)];
This part removes the offset (up or down) of the amplitude values from '0' axis.

3. Apply Fast Fourier Transform (FFT) to the original signal, transforms the signal from time to the frequency domain, [x] -> [X];
In short, Fast Fourier Transform gives the information about signal frequency content and specific frequency occurrence in the signal. More details about FFT can be found in *Springer Handbook of Acoustics*, page 584.

4. Apply Band-pass filtering -> Cuts only frequencies within hearing spectrum $[X_{20-20k}]$;
In order to avoid calculating energy from 'downsampled' frequencies, band-pass filter has to be applied. It mutes frequencies below 20 Hz by assigning them values close to zero, and rejects all frequencies above 20 kHz.

5. Apply A-weighting filter -> $[X_A]$;
A-weighting as a frequency filter can be applied on the signal only in the frequency domain. It attenuates certain frequencies to roughly represent the human auditory response to the sound in an audible spectrum.

6. Use Parseval's theorem to estimate total signal energy -> estimate of dBA level;
Parseval theorem allows to calculate signal energy directly from its frequency content, so there is no need of performing inverse FFT. This simplifies calculation process and enhances its performance.

7. Windowing of [x] vector to 125 ms intervals -> $\Delta t = 0.125s$;
This step divides 30 s long signal into 125 ms samples to allow sound level calculation at each intermediate point.

8. Apply Fast Fourier Transform (FFT) to the windowed signal, transforms signal from time to the frequency domain, $[x_i]$ -> $[X_i]$;
Note that for reverberation time calculation, there is no need to apply A-weighting filter. Reverberation time is being calculated based on the SPL values.

9. Apply band-pass filter -> Cut only frequencies for RT assessment $[X_{125-4000}]$;
Frequency content for reverberation time estimation differs from the range taken for sound level estimation. Above frequency range was chosen based on the one adopted in Brüel& Kjær Hand-held analyzer type 2270 and suggested by the relevant ISO standard (*DS/EN3382-2:2008 - Acoustics – Measurement of room acoustic parameters*).

10. Estimate Sound Pressure Level (SPL) of each window -> $[dB_i]$;
This part allows to create sound level curve retrospectively for entire 30 s recording, as sound level is assessed for every 125 ms time interval.

(11) Find "PEAKS" and "BOTTOMS" in $[dB_i]$ -> $DynamicRange \geq 25dB$ within $\Delta t = 3s$ time intervals -> RT_{value};
Script then searches for successively occurring (within 3 s time frame) 'peaks' - local maximum, and 'bottoms' - local minimum that have sufficiently high dynamic range (ΔdB). If such points are found, reverberation time is estimated based on the slope of the line that connects those points. Dynamic range and time span limits can be defined in the initial script part.

(12) Create scoring vector -> gives "BLOCK" numerical score [5/4/3/2/1] that corresponds to [A/B/C/D/E];
Each loop creates Raw values vector $RWV = [L_{eq,A}, RT_1, RT_2, RT_3, ..., RT_30]$; where $L_{eq,A}$ value is stored in the first place and all found reverberation time values respectively. Based on the raw values vector the score for dB(A) level is assigned according to the scheme below

Full code including instructions and basic 'know how' is provided as a digital attachment to the project.

It is important to note that the resulting $L_{eq,A}$ value from the script is not valid unless proper calibration procedure will be performed and calibration constant defined. Procedure for finding calibration constant for such audio script can be found in "EN 253: Matlab Exercise #3 Design of a Sound Level Meter".

As the RT design target values depend on the evaluated space type (office, classroom, auditorium) it is excluded from the qualitative assessment. Reverberation time is calculated but given only informatively, as the room characteristic parameter. Therefore, only sound level will we evaluated qualitatively as follows:

Parameter score	dB(A) Limits
A	$L_{eq,A} \leq 45dB(A)$
B	$45 < L_{eq,A} \leq 55dB(A)$
C	$55 < L_{eq,A} \leq 65dB(A)$
D	$65 < L_{eq,A} \leq 75dB(A)$
E	non-compliance

Complete scoring system together with selected weightings can be found in chapter 5.

In terms of audio data acquisition RAW data refers to the analog voltage fluctuations that correspond to the sound wave AMPLITUDE, which ranges from -1 to 1 after digital conversion (depending on the ADC bit resolution). Although it seems like only one parameter is being constantly recorded - sound wave amplitude, the appropriate sampling FREQUENCY allows to extract information about frequency content of a sound wave using mathematical tools such as Fast Fourier Transform.

4.3.4 Discussion

Utilizing manikin for the acoustic environment assessment seem challenging. Advanced binaural measurements, which are widely used for headset or hearing aid systems, seem not to fit best the project purpose. However, a simplified binaural setup that was adopted, could be a trade-off between setup complexity and its expansion potential. It allows application of the 3D-printed ears, that secures appropriate microphones location which is not the case while using single microphone measurement. Microphone placement is important as the device location strongly affects its indications (see chapter 2.3).

Despite the fact that all standards are still using the A-weighting measurements assessing perceived sound level it receives a lot of critique as an obsolete and inaccurate measurement. The main reason for its wide application is its ease of use, not involving complex calculation or measuring procedures. However, authors see the possibility of adopting both measuring techniques into the Manikin sensing unit in the future. That could be the starting point to establishing a correlation between binaural sound level indication and currently used A-weighted method. With a single omnidirectional microphone that would have SLM (Sound Level Meter) characteristic, and set of microphones arranged in the binaural setup with appropriate HRTF (Head Related Transfer Function) together one would get two different sound level reading that could be compared and correlated with people response. Based on that correlation new limits for binaural measurements could be established without excluding previously developed relationships but taking them into account.

Reverberation time measurement is excluded from the qualitative evaluation, as the current solution does not allow the **active inputs** into the assessment application. Since for different spaces RT class criteria varies it is impossible to give one universal ranges that will be appropriate for all rooms. Moreover, parameters that affect the overall perceived quality of IEQ such as clothing value (clo), metabolic rate (met), occupant sex, current season, building or room type etc.; cannot be easily changed without modifying the application code. However, there is huge potential for further research to extend the application with such possibility. Then adaptive scoring system could be developed that would change its class limits, or parameter weightings according to the particular occupant-space case. More to that, there are number of studies trying to establish a method of STI prediction based on measured reverberation time of the room. With the development of such methods they could be incorporated into the script and by that, measuring unit functionality would be expanded.

Programmed method of calculating sound level and reverberation time differ from the standardized. Nonetheless, field tests of the manikin will show how well indications of such prototype will correspond to the commercial high-end devices. Regardless of the field test outcomes, it is worth noting that this is an initial implementation stage. There is still huge room for improvement that could increase measurement accuracy without significant cost raise, for instance by:

- Refining the assessing application - adopting more advanced calculation method, active input feature etc.
- Proper device calibration - even with cheap technology it is possible to obtain reasonable outcome after proper calibration
- Refining sensor distribution or expanding setup with more sensors

4.4 Visual module

Introduction

In this module, the measurements and processing of indices are described. The ***main chosen indices*** *assessing visual comfort were summarized in section 2.4. The designer is provided with all the limitations and advantages, hence help them with the selection of the most suitable indices when dealing with such visual assessment. The following outcomes are important to mention: Visual comfort is assured by coexisting factors, but the existing metrics generally just evaluate one of them at a time. There's no single parameter or established methodology representing visual environment and its comfort. Indices that are represented by a single value seem to be more useful when doing long-term evaluation because the output data otherwise would need intensive post-processing to maintain a reasonable outcome and computational effort.*

4.4.1 Principle

The basics of the measuring and data flow is explained in this chapter, separately for all the indices.

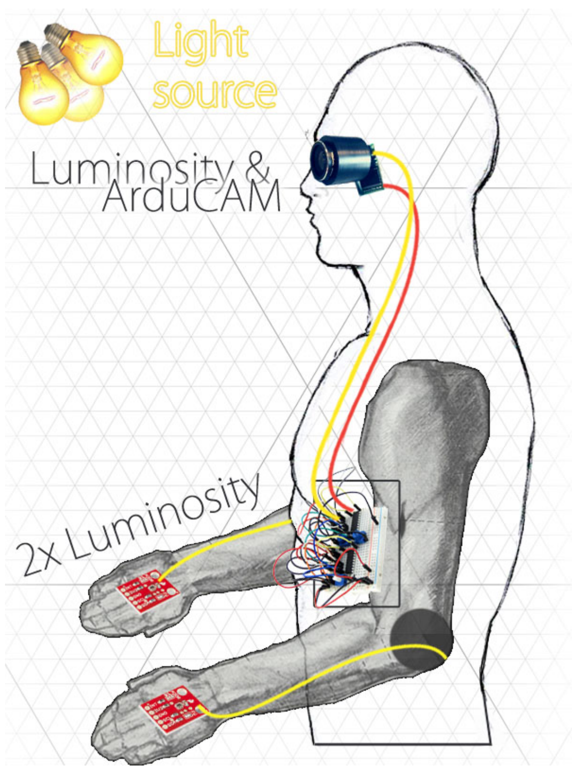


Figure 4.11: Scheme of the visual prototype model

LUX

Illuminance is measured by light-to-digital converters (luminosity meters). Light intensity [*lux*] is transformed to a digital signal in a direct I^2C interface provided by the **TSL2561** sensor. The sensor is **approximating** the human eye response. This is achieved by using two diodes, firstly a broadband photodiode (visible and infrared spectrum) and a solely infrared responding diode, which together provide a **near-photopic response** (human eye response). Illuminance measurements will take place, while the photographs for glare assessment are taken. The reasoning behind this is to have data acquired at the same time span. Luminosity sensors are providing **instantaneous** illuminance values in *[lux]*, therefore evaluate the **quantity** of light at the same moment. Scoring and categorizing illuminance levels is based on literature review, focusing on the photopic human eye light perceiving law. Illuminance sensor is located on the top of the hand (both hands).

HDR

Luminance uniformity is calculated and evaluated from the luminance values obtained after the photo processing. The area of the performed task and the surrounding area is captured. The photos are taken by a **OV5642** (low-voltage, high-performance) **camera**. The data flow of the luminance $[cd/m^2]$ is translated through the sensor core to an image processing processor, where it is translated to a digital signal (luminance map). Further processing is needed to calculate and assess the quality of the uniformity.

HDR

Glare evaluation lacks standardized metrics of glare and a general agreement on factors causing it. Every proposed formula differs in the calculation process, since there is no common understanding of discomfort glare. The most suitable indice for glare evaluation through **HDR pictures** from the **OV5642 camera** is used. Obtained photos are processed into the same luminance maps are used as for the luminance uniformity. Further processing

DGP

Supplementing static metrics used for further development and calibration (of the camera's luminance output) is the **DGP** (Discomfort Glare Probability) **glare** indice. For this measurement a luminosity sensor **TSL2561** is placed in the right eye of the manikin. It measures light intensity and translates to a digital signal.

4.4.2 Post-processing

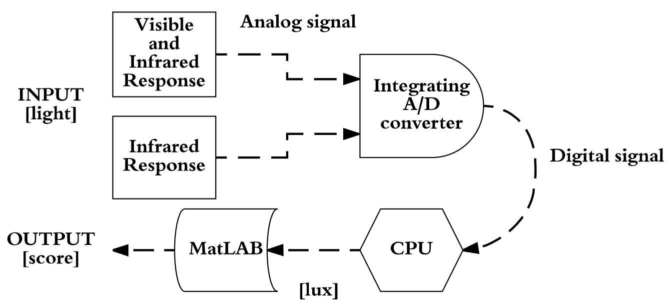


Figure 4.12: Light signal processing

Matlab input and illuminance processing code:

1. Import **illuminance** values in $[lux]$ - imports 2 columns of data from both sensors placed on hands and the third column of data from the eye height level,
2. Illuminance values **averaged** during a variable period of time from both sensors $[meanill]$, this time solely depends on the time needed to take all the pictures with the camera, to have aligned measurements,
3. **Logarithmically spaced vector** is created for excessive/insufficient lighting conditions to obtain the boundaries for further classification
4. $[meanill]$ is then compared and categorized to a **score** threshold $[A/B/C/D/E]$. This value only represents the illuminance average from hands,
5. Illuminance measured at the eye height level is used for further glare processing.

HDR

Matlab input a **luminance uniformity** processing code:

1. Low dynamic range photos are taken with different exposure values by ArduCAM,
2. **Input** format of the pictures is a $f[jpeg]$ file with specified EV (exposure value),
3. Coupling of LDR photos into a HDR is used, using the CRF function to obtain the correct luminance values on each pixel. **Output**: HDR,
4. Data included in the HDR photo is recalculated into a **luminance map** $[cd/m^2]$,

$$L = 0.2126 \cdot R + 0.7152 \cdot G + 0.0722 \cdot B \tag{4.7}$$

5. Areas of interest are evaluated and the mean values of **luminance** are obtained $[cd/m^2]$,
6. Weber's equation is used to obtain the contrast value $[-]$,
7. The result is categorized and evaluated $[A/B/C/D/E]$.

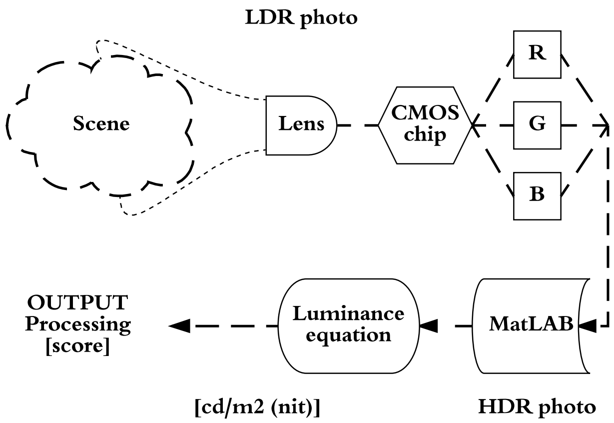


Figure 4.13: Photo signal processing

Matlab program and its steps to analyse **glare**:

HDR

1. Pick an indoor scene with no direct sun to the camera,
2. Fix the camera to eliminate variance in the scene,
3. Low dynamic range photos are taken with different exposure values by ArduCAM,
4. **Input** format of the pictures is a $f[jpeg]$ file with specified EV (exposure value),
5. Coupling of LDR photos into a HDR is used, using the CRF function to obtain the correct luminance values on each pixel. **Output**: HDR,
6. The equation to obtain the luminance values from RGB spectrum is introduced,
7. Data included in the HDR photo is recalculated into a **luminance map** $[cd/m^2]$,
8. Areas of interest are picked and evaluated (field of view and wider field of view)$[cd/m^2]$,
9. The calculated values are compared to the thresholds (based on literature review),
10. Assign the corresponding score $[A/B/C/D/E]$

4.4.3 Discussion

Usage of the manikin to evaluate lighting conditions/comfort shows big potential. Combining aspects such as illuminance, luminance and glare is a **complex evaluation** accounting the factors, which can be measured by an **artificial** being. Most **expensive** traditional measure from the above-mentioned categories is the luminance. Calibrated luminance measuring tool is very **expensive**, therefore substituting it with a different measure is more than beneficial.
To be exact, any other luminance measure than a luminance meter needs to be accordingly **calibrated**. In the case of using a CMOS sensor, the **calibration constant** value needs to be added to the luminance calculating equation. Therefore using a modified equation transforms a **cheap photo sensor** into a relatively accurate luminance measuring tool. Considering the costs for this measure a price of a luminance meter can be hundred times higher, than a simple digital camera.

Extensive research to validate and measure the accuracy of cheap photo sensors should be conducted. Papers regarding this case are generally short and do not include all the necessary details, nor the differences of these measures(between a calibrated tool and a camera).

HDR Imaging limitations

High accuracy can only be maintained while having stable conditions during the measurement time. The more dynamic the lighting conditions are, the more differently exposed photographs can deliver accurate end results.

Inanici in 2004 stated: "There is a need for the developement of new glare indices utilizing the advanced measuring capability of modern technology."

Referring to the today’s used glare indices, which were developed long ago, not compatible with modern technologies since they were oversimplified or based on impractical assumptions. The above-mentioned thresholds do work **accurately** for relatively low light levels. The luminance threshold used in the developed Matlab script detects also very **small sources of excessive luminance** from highly reflective materials (shiny surfaces) and accounts them as a **glare source** with very high luminance. The "faulty" pixels are treated with 95 % confidence interval. To fix the above mentioned "glare sources" pixel clustering is used in very developed software to specify if it is a glare source or not.

Further development for distinguishing bright interiors, surfaces and glazed areas instead of accounting them as glare sources need to take place. The glare is a complex phenomena and for now the "glare assessment" gives a deeper insight into illumination condition of the interior. The potential of glare assessment through HDR imaging is great and further research is needed.

5. Scoring System

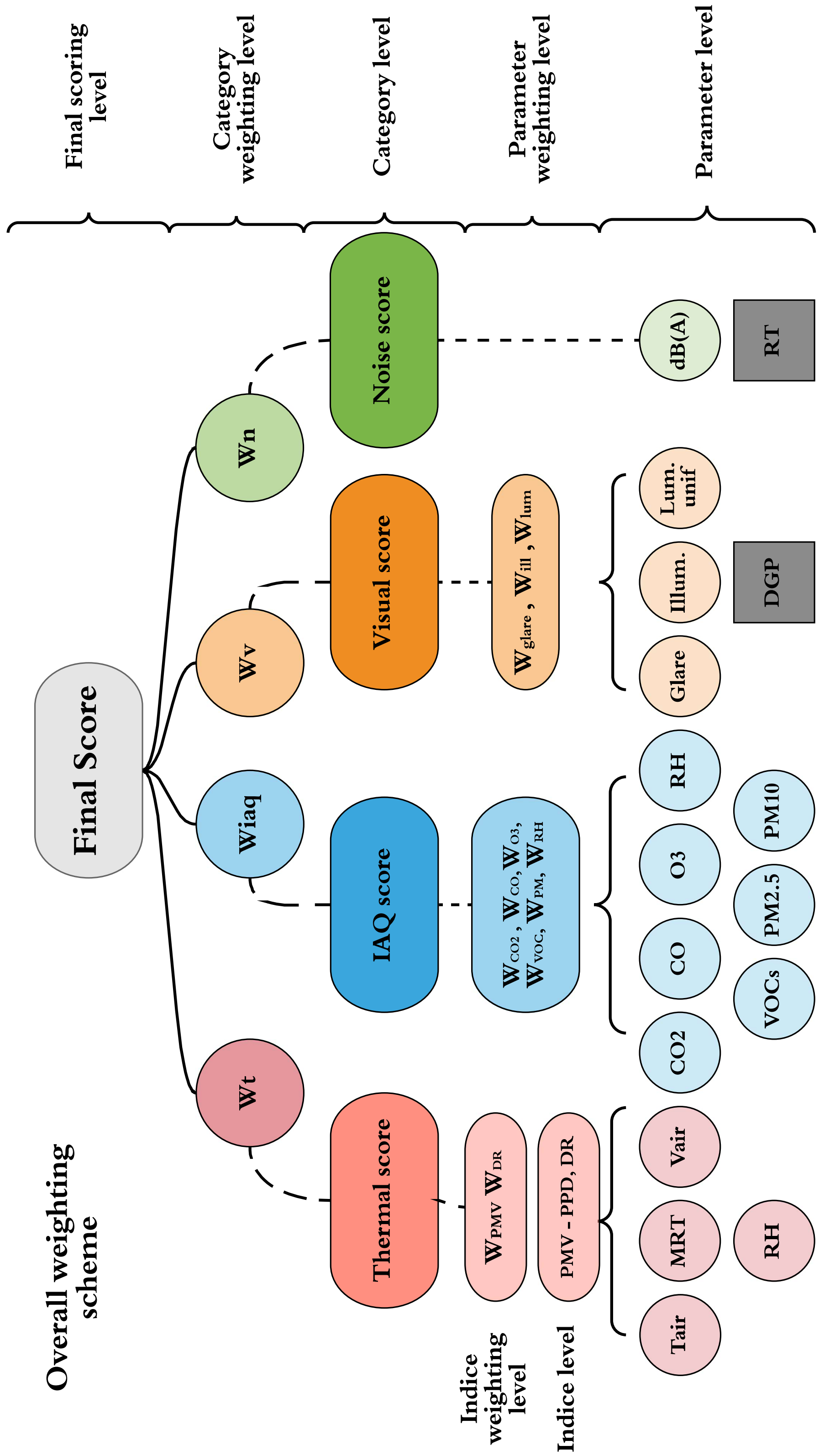
The idea behind the scoring system is to assess the data obtained from sensors and combine them into one score for a given space. Initially, scoring system works on a parameter level, gives each reading a score that corresponds to the programmed class limits. After the parameters are assessed within the category, they contribute to the category score with respect to their importance. Eventually, category scores are weighted and overall IEQ score is assigned for evaluated space. More detailed description of the scoring algorithm is given further in this chapter.

5.1 Scoring system principle

The main principle of the scoring method is going from detailed to general evaluation. This means that scoring starts from the smallest elements of the evaluated IEQ. In this case, they are the parameters, either measured or calculated based on the measured values. All levels on which the scoring is performed are:

1. **Parameter level:** Each parameter is checked for compliance with the limits chosen by authors and gets a score accordingly.
2. **Category level:** Categories consisting of more than one parameter are then evaluated internally. Parameters are weighted based on their importance and combined to get a category score.
3. **IEQ level:** Overall score is a value established based on all 4 category scores. Again the importance (weight) is assigned to the elements.

Weights ascribed to parameters are dynamic and change depending on their number (i.e. IAQ) or instantaneous importance (i.e. Visual). The importance of the measured parameters was assigned based on thorough literature review and qualified guess. Specific relationships used within category assessments require more explanation, which is provided in proceeding section.



○ *a circle around the parameter symbol means that it is used for scoring*
⊡ *a square around the parameter symbol means that it is an auxiliary value, not used for scoring*

Figure 5.1: Basic overall weighting scheme, depicting levels and parameters in the evaluation.

As it can be seen in figure 5.1, each comfort category score is reduced on a category weighting level by the importance factor. Those factors were chosen based on research in the field of existing assessment schemes. Biggest impact on the established weights had the meta-analysis made by Heinzerling et al. (2013). Table with weighting schemes resulting from this meta-analysis is shown in figure 5.2.

Summary of IEQ category weighting schemes.

Study	Number of occupants surveyed	Acoustics	IAQ	Lighting	Thermal comfort
1. [17],[a]	12 professionals	0.23	0.34	0.19	0.24
2. [19]	293	0.24	0.25	0.19	0.31
3. [16]	500	0.27	0.14	0.21	0.38
4. [15]	68	0.18	0.36	0.16	0.30
5. [14],[a]	–	0.25	0.23	0.23	0.29
6. Proposed PMP-based	52,980	0.39	0.2	0.29	0.12

[a] Adjusted weights.

Figure 5.2: Gathered weighting schemes for IEQ assessment (source: Heinzerling et al. (2013)).

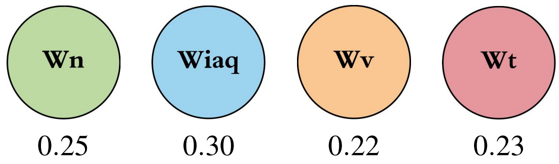
Since scoring procedure is done by the MatLab scripts, all specified classes (A,B,C etc.) have their own corresponding numerical values according to the table 5.1 below.

Parameter score	numerical value
A	5
B	4
C	3
D	2
E	1

Table 5.1: Classes division with assigned numerical values

The preliminary weights were assigned based on the investigation of the table in figure 5.2. What stands out is the fact that 12 professionals gave the most importance to the IAQ category. We tend to agree that IAQ is the most important category because it affects occupants health, comfort and productivity altogether. More to that, its health impact is often underestimated by occupants as they are not aware of the indoor air contents and their impact. It is worth noticing that the last study listed in the table, with the greatest test group, indicated that the least important category for occupants is thermal. It is understandable taking into consideration the fact that for decades engineers have been working on assuring appropriate thermal environment in buildings. The other reason might be the fact that occupants tend to adapt to the thermal environment easily, for instance, by adjusting their clothing. Also the same study indicates that users gave the most importance to the acoustic category. It corresponds to the observation that modern office buildings, mostly adopting open plan layout, suffer from excessive noise. Rest of the studies does not present any common pattern and therefore were treated only informatively.

From carried investigation only two important conclusions can be drawn. First, is the observation that professionals judgement does not correspond to occupants response at all. Second is that category weights should not be assigned based on the biased, subjective responses, but rather on the hard data that support it. Therefore, we decided to put the most importance on IAQ category and weigh the other ones almost equally what is presented in the table below. Selected weights should be treated as the preliminary choice and are supposed to be refined after a long-term testing period.



These values are overwritten if any of the categories receive an 'E' score. In such situation importance of the poorly performing category is increased. The overall score of the space decreases significantly in this case, therefore it will more-likely bring the attention of the system's user. Such action combined with appropriate message for the occupant, including possible reasons for current situation and tips for improvement, should limit the negative effects of bad IEQ and increase the awareness of users. Since 'E' category score increases its importance to 50 %, two such a bad scores will result in 'E' score for entire space. The reason for increasing the weight of the poorest performing category is that the worst score correspond to non-compliance and therefore should not occur during regular building operation.

Adjustment of the category weights is done for such cases:

A. All categories comply with limits for categories 'A-D'
   W_t, W_{iaq}, W_n, W_v are given the 'initial' values presented above;
B. One of the categories performed poorly and was scored 'E'
   Weight of this category is increased to 0.5 and the other category weights are decreased in respect to their initial contribution;
C. Two categories scored 'E'
   Those two categories are getting their weights increased to 0.5 each, resulting in 'E' score for entire evaluated space;

5.2 Scoring within categories

This section is providing information on details of scoring performed within categories. Each category is mentioned separately to provide the reader with neat description of the idea behind the entire system.

5.2.1 Thermal comfort evaluation method

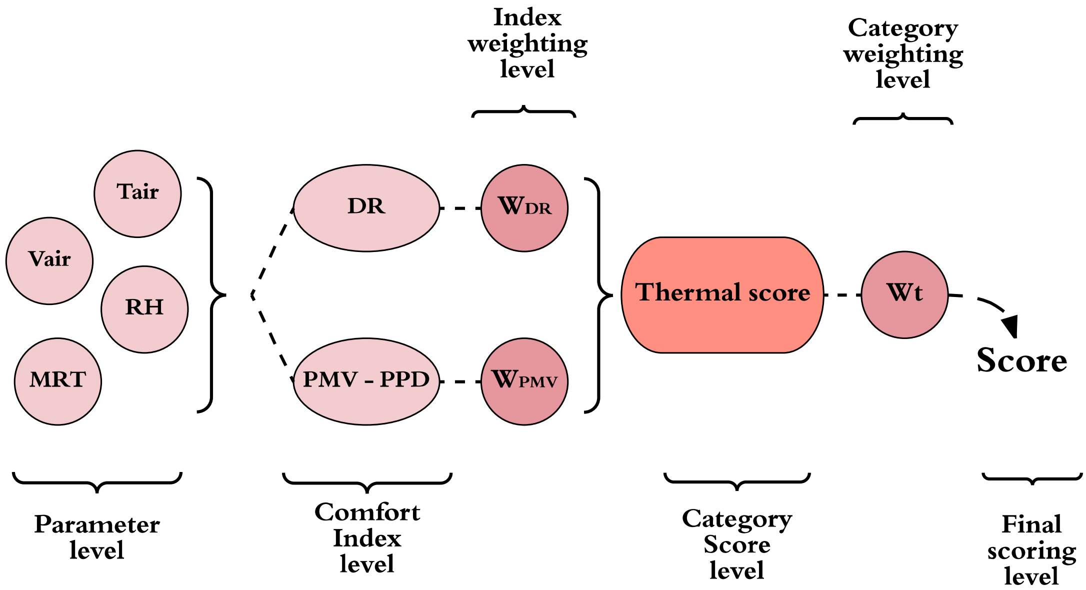
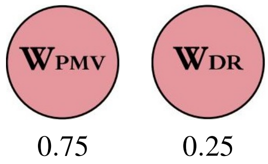


Figure 5.3: Schematic representation of scoring method within thermal comfort category.

Thermal comfort assessment is made based on two main parameters $PMV - PPD$ and DR indicators. Those factors are a result of calculations done by the "Thermal module" script and are assessed based on the time of the measurement (described in detail in chapter 4, section 4.1) and assigned thresholds:

Parameter score	*PMV* limits	corresponding *PPD*	$T_a \leq 25\,^{\circ}$C *DR* limits	$T_a > 25\,^{\circ}$C *DR* limits
A	$\pm$ 0.5	$\leq$ 10 %	$\leq$ 5 %	$\leq$ 10 %
B	$\pm$ 1.0	$\leq$ 22 %	$\leq$ 10 %	$\leq$ 20 %
C	$\pm$ 1.5	$\leq$ 50 %	$\leq$ 15 %	$\leq$ 30 %
D	$\pm$ 2.0	$\leq$ 75 %	$\leq$ 20 %	$\leq$ 40 %
E	non-compliance with preceding thresholds			

After assigning the score to the indicators, they have to be reduced by the importance factor and summed up. This way the category score is obtained. Weights assigned to the factors are:



These values are a result of literature review and a so-called qualified guess made by the authors, based on the fact that even though an acceptable thermal sensation is calculated from the measurements, there might be draught problem in the room. Lower importance of *DR* results from the specific $PMV - PPD$ formula that includes in the calculation airspeed value.
In case the air velocity is equal to zero, what indicates that there is no airflow in the room or that the sensor might be broken, the weight of $PMV - PPD$ in increased to 1. If such situation occurs during long period of time a warning is sent to the user to check whether the sensor is working.

5.2.2 Indoor Air Quality evaluation method

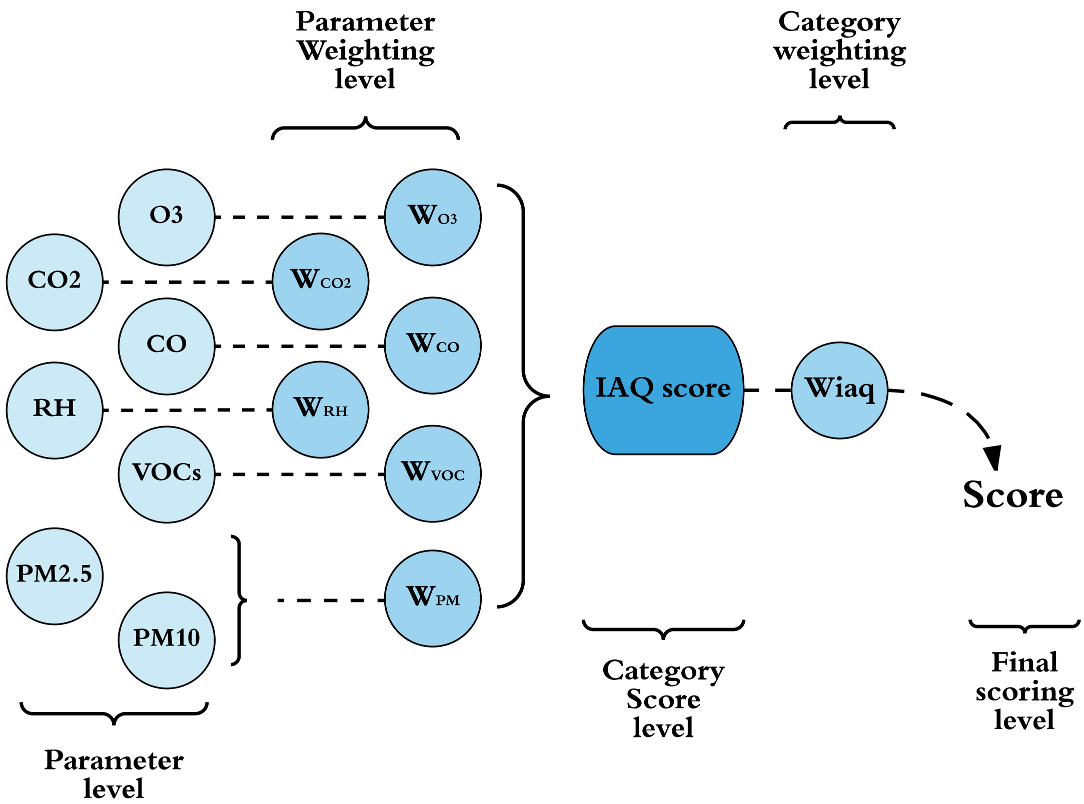


Figure 5.4: Schematic representation of scoring method within IAQ category.

Assessment of IAQ is done based on measured concentrations of chosen parameters, visible in figure 5.5. Parameters are scored according to the list of thresholds:

Parameter score	CO_2 [ppm]	CO [ppm]	O_3 [ppb]	VOC [ppb]	$PM_{2,5}$ [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	RH [%]
A	≤ 800	≤ 3	≤ 30	≤ 3	≤ 18	≤ 60	45-55
B	≤ 1000	≤ 7	≤ 60	≤ 10	≤ 36	≤ 120	40-60
C	≤ 1200	≤ 11	≤ 90	≤ 17	≤ 54	≤ 180	35-65
D	≤ 1400	≤ 15	≤ 120	≤ 24	≤ 70	≤ 240	30-70
E	non-compliance with preceding thresholds						

Only $PM_{2,5}$ and PM_{10} scores are recalculated further on the parameter level. If the two scores are identical the grade stays without changes as an overall dust score. However, if the scores are different the worse of them is taken further as the dust score.
On the parameter weighting level there are now 6 scores that require weighting. Equal scores are assigned to the parameters, with the general rule that only the sensed parameters are scored. This means that in case of one parameter not occurring in the air, even though it would obtain the best score, it is not included into the category score. In this way if the space is not contaminated by unwanted substances, only CO_2, RH and dust should be present. Such treatment brings more attention to the pollutants that are potentially affecting the occupant. Jet again, this method has to be thoroughly tested in order to check the validity of those assumptions.

5.2.3 Noise evaluation method

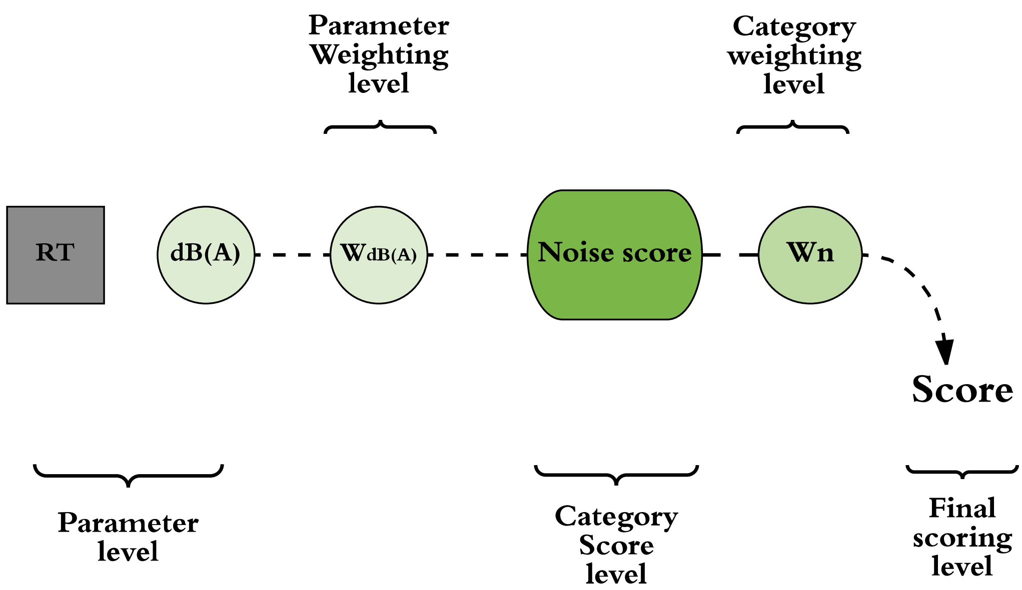


Figure 5.5: Schematic representation of scoring within acoustic comfort category.

At the parameter level in acoustic category the scoring system contains two indices identified as a 1^{st} priority for implementation based on the literature review. Nevertheless, for reasons included in section 4.3 reverberation time is not yet included into qualitative assessment. Therefore sound loudness represented by $L_{eq,A}$ - equivalent, continuous, A-weighted sound level is given 100% importance as a single parameter within acoustic category. The suggested class limits were arbitrarily chosen by the authors as the result of literature-review analysis, with indication on the paper Heinzerling et al. (2013) as the most influential. Figure below presents the suggested class division for offices together with parameter ranges for each:

Parameter score	dB(A) Limits
A	$L_{eq,A} \leq 45dB(A)$
B	$45 < L_{eq,A} \leq 55dB(A)$
C	$55 < L_{eq,A} \leq 65dB(A)$
D	$65 < L_{eq,A} \leq 75dB(A)$
E	non-compliance

In this method, non-compliance refers to the case when the equivalent sound level is above the limits of the worst, yet complying D class which is considered safe for occupant health for usual working day exposure time of 8 h. Although long exposure to the noise of a level from higher classes might also be detrimental to the occupant's health, these effects are not adverse and specific limits are not forced by any international regulations. Suggested limits need to be tested in real life offices in order to evaluate its performance and credibility.

5.2.4 Visual comfort evaluation method

The parameter level in the visual score assessment contains three main parameters (glare, illuminance, luminance ratio) and an auxiliary DGP parameter. Assigning weights at a parameter level provides the scheme always accounting the **worst** case scenario. Based on this approach **three** cases were created:

1. **General case**, where scores from A - D are given for all the parameters specified, the weighting is equal for every indice w_{glare} & w_{ill} & $w_{lum} = 1/3$,

2. **Excessive glare** (score E and worse) introduces an increased weight for this parameter $w_{glare} = 1$ and w_{ill} & $w_{lum} = 0$. This means that if a case of intolerable glare occurs a good score cannot be obtained,

3. If **insufficient illuminance** $< 100\ lux$ is measured, there's no need to evaluate glare and contrast ratios, the overall conditions are not suitable to perform a visual task ($w_{ill} = 1$ and w_{glare} & $w_{lum} = 0$;

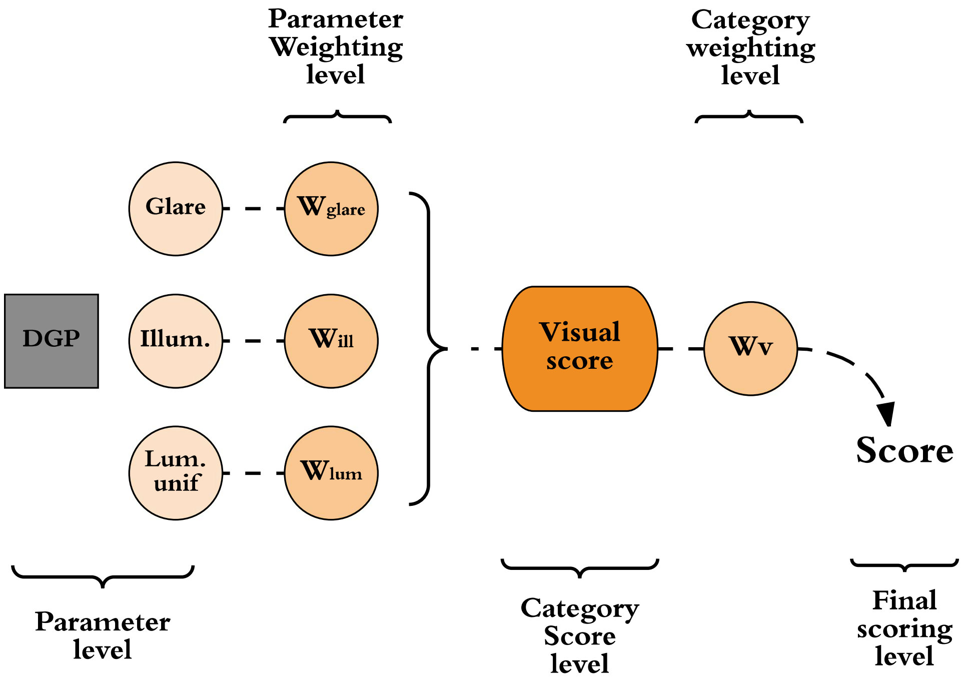


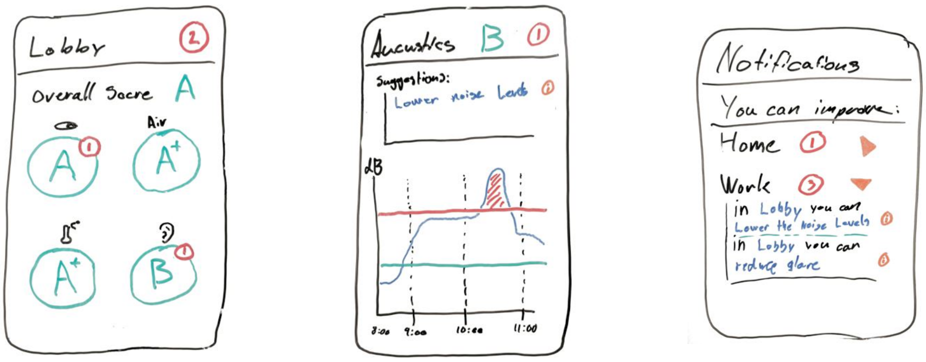
Figure 5.6: Schematic representation of scoring within visual comfort category.

The primary evaluation is on a **parameter** level. Depending on the measured value of each indicator a score is given. Further, depending on the case which occurs, the Matlab script picks the **evaluation scheme** and the overall category (**visual**) score is being obtained. Further the score of each **category** is weighted together to give a **final scoring** level.

Parameter	**Glare** Limits [cd/m^2]	Insufficient **Illuminance** [lux]	Excessive **Illuminance** [lux]	Higher **Contrast** [-]	Lower **Contrast** [-]
A	0 - 1920	500 - 750	500 - 750	0.65 - 0.70	0.65 - 0.70
B	1920 - 5014	500 - 292	750 - 1041	0.65 - 0.35	0.7 - 0.79
C	5014 - 8366	292 - 171	1041 - 1443	0.35 - 0.19	0.79 - 0.88
D	8366 - 11718	171 - 100	1443 - 2000	0.19 - 0.10	0.88 - 0.99
E	> 11 718	< 100	> 2000	-	-

5.3 Scoring Application Design

One of the project goals was to develop a user-friendly application for making scoring system more accessible and entertaining. The collaboration with a group of IT students was fruitful on this field as well. Based on joint brainstorming and discussion an idea of the mobile application with certain features came to life. The selection of mobile devices as the target platform for the application introduced numerous possibilities. Mobile layout forces application to be more visual and interactive, helping to encourage the user to examine the examined IEQ further. Thus, starting from the general, 'live' room condition overview, the user can reach different degrees of complexity by tapping different categories on the screen revealing another layer of information. As we all agreed, the application should be as transparent and straightforward as possible, for the regular user, without any background on IEQ assessment. Figures below present the basic app functionality together with the successive stages of insight.



(a) (b) (c)

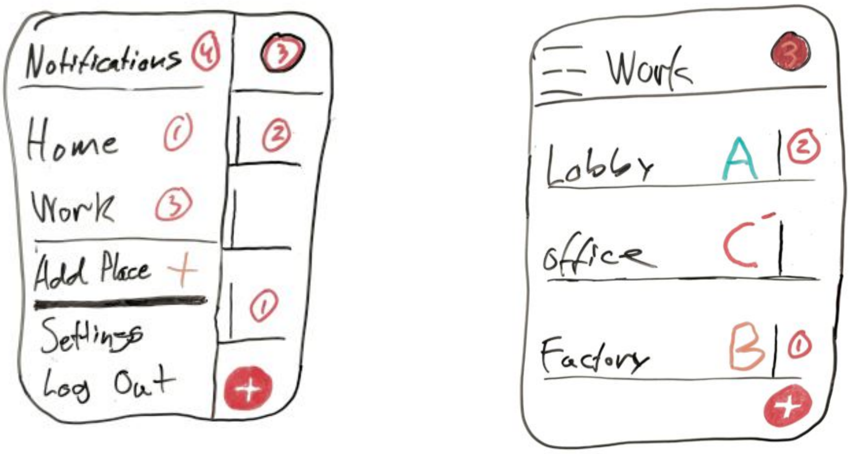
Figure 5.7: Conceptual design of the scoring application (source: *Improving Indoor Environments through Embedded Systems and Cloud-based Analysis*).

Picture (a) in figure 5.7 presents a 'default' screen for space called 'Lobby'. Small icons represent four main categories. Starting from the top left, visual, IAQ, thermal and acoustic respectively, and are given a score that corresponds to the live sensors readings. Then, at the top, an overall score for entire space is given based on the successively updating partial scores. Superscripts (numbers in red circles) are notifications indicating exceeded safety limits or warnings for users.

Picture (b) in figure 5.7 is showing the typical screen for selected category. It gives a more detailed insight of the process variables live plot and reveals notifications for the users. In this example, the notification is prompted because measuring unit detected excessive noise, above the predefined safety limits.

As a further expansion of the app design, IT students suggested a feature that will allow adding more rooms to examine and grouping them together into zones. It will allow the user to place the measuring unit into different rooms and compare their performance based on the logs saved in the application. The user is allowed to tag a space f.ex. office, bedroom and refer to either live readings for the room, while the unit is running, or to the logged data.

Last picture, (c) in figure 5.7 gives the user access to the complete list of notifications that were gathered for all specified zones, such as 'Home' and 'Work', in this example. That gives a quick summary of most important issues that were found in all spaces.



(a) (b)

Figure 5.8: Increased functionality with adding more rooms for assessment (source: *Improving Indoor Environments through Embedded Systems and Cloud-based Analysis*).

Picture (a) and (b) in figure 5.8 present an 'initialization' screens that allow user to manage basic app setting, adding more spaces, zones, configure connection with server and establishing Wi-Fi connection.

6. Manikin Design & Assembling

In this chapter entire process of manikin design and prototyping is described. Starting from the concepts, through idea development and problem solving, every iterative step is briefly described up to completion. The purpose is to give an insight to the reader what are intermediate steps involved in such project.

Concept

The very first concept of project theme emerged with the selection of the long master thesis topic by our group. Initially, the project was aiming to design only manikin head that could be used with another Thermal Manikin called "Comfortina" and expand gradually its functionality. As Comfortina has had thermal and breathing modules already developed, there was huge potential for adding new features. As a very expensive tool, existing thermal manikin could not be used for prototyping process. With numerous areas of focus to select from, the decision was made to 'go broad' - to lay the grounds for complete IEQ assessment method and develop a 'brand new' manikin to achieve this goal.

step 1 - Prioritization

As we found out during the process, the thermal function is well described in the literature and widely adopted among manikin projects that were carried out. Therefore we put a higher priority on other features such as IAQ, visual and acoustic modules. As each of the module itself could be a subject of an extensive study it had to be narrowed down further. It was decided to perform comprehensive literature review first in order to establish what are the important IEQ parameters to measure. This effort resulted in a long list of parameters identified as having an impact on the occupants. Eventually, we consulted AAU scientific staff and external experts respectively to their field of expertise about parameters we selected. That gave us more insight into currently evaluated parameters and have helped us to create a final parameter list on which we started to build up a scoring system.

step 2 - Initial choices

With the knowledge of what is worth measuring, the subsequent step was to find out how to measure. We went through many standards to find out the appropriate measuring procedures and tools that we need to use in order to succeed. At that point, we encountered the following issues:

- Standards provided guidelines on how to measure only for a few of the selected parameters
- For others it involved very complex procedures and use of professional, expensive equipment
- It seem not possible to follow standardized measurement with the tool that we aimed to develop.

That has led us to the refinement of our concept and turn to maybe less scientific measuring procedure, but the one certainly possible to adopt into the manikin - embedded electronics and open hardware architecture. As it was entirely foreign field of knowledge to our group we started getting familiar with basic concepts and solutions. We were experimenting with Arduino and Intel Edison platforms and decided to use one of them as the architecture suitable for our project. Also, we have been browsing online embedded electronics shops worldwide in the search for appropriate sensors that could be implemented. That process was not only challenging but also very time-consuming. Eventually, we succeeded in finding all the necessary sensors, with preferred specification, in reasonable price available within the EU.

step 3 - Collaboration

Gradually completing the setup we have been offered the possibility of collaboration with Computer Science students working on the embedded systems as the main theme of their semester project. After initial meeting and presentation of each other project goals and ideas, it was decided that both groups could benefit from mutual collaboration. As a much more advanced in programming, IT students offered their help in implementing sensors into their architecture. That allowed us to focus on the assessment method itself instead of setup development. As our main input into their project, we offered our scoring method as the qualitative assessment of IEQ not only quantitative (sensor readings). As the collaboration introduced another shift of approach and required mutual adjustments, both groups were concerned about the final outcome. Nevertheless, with a lot of shared effort successive milestones were reached and considerable progress achieved. That allowed us to reach more goals and push the limits of our project further. As project team grew in size we had to develop a way of task division and progress evaluation.

step 4 - Manikin development

While the system was becoming more complex we started to plan sensor distribution within the manikin. Since one of the project goals was not to rely on high-end solutions we decided to order, and later customize a manikin usually used in the fashion industry. Although it did not hold-normalized dimensions, it had other advantages, among others: head rotation and easy access to its inside, as it is made from the glass fiber. Because we were mostly concerned about the upper body the manikin does not have legs. Nevertheless, with developed stand construction it can be placed on a chair when sitting position needs to be applied or on a desk when standing. The customization process was done with the considerable help of the Technical Staff from the Civil Engineering Department of Aalborg University and software engineering students. Our task was to coordinate entire process and to give design requirements that should be met. The following figures present the manikin adaptation process.

Figure 6.1: The manikin body as it arrived from the manufacturer

Figure 6.2: The manikin after assembling process

The following steps present the head customization process:

- Design of various fittings and mounting supports
- Preparation of the openings for ears and camera fitting
- Preparation of the service opening underside the head
- Mounted camera fitting and artificial ears onto the head

Figure 6.3: Head 1

Figure 6.4: Head 2

Figure 6.5: Head 3

Afterward, the service openings were created for the components that were supposed to be placed inside of the manikin. Figures below present the front and the back side of the manikin as it was ready for sensor implementation.

Figure 6.6: Manikin

Figure 6.7: Manikin

Next step was to develop an air-tight box, in which all IAQ sensors could be placed. It consists of an elastic tube - airways imitation, a box with sensors to which an electric fan is attached and an exhaust opening. The electric fan forces the airflow through the box, in the direction that corresponds to constant inhalation. Sensors placed in the airflow are:

- Temperature & Humidity sensor - in the manikin's airways
- VOC sensor - in the box, but not directly in the strongest airflow (according to MiCs manual)
- PM sensor - in the box, in direct airflow
- CO_2 sensor - in the box, in direct airflow (tilted towards inlet)
- O_3 sensor - in the box, next to the exhaust

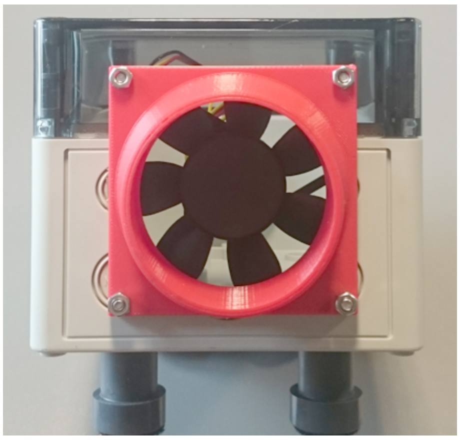


Figure 6.8: Box 1

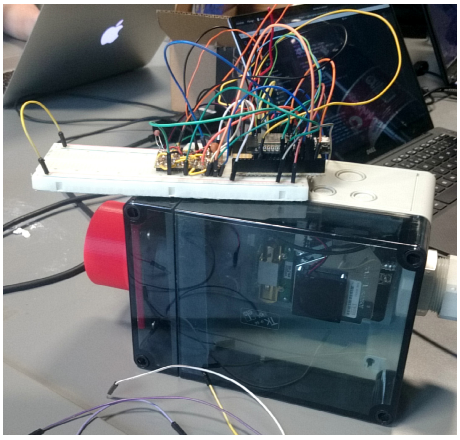


Figure 6.9: Box 2

Figure 6.10: Enclosure created for the temperature & humidity sensor.

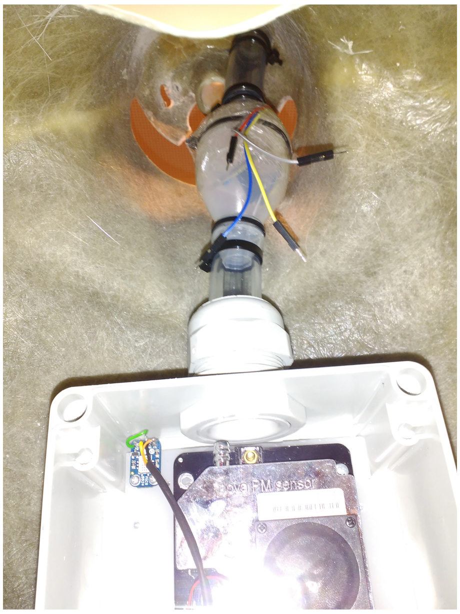


Figure 6.11: Location of the temperature & humidity sensor's enclosure inside the manikin.

Figure 6.12: Placement of all the luminosity sensors on the manikin's body.

Figure 6.13: Expected arrangement of the manikin's hands on the work plane during measurements.

To avoid any faulty readings, since some of the sensors are generating heat, the temperature and humidity sensor was located in an isolated enclosure between the mouth opening and the IAQ sensor box. The vinyl tube was cut in half and the chamber was fit-in. The sensor used for the prototype is a different one than the sensor described in section 4.1. However, the characteristics of the two elements are very similar and the change does not affect the project assumptions. Changing of this sensor resulted mainly from the fact that it was tested and implemented by the IT students before our collaboration started.

For the visual assessment, to evaluate DGP, an eye-height level lux sensor was mounted in the right eye. Left eye opening is fitted with the Arducam and the fish-eye lens. Two sensors were located separately on both hands, to measure illuminance levels at the work plane height.

Figure 6.14: View on the prepared inside of the manikin's head.

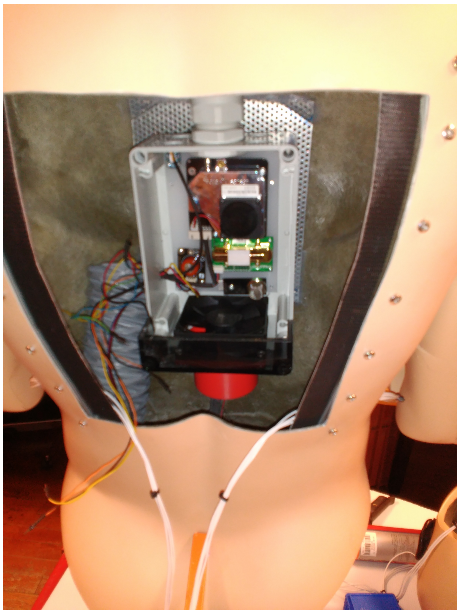


Figure 6.15: The 'air box' mounted inside the torso.

A custom made mouth fitting was developed and 3D printed, to allow flexible and detachable connection of the tube and the 'air box'. This way the box and the temperature & humidity enclosure can be easily taken out if needed, without destroying the prototype. The IAQ sensor box is mounted on the metal sheet glued inside the torso. It can be easily taken out since the "Velcro" tapes were used for mounting. The fan located it the 'air box' is connected to the exhaust opening through the flex tube. The exhaust is located in the bottom part of the manikin. Again, 3D printing was used to create specific fittings that make all parts easy to disassemble.

Knowing that only by experimenting we can found out the best solutions, two manikin shells were bought. The entire prototyping process aimed to discover the most practical solutions and configurations, which adaptation will give the manikin most flexibility and capabilities. It can be easily summed up by a sort of 'evolution' process, where only the beneficial features are passed on to the next generation. However, due to many issues that arose in the process, only one prototype was created. At this moment it is not equipped with all the sensors, but not much is left to implement. Manikin's first prototype is equipped with:

1. incomplete thermal module, only temperature & humidity sensor is used,
2. almost complete IAQ module, all sensors except for MQ-7 (measuring CO) are implemented,
3. complete acoustic module,
4. complete visual module.

III

Evaluation

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8.2 Conclusion
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7. Performance Testing

This chapter provides description and evaluation of the codes that were developed for scoring system implementation. It shows the way of inputting data to the scripts and resulting outcomes. Also, the entire scoring system performance is tested. Weighting method for the overall IEQ scoring is presented on examples, and troubleshooting is performed.

7.1 Scripts Outcomes

This section briefly shows the scripts performance for comfort category scoring. The data flow is presented graphically for easier understanding of each step. Data used for testing was generated based on real-life measured values and arranged in a way to create two test cases for each category. Testing is supposed to point out any potential issues occurring in the scripts and faults in primary assumptions.

Thermal Comfort Script

The script used for thermal comfort scoring was described in detail in chapter 4, section 4.1. Testing of the script's performance is done with two different data sets. Case 1 contains values that are supposed to give a high score (A or B). Case 2 should perform worse than Case 1. Values used for testing can be found in the attachment to this report (sample1-IAQTC.txt and sample2-IAQTC.txt).

Case 1

This example represents pleasant thermal conditions and is evaluated based on limits and constants established for the cooling season. First few samples of data going in and out of the script are used to describe the transformation of measured values into the thermal comfort score. The flow of information is presented in figure 7.1.
As it can be noticed in the figure, values used in this case yield high scores. The overall score of the thermal comfort category is equal to A, even after evaluation in time. Time-assessment is done with a 90 % threshold, what means that the score is obtained only if it (or a higher score) occurs for

90 % of the total time of measurements.

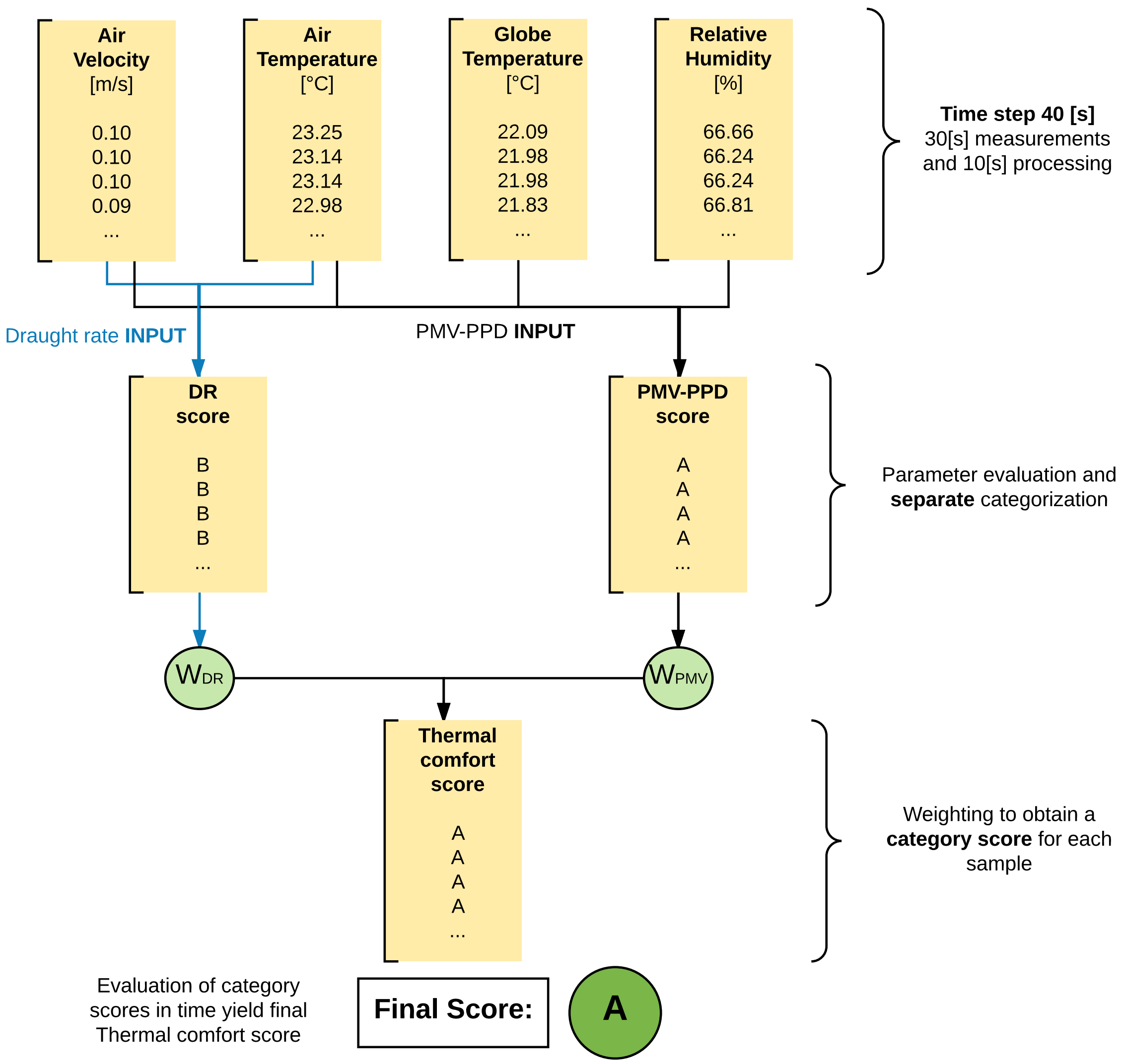

Figure 7.1: Data flow through the thermal comfort script in Case 1.

Case 2

For Case 2 the data flow is again presented graphically (in figure 7.2). Even though, it was not intended during sample generation the worst possible score (E) is obtained for the data set.
What can be noticed from both test cases, DR and PMV-PPD scores are very similar. The reason for using DR index in the scoring was to enable more flexibility to the thermal conditions, by setting the limits for air velocity in relation to the air temperature. However, this was probably not achieved, but in order to be sure of this more cases have to be evaluated.

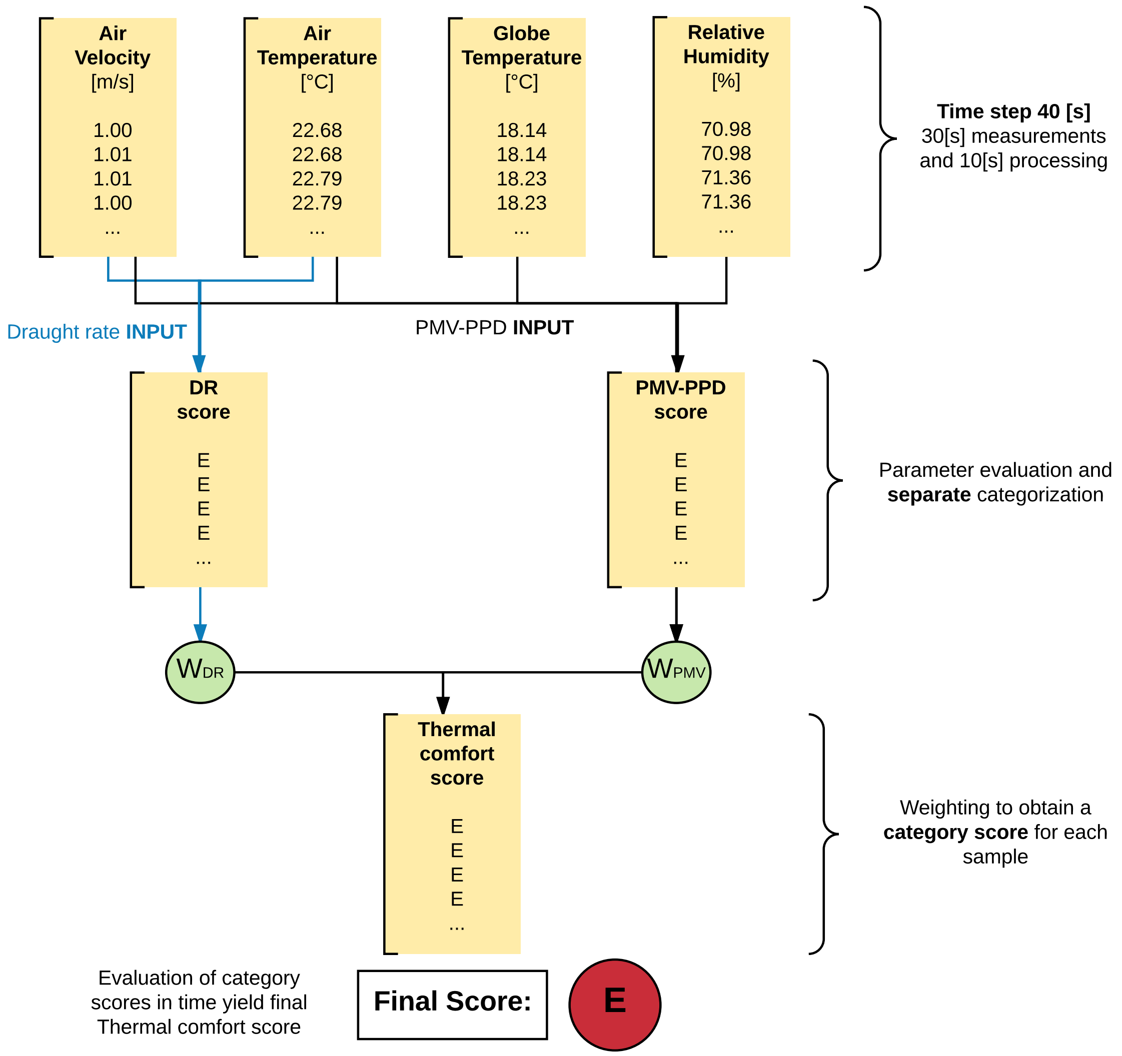

Figure 7.2: Data flow through the thermal comfort script in Case 2.

IAQ Script

IAQ scoring procedure is tested with use of two different cases. Values were generated in a way to create a significant differences between the data sets and also to obtain rather moderate results from both of them. Files containing numeric values used for Case 1 and 2 can be found in attachment to the report (sample1-IAQTC.txt and sample2-IAQTC.txt).

Case 1

Data flow and outcomes from each scoring step are visualised in figure 7.3. Evaluated data set contains 6 parameters, including one (CO) with is indicating concentration equal to 0. In such situation, CO score is not used for obtaining category score. It is treated as not present in the indoor air and therefore not affecting its' quality. Weight factors for the other parameters are calculated as 1/'number of sensed parameters'. Equal weights are assigned to all factors.
Final IAQ score is taken as category that was obtained for 90 % of the measuring time. In this case even though one of the parameters scored 'D' most of the time, category 'B' is maintained as the

final IAQ score. This can be better understood on the numerical marks recalculation:

$$IAQ_{SC} = (CO_{2SC} + O_{3SC} + VOC_{SC} + Dust_{SC} + RH_{SC}) \times W_{PARAM}. \tag{7.1}$$

$$(5+5+3+3+2) \times 0.2 = 3.6 \longrightarrow \text{rounded to: } 4 \tag{7.2}$$

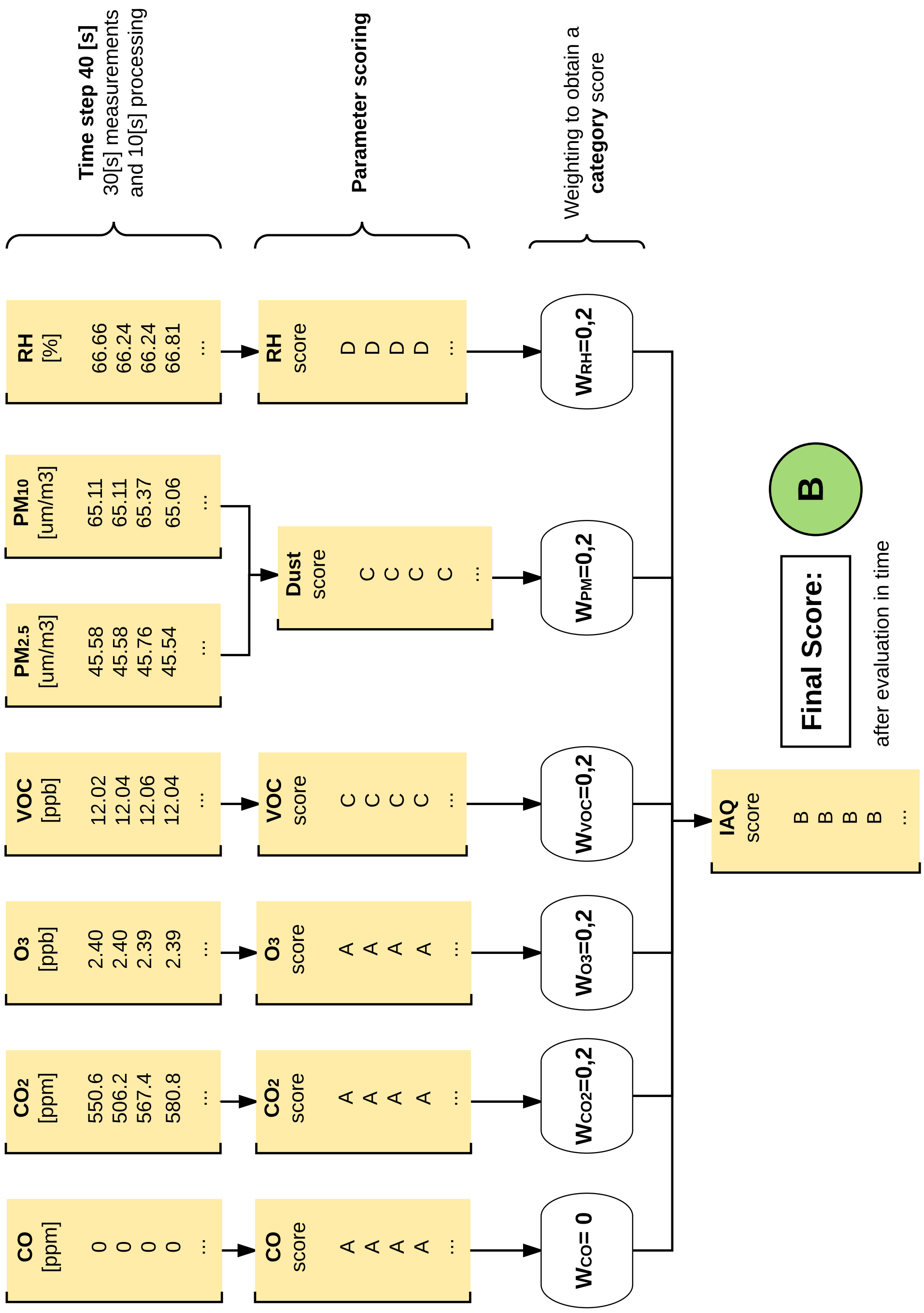

Figure 7.3: Data flow through the IAQ assessment script in Case 1.

Case 2

Figure 7.4 shows a small sample of the data treatment in Case 2. This time all parameters included in the scoring method occur in the air. Weight factors are calculated as 1/'number of sensed parameters',

where the parameters number is 6. Again, equal weights are assigned to all factors.
Final IAQ score (obtained for 90 % of the measuring time) is equal to 'C'. What is again a result of poor performance of some parameters. Final score recalculation in this case would look like:

$$IAQ_{SC} = (CO_{SC} + CO2_{SC} + O3_{SC} + VOC_{SC} + Dust_{SC} + RH_{SC}) \times W_{PARAM}. \tag{7.3}$$

$$(5+2+5+4+2+2) \times 0.16(6) = 3.3(3) \longrightarrow \text{rounded to: } 3 \tag{7.4}$$

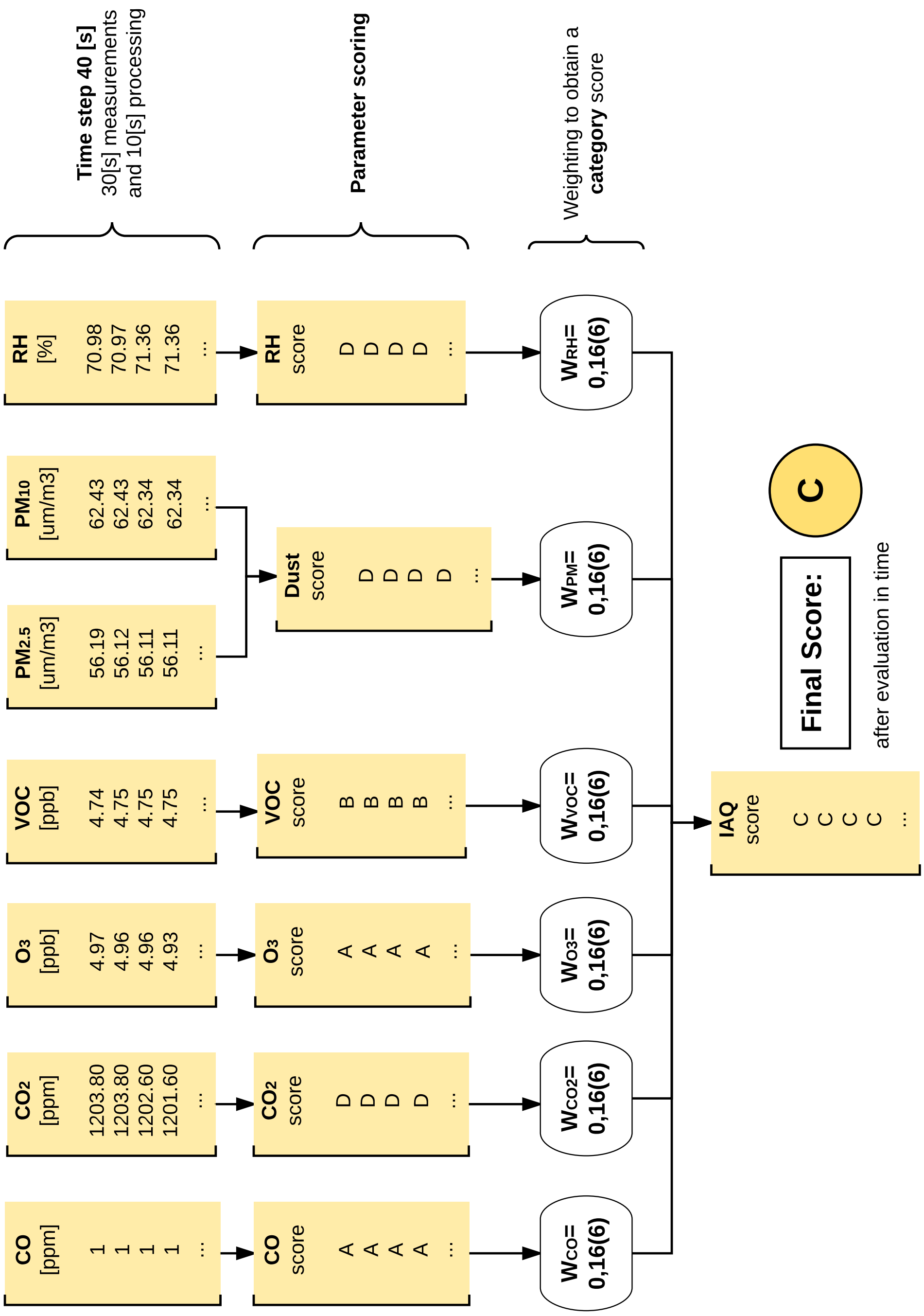

Figure 7.4: Data flow through the IAQ assessment script in Case 2.

Looking at performance of the scoring script in both cases it can be stated that the primary assumptions made while programming were accomplished. The weighting of the parameters works according to the main idea, and adjusts depending on the case. More cases have to be tested out in order to find out if there are no minor faults in the script, however, results of these tests can be treated as positive.

Acoustic

The script used for acoustic comfort scoring was described in detail in section 4.3. Testing of the script's performance is done with two different data sets. Audio file for Case 1 was recorded in rather mild background noise environment and represent the situation that is expected to score high. Case 2 should perform significantly worse as it was created from digitally amplified file in a editing software. This simple evaluation procedure aims to point out potential issues with script performance. Because at this stage evaluation scripts are not implemented to the server architecture, no remote modification of the inputs is possible. Therefore, one has to check all important inputs (explained in the script code with comments) before testing. This evaluation was made with the following inputs to the script:

- $T_A = 3600s$ - analysis time [s]
- $t_aud = 30s$ - single sample time [s]
- $C = 37dBA$ - calibration constant [dB(A)]

More details on establishing calibration constant and procedure is given in acoustic module description in section 4.3.3.

Case 1

Case 1 represent regular university background noise, it was recorded on the university corridor for one hour. As such situation is not perfect for estimation of the reverberation time it should not be considered valid for such short audio, of 1 h duration, and single spot measurement. Nevertheless, RT is given only informatively and does not affect the space quality score as it was described in Acoustic module.

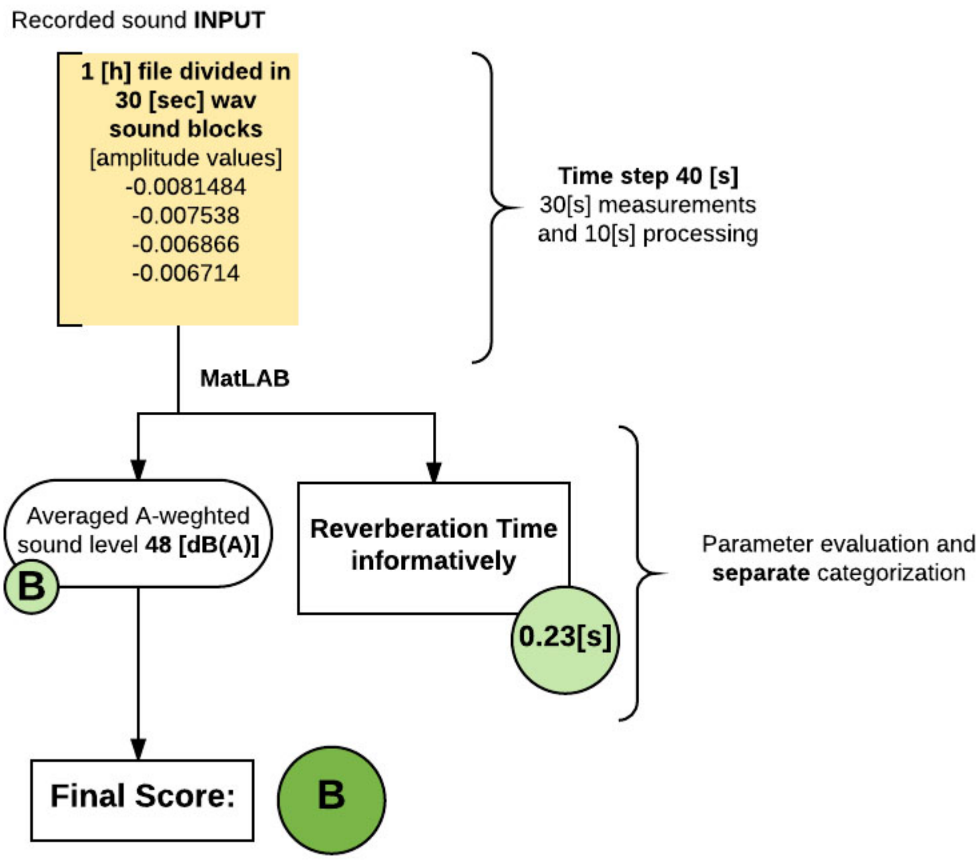

Figure 7.5: MatLAB acoustics input data and evaluation depicted - Case 1

Figure 7.5 showed that after processing, examined space resulting score was **B**. This can be interpreted as a reasonable score for a space without any loud sound event but with considerable background noise.

Case 2

Case 2 represent increased level of university background noise. As the base for creation of the 2nd case was the same audio recording it is expected that only score will change. Again recording conditions were not well-suited for estimation of the reverberation time. Thus RT is given only for troubleshooting purposes.

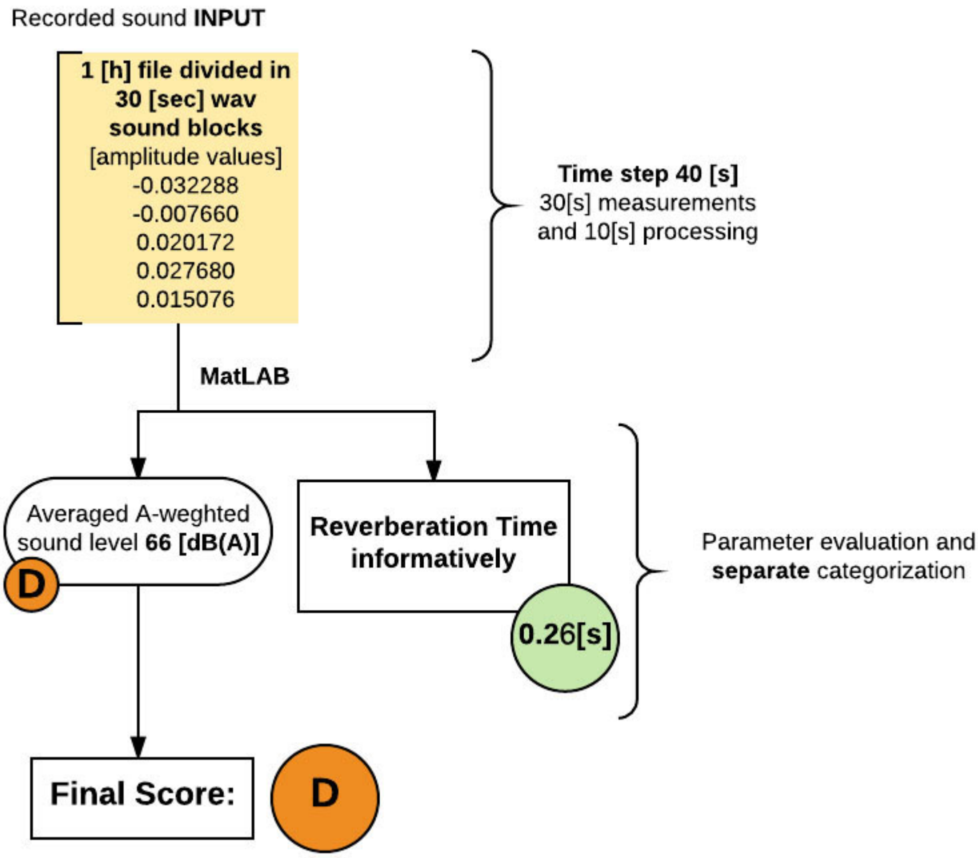

Figure 7.6: MatLAB acoustics input data and evaluation depicted - Case 2

Figure 7.6 showed that after processing, examined space resulting score was **D**. Such a poor score is a result of an excessive sound level averaged for entire recording 66 dB(A). It is worth mentioning that this score is still in the compliance range, so category weight for acoustic part will remain unaffected. Moreover we also noted that reverberation time has changed, from 0.23 s to 0.26 s. In reality that should not be the case since RT is a given value for a space. However, we consider this change minor as for recording in such a complex space as a open-space university corridor. Accuracy of RT estimation will be increased if the measurement will be prolonged and taken in several spots.

Visual

Visual script evaluation starts with reading the input data. These inputs are **three vectors** of generated illuminance values: left-hand illuminance, right-hand illuminance, and eye height level illuminance readings. These values are measured for 30 seconds and then there's a 10-second data pulling time frame, where no measured data is logged (intended resolution to for the methodology). The measuring frequency of illumination values is 1 second. The next input is a set of **photographies** taken by the ArduCAM. Five consecutive photos are taken, each with a different exposure value. Pictures are taken at beginning of the 30-second window. All the inputs are evaluated after the 30 second measuring period separately and a score is given. The further weighting depends on the specific cases, which were mentioned for all the categories in the description of the scheme. The different weighting scenarios will be presented by an example.

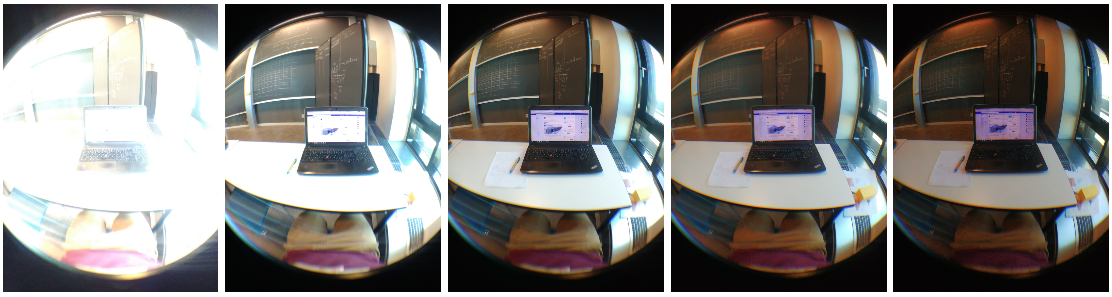

Figure 7.7: Photographies with different exposure values in case 1.

Case 1 represents a regular office work situation, where the working area is near a window, with a view outside and sunny conditions. However, the window is oriented to the north, therefore artificial lights were turned on. The situation is shown in 7.7. The illuminance data input is shown in the following graph 7.11

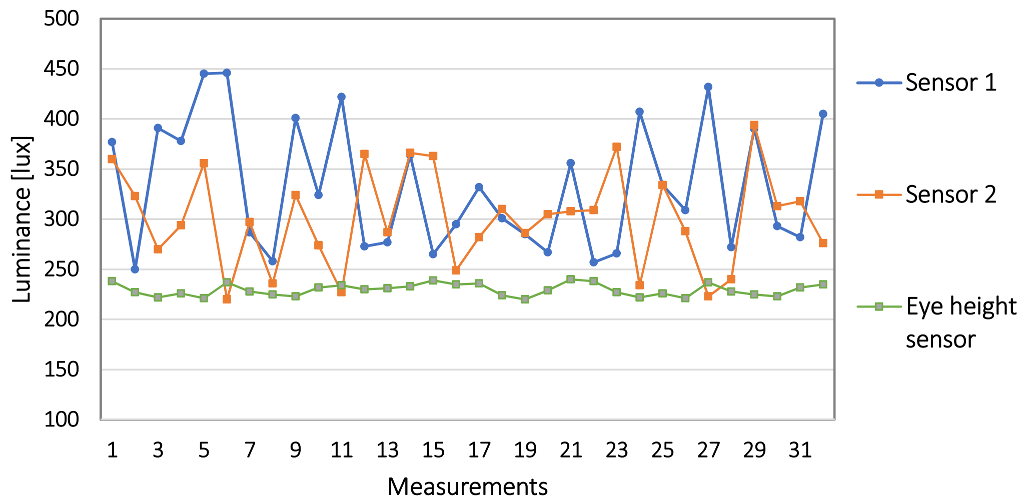

Figure 7.8: Illuminance input data in case 1.

The partial results obtained from the Matlab script are displayed as the small scores and also the corresponding values are highlighted. In this case, no indicator shows an insufficient (E) score, therefore the weighting is equal (1/3) for each of the indices. The separate scoring is the following:

1. Illuminance - 318.5 lux - B score,
2. Luminance uniformity - 1:3:10 ratio maintained - A score,
3. Glare evaluation - glare source luminance 183.5 cd/m^2 - A score,
4. Auxiliary glare - DGP score 0.327 - B score.

The final score for this case is A, therefore the highest visual comfort score. The auxiliary glare metrics shows the worse score, that might be the result of the artificially generated data.

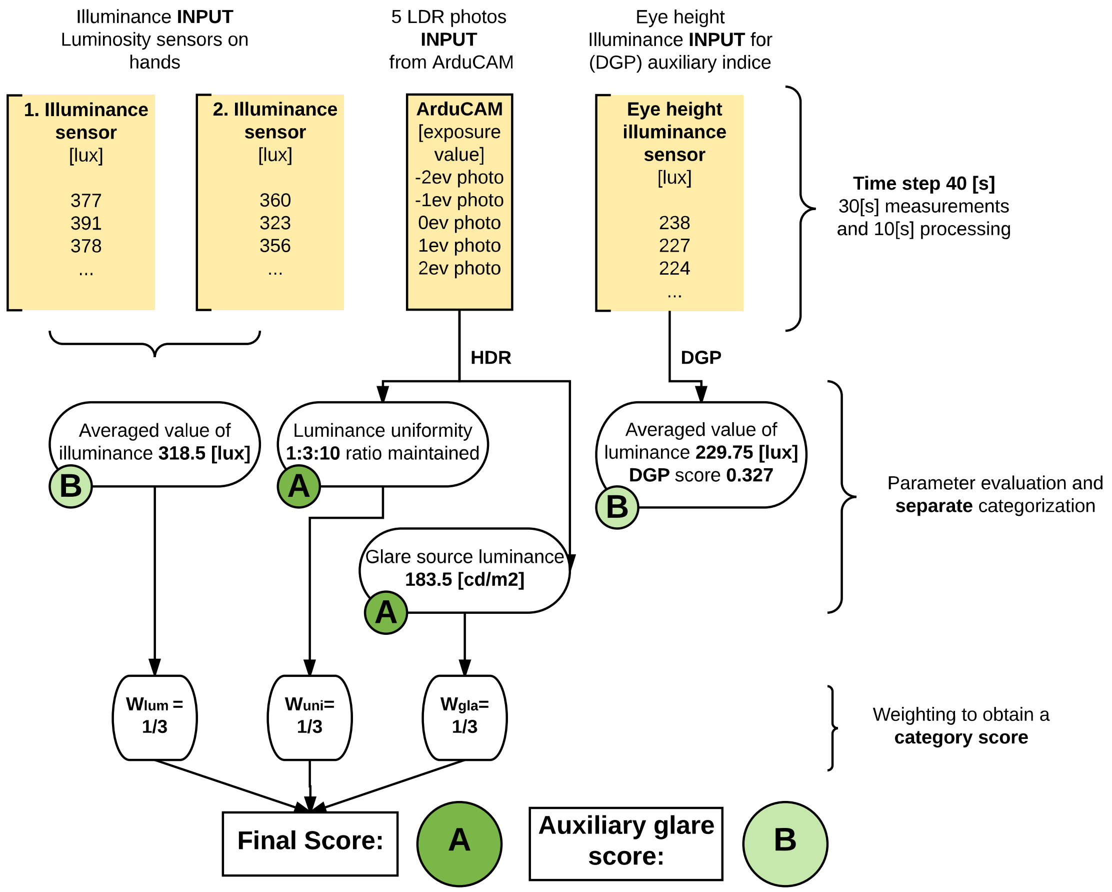

Figure 7.9: MatLAB visual category code evaluation depicted

Case 2 is an absolute extreme case. Direct sunlight, intolerable for a human being. For presenting a case that would make DGP unusable (DGP is not valid when the glare source is present in the field of view), show extreme glare, excessive illuminance and not maintained brightness ratios a case outdoors was taken.

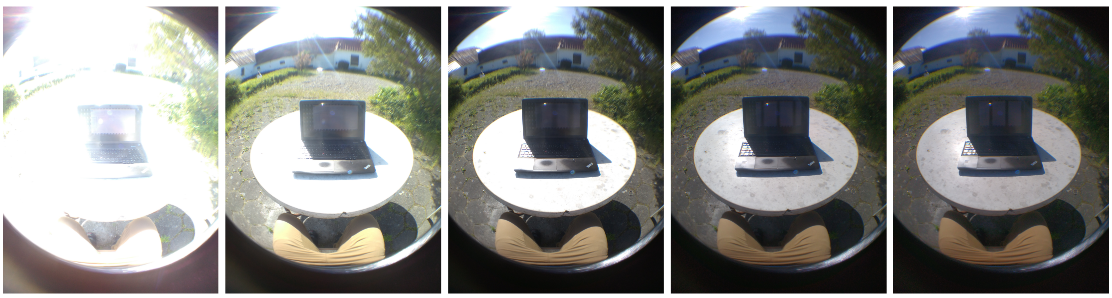

Figure 7.10: Photographies with different exposure values in case 2.

For this particular case, the Matlab code created yields as expected errors in calculating the DGP index, the glare source luminance is limited to 50 000 cd/m^2 (that is a user input).

1. Illuminance - 2102.7 lux - E score,
2. Luminance uniformity - not maintained - E score,
3. Glare evaluation - glare source luminance 50 000 cd/m^2 - E score,

(4) Auxiliary glare - DGP score Err - no score.

The overall score is E for this case. It is an absolute extreme case, trying the limits of the assessment and the results are showing some possible improvements on the script. Especially the part, where the detection of the glare source is needed and its accurate evaluation.

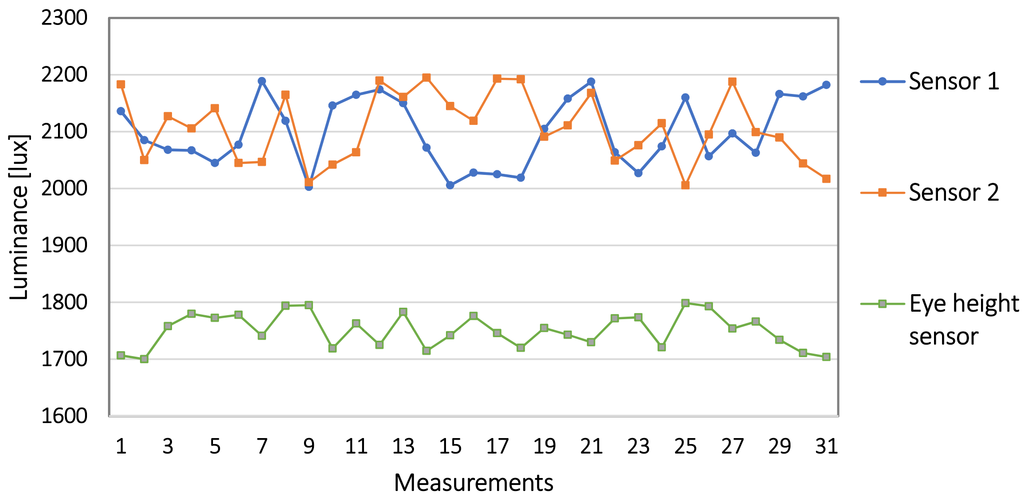

Figure 7.11: Illuminance input data in case 2.

7.2 Scoring System Outcomes

This section provides examples of recalculation of the category scores into IEQ score. Three cases are presented in order to present how the category weighting algorithm works and adjusts depending on specific scores. Chosen data sets are supposed to represent one situation with moderate environmental quality, and two situations where the IEQ is worsened gradually.

Case 1

First example is a 'moderate environment' where all parameters obtain scores within compliance limits (A-D). Figure 7.12 contains 10 first samples of the data used for testing. The numeric scores are given to better illustrate how the weighting is done.
A data sample for each module results in a vector containing a number of category scores. After all the samples in the given set are assessed, values in the score vector are checked for compliance with the 90 % of the time rule. This step yields one final score for each comfort category. Based on these values weights are assigned to categories and a final IEQ score is calculated. Before assigning a final 'letter' to the IEQ score the numerical value is rounded.
Weights assigned in this case are equal to the initial set, since no parameter scored 'E'. In this case the recalculation and weighting looks like:

$$IEQ_{SC} = IAQ_{SC} \times W_{iaq} + Thermal_{SC} \times W_t + Acoustic_{SC} \times W_n + Visual_{SC} \times W_v \tag{7.5}$$

$$3 \times 0.30 + 5 \times 0.23 + 4 \times 0.25 + 2 \times 0.22 = 3.49 \longrightarrow \text{rounded to: } 3 \tag{7.6}$$

Sample number	IAQ score	Thermal score	Acousti c score	Visual score	IEQ score	
1	3	5	4	2	3.49	C
2	3	5	5	4	4.18	B
3	3	5	5	2	3.74	B
4	3	5	5	4	4.18	B
5	3	5	5	3	3.96	B
6	3	5	5	4	4.18	B
7	3	5	4	3	3.71	B
8	3	5	4	2	3.49	C
9	3	5	5	4	4.18	B
10	3	5	4	2	3.49	C
Final scores	C	A	B	D	C	

Figure 7.12: Weighting of the category scores and resulting IEQ score for Case 1.

Case 2

Second example is also a 'moderate environment' but one of the categories obtain 'E' score. Figure 7.13 contains 10 first samples of the data used for testing.
This time the scoring script proceeds the same as in Case 1 until the moment of assigning weights to the final category scores. Since IAQ obtained 'E' score as the final result, it's importance in IEQ score is increased to 0.5. Weights of the other categories are therefore reduced. The weighting factors assigned in Case 2 are:

Wn	Wiaq	Wv	Wt
0.18	0.50	0.16	0.16

In this case the recalculation and weighting looks like:

$$IEQ_{SC} = IAQ_{SC} \times W_{iaq} + Thermal_{SC} \times W_t + Acoustic_{SC} \times W_n + Visual_{SC} \times W_v \tag{7.7}$$

$$1 \times 0.50 + 3 \times 0.16 + 4 \times 0.18 + 2 \times 0.16 = 2.98 \longrightarrow \text{rounded to: } 3 \tag{7.8}$$

Sample number	IAQ score	Thermal score	Acousti c score	Visual score	IEQ score	
1	1	5	4	4	2.66	C
2	3	4	4	2	3.26	C
3	3	3	4	3	3.25	C
4	1	5	5	2	2.53	C
5	3	5	4	3	3.71	B
6	1	5	4	4	2.66	C
7	3	4	5	3	3.73	B
8	3	3	5	2	3.28	C
9	3	5	5	5	4.40	B
10	3	3	5	5	3.94	B
Final scores	E	C	B	D	C	

Figure 7.13: Weighting of the category scores and resulting IEQ score for Case 2.

Case 3

Second example is a 'poor environment' where two categories obtain 'E' score. Figure 7.14 contains 10 first samples of the data used for testing.
This time the scoring script proceeds the same as in Case 2. Since Thermal and Visual categories both obtained 'E' score as the final result, their importance in IEQ score is increased to 0.5. Weights of the other categories are reduced to 0 in this case. The weighting factors assigned in Case 3 are:

Wn	Wiaq	Wv	Wt
0	0	0.50	0.50

In this case the recalculation and weighting looks like:

$$IEQ_{SC} = IAQ_{SC} \times W_{iaq} + Thermal_{SC} \times W_t + Acoustic_{SC} \times W_n + Visual_{SC} \times W_v \tag{7.9}$$

$$4 \times 0 + 1 \times 0.50 + 3 \times 0 + 1 \times 0.50 = 1 \tag{7.10}$$

Sample number	IAQ score	Thermal score	Acoustic score	Visual score	IEQ score	
1	5	3	3	2	3.38	C
2	4	1	3	1	1.00	E
3	5	2	3	1	2.24	D
4	4	1	4	2	2.21	D
5	5	3	4	1	2.54	C
6	5	3	4	2	3.63	B
7	5	2	3	1	2.24	D
8	4	1	5	2	2.38	D
9	5	3	4	1	2.54	C
10	4	2	5	2	3.35	C
Final scores	B	E	C	E	E	

Figure 7.14: Weighting of the category scores and resulting IEQ score for Case 3.

Tests described above show how the IEQ scoring is done depending on performance of different categories. Based on the results it can be stated that the primary goals of the scoring system were accomplished with such scoring method. More tests, especially after implementation of this method into the SU prototype are required to test the robustness of the script.

8. Summary

This chapter consists of three main parts that aim to sum up entire project work done. The entire process is briefly commented, from the beginning up to the implementation stage, in the Discussion section. Then all reflections that emerged during and after project completion are gathered in the Conclusion part. Eventually, suggestions for further project development and possible improvements are given in section Future Development

8.1 Discussion

The project topic was different at the very beginning, in the fall semester 2016. Its main aim was to develop a head with the detailed human airways model, to develop a breathing function with use of an artificial lungs. The addition of the other "senses" was just an option. Since the project was mostly concerned to develop a head and respiratory tract, it was supposed to be connected with previously introduced thermal manikin "comfortina". From that point the project plan goals became more ambitious and project aimed to achieve a manikin with all the "senses" together with the breathing possibility. Then the idea of creating a manikins torso was introduced. At that point, the aim of the project shifted the first time and the concept of the work had to be done again. As the end of the fall semester was coming, the literature review was almost finished and the most important parameters were identified. At that time we were assuming mainly the use of expensive and already calibrated measuring tools. One of the most influential concept shift came, when a small air quality measuring box was introduced to us. It was based on embedded systems with a set of cheap measuring sensors. This was the second big shift in our thesis plan. Change of the measuring principle and adoption of an absolutely different concept forced us to change some of the initially picked parameter due to the limitation of such system. As we further developed and studied the field of IoT (Internet of things), a meeting with the group of IT students was arranged. We agreed on the collaboration on the project and were expecting a boost to the process speed. With better insight into the IoT concept, the first thoughts were to create matlab scripts and have them assess the data on a cloud server. An excessive amount of time was spent on picking the right sensors, the compatible platform and the establishing data transfer principles. As the collaboration truly began, the priorities of each of the group seemed different and therefore the process took more time than was expected. Our group was focusing on the IEQ assessment scripts, and resolving data acquisition problems that were brought up by the IT students. The other group was focusing on the platform development for their project purposes. We believe, that the entire process of collaboration was beneficial for all parties as we have been sharing knowledge and solving issues together. We gained a lot of useful knowledge regarding embedded systems that can be applied in our field of study to the development of BMS systems. The other group get the idea of how to implement programming skills to solve engineering issues. However, there was a lot of space for improvement. The comprehensive prototype testing was not possible, as assembling and programming process took far more time than expected. Number of unpredictable issues arose that were hard to solve for students without prior expertise in this matter.

The goal that we set in this project was undoubtedly one of the most ambitious ones in our lives. The thesis itself was very demanding, not only regarding the set of goals, but also dealing and adapting to the changes and problems that occurred. The literature review part was very broad and in-depth. Multiple sources, big discrepancies in outcomes made us to dig deeper in search for the most credible. Focusing on minor things prolonged the reading phase, but by far made it more thorough. During the literature review and the attended meetings our ideas were changing and different plans were created multiple times. We consider this as a part of an iteration process, but it was often challenging and time consuming. The most difficult phase of the entire thesis was the manikin prototyping part. Taking into account ordering of necessary equipment, discussing project budget, coordination of number parties involved in the process, one has to be aware that a lot of time is required in a project of this depth. Further when all the necessities were gathered, the development of the measuring system and the assessing methodology were parallel processes. In real life, companies dedicate considerable budget and groups of professionals to work on such ventures. Prior experience and collaboration on mutually agreed set of goals from the beginning is required in order to succeed. Although priorities for both groups were different, maybe more emphasis should be put on everyday communication between us. That will certainly help to avoid misunderstanding and eliminate bad decisions that were made due to the unknown project status or current priorities. Towards the end of the collaboration, the implementation of the less prioritized sensors was dropped and more focus was put on server adjustment and thesis writing. The entire electronics expansion was done by a single IT student, who helped us to have most of the sensors implemented into the measuring unit. In the last working week, the manikin was almost completely finished. However, the integration of the assessment method with the server was not completed. Nevertheless, most of the sensors were showing readings on the server. Looking back at this process it is worth noticing, that such venture requires a huge amount of resources, knowledge and collaboration. Its not enough to mention technicians designing the 3D fittings during manikin customization phase, coming up with solutions for different problems, but also the IT students accomplishing tremendous work on solving all the software and hardware compatibility issues. With the help of the aforementioned people, project did a huge progress. Its further development is became attractive since its potential was being revealed at every single step, catching attention of many people.

8.2 Conclusion

The following conclusions can be drawn from entire project work done:

1. Because of the very broad project scope we expected that not all of the goals will be achieved in the required time frame. However, considering significant amount of practical things, that was accomplished, we think that project does not have many loose ends at this stage. A lot of innovative solutions were successfully implemented and proven to work. Project outcome lay the grounds for further development, and tool implementation. All areas that require refinements or further testing were pointed out and thoroughly discussed.
2. Having in mind that prototyping and thesis writing were parallel processes, it was sometimes hard to resolve *in situ* issues and keep the description constantly up to date. That is the reason why there might be slight discrepancies between description provided in the Setup chapter and work presented in Manikin Design & Assembling. In such case, the latter is valid as it documents real customization process.
3. Collaboration and coordination of many people work is considered as significant part of the project process. Although some of the tasks, mostly regarding electronics or manikin customization was outsourced, we had to coordinate entire process trying to keep successive deadlines and achieving milestones. It was nearly impossible to set up one time schedule for entire group as every party had their own duties and priorities. We believe that it could be possible to accomplish all goals in the required time span if collaboration with IT student would begin earlier.
4. Evaluation part, to the range that it was possible to conduct, proven that developed scripts, thus scoring system works. Therefore it is ready for server implementation and field testing using the manikin with the mobile app as soon as they are completed. Further section provides ideas and solutions, which, if implemented, will greatly expand and improve measuring unit performance.
5. Despite the fact that there are still some 'loose ends' of the project, we consider the accomplished work valuable. We overcame great number of challenges and issues and gain a lot of experience in previously unknown areas. Such ambitious venture gave us a very deep insight and understanding of group work with all its strengths and weaknesses. It required a lot of commitment and sense of responsibility, however, the final result seems rewarding.

At the final stage of the project the following goals were achieved:

- ☑ Create a list of important IEQ parameters
- ☑ Finding health, performance, comfort impact of selected parameters
- ☑ Development of the scoring system for IEQ assessment
- ☑ Design of the measuring unit
- ☑ Creation of measuring unit prototype

- [ ] Implementation of the scoring system to the prototype
- [ ] Prototype testing and evaluation
- [ ] Development of user friendly application

8.3 Future Development

During the prototyping and evaluation process we identified number of possible improvements that, when adopted, will increase the complexity and robustness of the IEQ assessment method even further. The following list presents our suggestions for system enhancements:

- **User guidelines** - list of actions for occupants to influence their environment quality in a positive way.
  Such list could be incorporated into the user mobile application in the form of notifications that will be prompted whenever some sensor reading will be alarming. Depending on a space indoor environmental quality, it could give the user hints of what action can be undertaken to increase the space score, thus improve user well-being, comfort or productivity.

- **Data visualization** - graphical representation of spaces performance.
  Graphical representation of data will help advanced users (i.e. building managers, janitors, technicians) to understand the users-building interplay, find out behavioral patterns that influences IEQ or find out correlation between manikin indication and building BMS system (if exists). It can improve overall building IEQ and lead to decrease of building's energy consumption simultaneously.

- **Calibration** - careful sensor calibration using precise scientific equipment under laboratory conditions.
  Usually, sensors manufacturer calibration cannot be trusted since the procedures and conditions are often unknown. Calibration based on scientific equipment will increase sensors accuracy, thus improve method credibility.

- **Measuring principle** - detailed guideline of how many measurements of what duration should be taken in order to take its outcome as representative for specific space.
  After the manikin long-time testing period, temporal and spatial resolution of the measurements should be defined to secure scoring system robustness and comparability of different zones scores.

- **Comparison to standard measuring equipment** - outcomes from the measuring unit could be compared to the readings of commonly used professional equipment.
  Manikin's senses outcomes could be compared to the commercially used measuring equipment and potential discrepancies identified and eliminated. Such comparison would show how close can a low-cost measuring unit come to the standard measuring methods.

- **Sensors** - adding more sensors or replacing the troublesome ones could enhance measuring unit performance and stability.
  Manikin functionality can be extended i.e. by occupancy detection function (PIR sensors), vibration detection (accelerometer), more advanced thermal module (more thermal nodes or complex thermoregulatory model), additional IAQ sensors (Radon, Nitrogen Dioxide). With

development of cheap micro-electronics sensors could be replaced by the ones that are more accurate and stable.

- **Dynamic inputs** - allow to specify user inputs directly from the mobile application.
  Adding flexibility to the scoring system by allowing the operator to define all important inputs (gender, met and clo values, space type etc.) without manipulating in the code. Thus, scoring system should adjust its class limits by itself to guarantee that score will correspond to the environment-occupant characteristics.

- **User responses** - adding possibility of collecting users feedback on local IEQ.
  Adding polling application on mobile device i.e. tablet built-in to the manikin's back, with encouraging interface to ask people for their feedback could create a link between measured data and users assessment. Then, weighting factors either on the parameter level or the category level can be adjusted according to the occupants or space features.

IV

Bibliography

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Books
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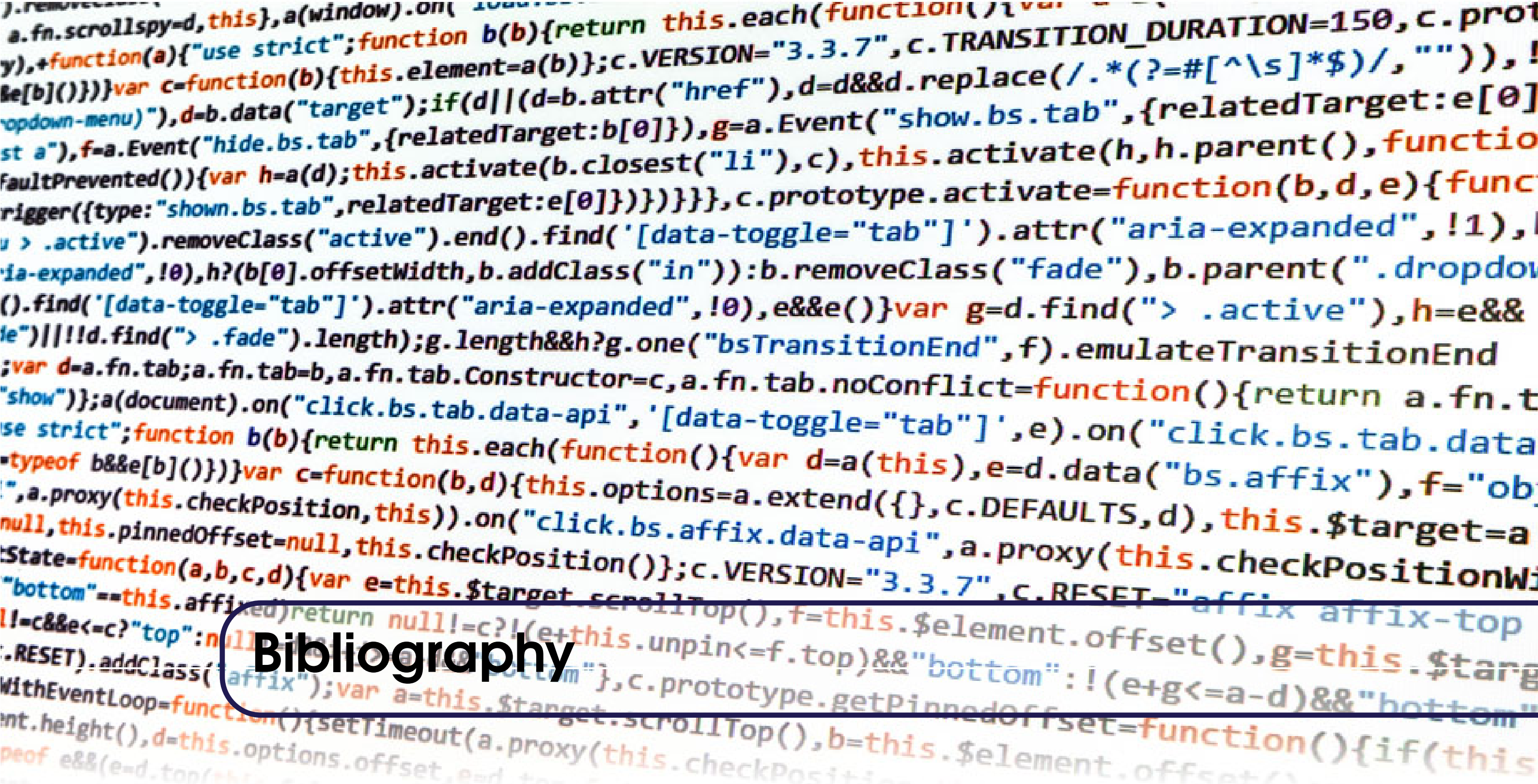
Online sources



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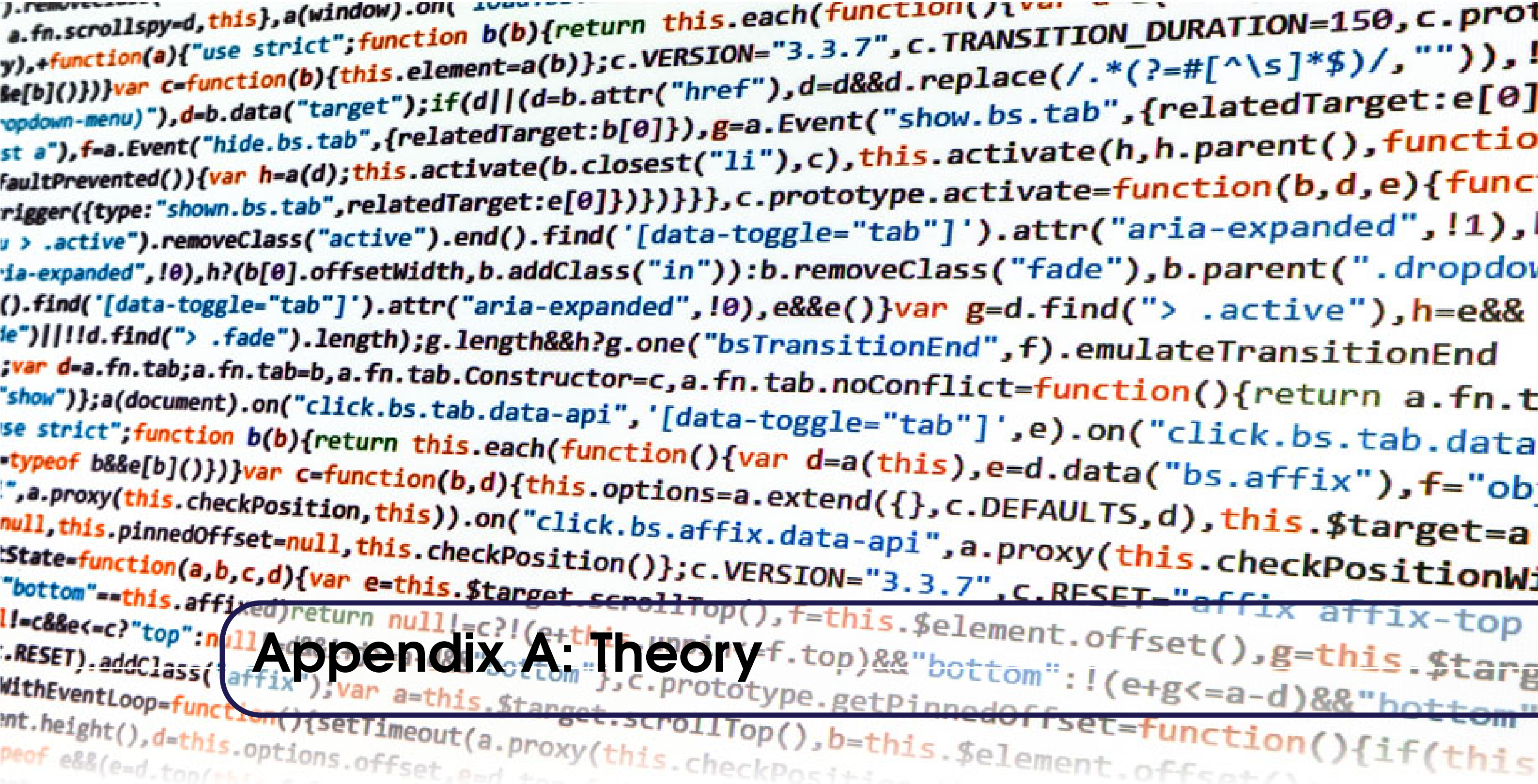
V

Appendix

8.4 Visual comfort
8.5 Lists of equipment
8.6 Equipment specifications



Appendix A: Theory

8.4 Visual comfort

Illumination equation supplementing the explanation in the visual indices chapter:

$$E_v = \frac{d\phi}{dA} \quad [lx] \tag{8.1}$$

where:
E_v is illuminance $[lm/m^2]$
ϕ is incident luminous flux $[lm]$
A is area $[m^2]$

Useful Daylight Illuminance (UDI) equation:

$$UDI = \frac{\sum wf_i \cdot t_i}{\sum t_i} \in [0,1] \begin{cases} UDI_{Overlit} & with & wf_i \begin{cases} 1 & if \quad E_{daylight} > E_{upperlimit} \\ 0 & if \quad E_{daylight} \leq E_{upperlimit} \end{cases} \\ UDI_{Useful} & with & wf_i \begin{cases} 1 & if \quad E_{lowerlimit} \leq E_{daylight} \leq E_{upperlimit} \\ 0 & if \quad E_{daylight} < E_{lowlimit} \vee E_{daylight} > E_{uplimit} \end{cases} \\ UDI_{Underlit} & with & \begin{cases} 1 & if \quad E_{daylight} < E_{lowerlimit} \\ 0 & if \quad E_{daylight} \geq E_{lowerlimit} \end{cases} \end{cases} \tag{8.2}$$

Illumination uniformity is calculated by the following formulations:

$$U_{O,average} = \frac{E_{min}}{E_{average}} \tag{8.3}$$

$$U_{O,max} = \frac{E_{min}}{E_{max}} \tag{8.4}$$

Luminance equation:

$$L_\gamma = \frac{dI_\gamma}{dA_{visible}} \qquad [nit\, or\, cd/m^2] \tag{8.5}$$

where:

γ is the angle between the normal to the emitting surface and the line joining the emitting-observation point.

Glare

British Glare Index

$$BGI = 10log_{10}\left[0,478\sum_{i=1}^{n}\left(\frac{L_{s,i}^{1,6}\cdot\omega_{s,i}^{0,8}}{L_b\cdot P_i^{1,6}}\right)\right]; \qquad \omega_s \in \langle 0;0,027\rangle\, sr \tag{8.6}$$

where:

ω_s is the solid angle between the source i from the position of the observer

P is the Guth position index depending on the position of the source i compared to the observer and expressing the perception of glare

L_{si} is the luminance in the direction connecting the observer with each source

L_b is the background luminance (for windows is the averaged luminance of the wall except the window)

CIE glare index

$$CGI = 8log_{10}\left[2\cdot\frac{1+\frac{E_d}{500}}{E_d+E_i}\right]\cdot\sum_{i=1}^{n}\left(\frac{L_{s,i}^2\cdot\omega_{s,i}}{P_i^2}\right) \tag{8.7}$$

where:

E_d is direct vertical eye illuminance

E_i diffuse light illuminance at eye level

DGI glare index

$$DGI = 10log_{10}\left[0,478\sum_{i=1}^{n}\left(\frac{L_{s,i}^{1,6}\cdot\omega_{s,i}^{0,8}}{L_b+0,07\omega^{0,5}\cdot L_{win}\cdot P_i^{1,6}}\right)\right] \tag{8.8}$$

where:

L_{win} window described by its luminance

ω solid angle subtended by each source from observer's point of view

P is the Guth position index described in equation 8.6

Modified DGI index:

$$DGI_n = 8log_{10}\left[0,25\frac{\sum_{i=1}^{n}L_{exterior,i}^2\cdot\Omega_{pN}}{L_{Adaptation}+0,07\left[\sum_{i=1}^{n}(\omega_{N,i}\cdot L_{window,i}^2)\right]^{0,5}}\right] \tag{8.9}$$

where:

Ω_{pN} is the corrected solid angle subtended by the sources from the point of observation
L_{window} is the average vertical luminance of the window
$L_a daptation$ is the average vertical luminance of the background
$L_e xterior$ is the unshielded luminance of the outdoors due to all components of daylight (direct, diffused and reflected).

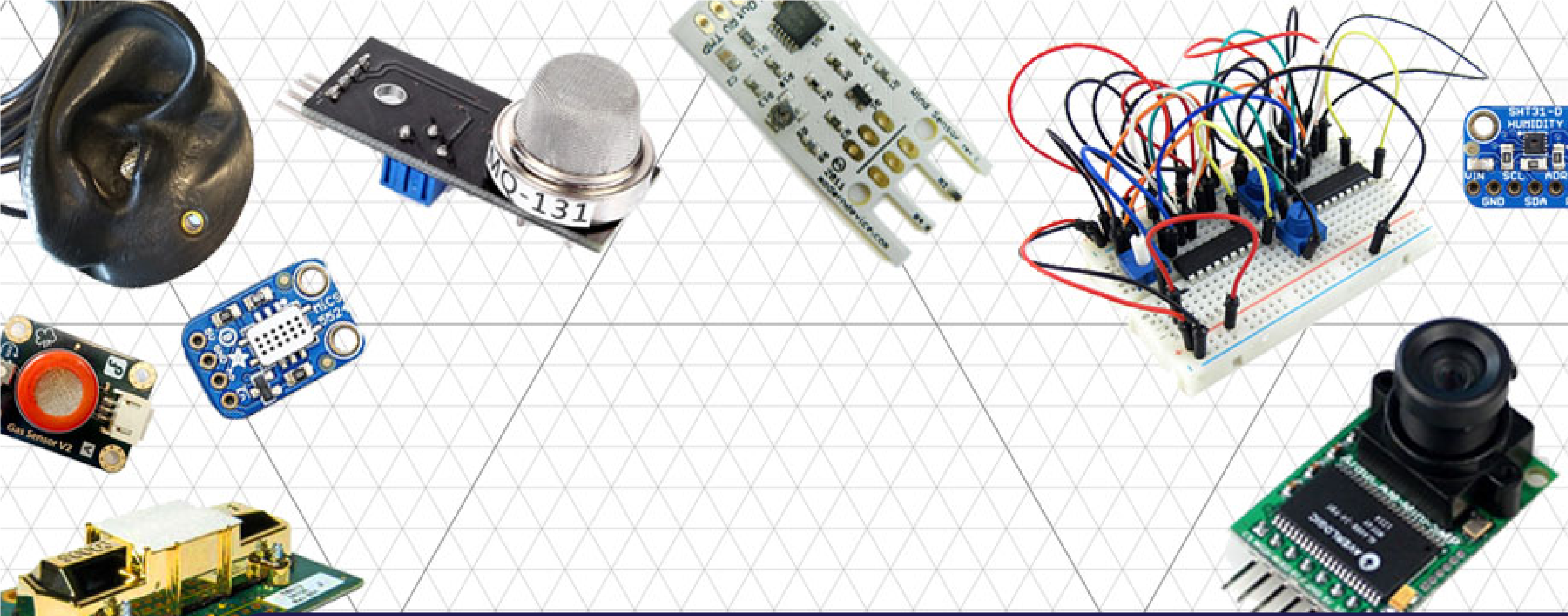
Daylight Glare Probability simplified at eye height level proposed by [1].

$$eDGPs = \underbrace{c_1 \cdot E_v}_{\text{vertical eye illuminance}} + c_2 \cdot \underbrace{log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1,87} \cdot P_i^2}\right)\right]}_{\text{computed local quantities}} + c_3 \quad (8.10)$$

The simplified DGP index, neglecting the position of the observer:

$$DGPs|_{Wienold} = 6,22 \cdot 10^{-5} \cdot E_v + 0,184 \quad (8.11)$$

[1] Hyiid et al 34



Appendix B: Equipment

8.5 Lists of equipment

This section contains tables characterizing in a nutshell all of the equipment that was obtained for needs of this thesis. Some of the parts were not used for prototyping, for list of sensors used in each measuring module see: chapter 4.

Sensor	Assessed parameters	Accuracy & info	Price (country)	VCC requirements (Protocol)
Arducam Mini Module Camera Shield 5MP + Fisheye lens	Illuminance uniformity Glare	1/4" 5 Mpx	400 DKK (UK)	ON: 5 V / 390 mA STB: 5 V / 20 mA (SPI)
Luminosity Sensor Breakout - TSL2561	Illuminance	0.1 Lux - 40 KLux	60 DKK (DK)	ON: 3.8 V / 0.24 mA (I^2C)

Table 8.1: Sensors obtained for visual module of manikin prototype.

Sensor	Assessed parameters	Accuracy & info	Price (country)	VCC requirements (Protocol)
PIR motion sensor HC-SR501	Detection of human occupancy	120 ∘ 7 m	60 DKK (DK)	ON: 4.5 to 20 V / 65 μA (DIGITAL)

Table 8.2: Other sensors obtained for manikin prototype.

Sensor	Assessed parameters	Accuracy & info	Price (country)	VCC requirements (Protocol)
CO_2 sensor MH-Z14(DE)	CO_2 concentration	Range: 0 - 5000 ppm	450 DKK (DE)	ON: 4 - 6 V Max current: 100 mA Avg current: 50 mA (Lowered range for PWM: 0 - 2000 ppm) (ANALOG)
VOC's sensor MiCS-5524	CO Ammonia Ethanol H_2 Methane/ Propane/ Iso-Butane	1 to 1000 ppm 1 to 500 ppm ~10 to 500 pp ~1 to 1000 pp ~1.000 ppm	150 DKK (FR)	ON: 5 V Heating voltage: 2.4 V Heating current: 32 mA (ANALOG)
Dust sensor SDS011	$PM_{2,5}$ PM_{10}	0.3 to 10 μm	350 DKK (PL)	ON: 5 V / 70 mA STB: 2.5 V / 1 μA (PWM)
CO sensor MQ-7	CO concentration	Range: 10 to 1000 ppr	100 DKK (DK)	ON: 5 V Preheat time over 48 h (ANALOG)
Ozone sensor MQ131	O_3 concentration	Range: 10 ppb to 2 ppm	150 DKK (IT)	ON: 5 V Preheat time over 48 h Warm-up temp. ~100 °C (ANALOG)

Table 8.3: Sensors obtained for IAQ module of manikin prototype.

Sensor	Assessed parameters	Accuracy & info	Price (country)	VCC requirements (Protocol)
Artificial ears + External sound card	Sound level Reverberation time	Frequency: 20 Hz – 22 KHz	- (AAU Acoustic Dep.)	48 V power supply phantom power (USB + ANALOG)
Microphones MEMS ADMP401	Sound level Reverberation time	Frequency: 100 Hz - 15 Kl	100 DKK (DK)	ON: 3.3 V / 250 μA (ANALOG)
Accelerometer ADXL345	Vibration	3-axis MEMS accelerometer ±16 g	180 DKK (DK)	ON: 2.5 V / 40 μA STB: 2.5 V / 1 μA (SPI or I^2C)

Table 8.4: Sensors obtained for acoustic module of manikin prototype.

Sensor	**Assessed parameters**	**Accuracy & info**	**Price (country)**	**VCC requirements (Protocol)**
Temperature and humidity sensor SHT31-D	air temperature relative air humidity	±0.3 °C ±2.0 %	150 DKK (DE)	ON: 3.0 to 5.5 V (I^2C)
Temperature sensor DS18B20 + gray globe	globe temperature	Range: -55 to 125 °C ±0.5 °C	40 DKK (DK)	ON: 3.0 to 5.5 V (DIGITAL)
Thermo – anemometer (hot wire) MD0550 rev.C	air velocity	Range: 0 to 25 m/s	250 DKK (UK)	ON: 4 to 10 V / 20 to 40 mA (ANALOG)

Table 8.5: Sensors obtained for thermal module of manikin prototype.

8.6 Equipment specifications

This section contains most relevant pages from data sheets of equipment that was actually used for the prototype of the manikin. Specifications of items that were bought but were not included in the prototype are not presented in the report. Those data sheets can be found in the archive ("Spec") attached to this thesis.

Arducam

OmniVision **5M Pixels CMOS OV5642 CAMERA MODULE**

2 Features

- ultra high performance
- automatic image control functions: automatic exposure control (AEC), automatic white balance (AWB), automatic band filter (ABF), automatic 50/60 Hz luminance detection, and automatic black level calibration (ABLC)
- programmable controls for frame rate, AEC/AGC 16-zone size/position/weight control, mirror and flip, scaling, cropping, windowing, and panning
- image quality controls: color saturation, hue, gamma, sharpness (edge enhancement), lens correction, defective pixel canceling, and noise canceling
- support for output formats: RAW RGB, RGB565/555/444, CCIR656, YUV422/420, YCbCr422, and compression
- support for images sizes: 5 megapixel, and any arbitrary size scaling down from 5 megapixel
- embedded TrueFocus™ light, enabling extended depth of field (EDoF)
- support for auto focus control (AFC)
- support for video or snapshot operations
- support for horizontal and vertical sub-sampling
- support for binning
- support for data compression output
- support for anti-shake
- support for external frame synchronization in frame exposure mode
- support for LED and flash strobe mode
- standard serial SCCB interface
- digital video port (DVP) parallel output interface
- MIPI serial input and output interface
- support for second camera chip-sharing ISP and MIPI interface
- embedded microcontroller
- embedded one-time programmable (OTP) memory for part identification, etc.
- on-chip phase lock loop (PLL)
- programmable I/O drive capability
- support for mechanical shutter, ND filter and IRIS control
- built-in 1.5V regulator for core

3 Key Specifications

- **active array size:** 2592 x 1944
- **power supply:**
  core: 1.5VDC ± 5% (internal regulator)
  analog: 2.6 ~ 3.0V
  I/O: 1.7 ~ 3.0V
- **power requirements:**
  active: TBD
  standby: TBD
- **temperature range:**
  operating: -30°C to 70°C (see table 8-1)
  stable image: 0°C to 50°C (see table 8-1)
- **output formats (8-bit):** YUV(422/420) / YCbCr422, RGB565/555/444, CCIR656, 8-bit compression data, 8/10-bit raw RGB data
- **lens size:** 1/4"
- **lens chief ray angle:** 24° non-linear (see table 10-1)
- **input clock frequency:** 6 ~ 27 MHz
- **shutter:** rolling shutter
- **maximum image transfer rate:**
  5 megapixel (2592x1944): 15 fps
  (and any size scaling down from 5 megapixel)
  1080p (1920x1080): 30 fps
  720p (1280x720): 60 fps
  VGA (640x480): 60 fps
  QVGA (320x240): 120 fps
- **sensitivity:** TBD
- **S/N ratio:** TBD
- **dynamic range:** TBD
- **scan mode:** progressive
- **maximum exposure interval:** 1968 x t_{ROW}
- **gamma correction:** programmable
- **pixel size:** 1.4 µm x 1.4 µm
- **well capacity:** TBD
- **dark current:** TBD
- **fixed pattern noise (FPN):** TBD
- **image area:** 3673.6 µm x 2738.4 µm
- **package dimensions:** 6945 µm x 6695 µm

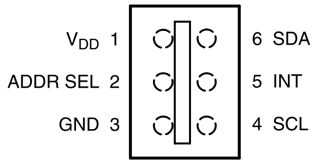
TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

TSL2560, TSL2561 LIGHT-TO-DIGITAL CONVERTER

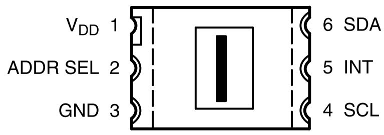
TAOS059N – MARCH 2009

- **Approximates Human Eye Response**
- **Programmable Interrupt Function with User-Defined Upper and Lower Threshold Settings**
- **16-Bit Digital Output with SMBus (TSL2560) at 100 kHz or I²C (TSL2561) Fast-Mode at 400 kHz**
- **Programmable Analog Gain and Integration Time Supporting 1,000,000-to-1 Dynamic Range**
- **Automatically Rejects 50/60-Hz Lighting Ripple**
- **Low Active Power (0.75 mW Typical) with Power Down Mode**
- **RoHS Compliant**

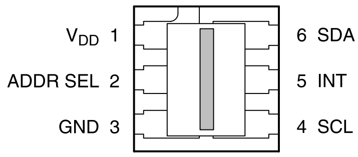
PACKAGE CS
6-LEAD CHIPSCALE
(TOP VIEW)



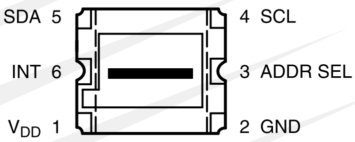
PACKAGE T
6-LEAD TMB
(TOP VIEW)



PACKAGE FN
DUAL FLAT NO-LEAD
(TOP VIEW)



PACKAGE CL
6-LEAD ChipLED
(TOP VIEW)



Package Drawings are Not to Scale

Description

The TSL2560 and TSL2561 are light-to-digital converters that transform light intensity to a digital signal output capable of direct I²C (TSL2561) or SMBus (TSL2560) interface. Each device combines one broadband photodiode (visible plus infrared) and one infrared-responding photodiode on a single CMOS integrated circuit capable of providing a near-photopic response over an effective 20-bit dynamic range (16-bit resolution). Two integrating ADCs convert the photodiode currents to a digital output that represents the irradiance measured on each channel. This digital output can be input to a microprocessor where illuminance (ambient light level) in lux is derived using an empirical formula to approximate the human eye response. The TSL2560 device permits an SMB-Alert style interrupt, and the TSL2561 device supports a traditional level style interrupt that remains asserted until the firmware clears it.

While useful for general purpose light sensing applications, the TSL2560/61 devices are designed particularly for display panels (LCD, OLED, etc.) with the purpose of extending battery life and providing optimum viewing in diverse lighting conditions. Display panel backlighting, which can account for up to 30 to 40 percent of total platform power, can be automatically managed. Both devices are also ideal for controlling keyboard illumination based upon ambient lighting conditions. Illuminance information can further be used to manage exposure control in digital cameras. The TSL2560/61 devices are ideal in notebook/tablet PCs, LCD monitors, flat-panel televisions, cell phones, and digital cameras. In addition, other applications include street light control, security lighting, sunlight harvesting, machine vision, and automotive instrumentation clusters.

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Texas Advanced Optoelectronic Solutions Inc.
1001 Klein Road • Suite 300 • Plano, TX 75074 • (972) 673-0759
www.taosinc.com

G.R.A.S. microphones

G.R.A.S. 40AD 1/2" Prepolarized Pressure Microphone, High Sensitivity

Freq range: 3.15 Hz to 10 kHz
Dyn range: 16 dB(A) to 148 dB
Sensitivity: 50 mV/Pa

The 40AD is an IEC 61094 WS2P ½" prepolarized pressure microphone with rear-venting. The externally polarized equivalent is G.R.A.S. 40AP

Specifications

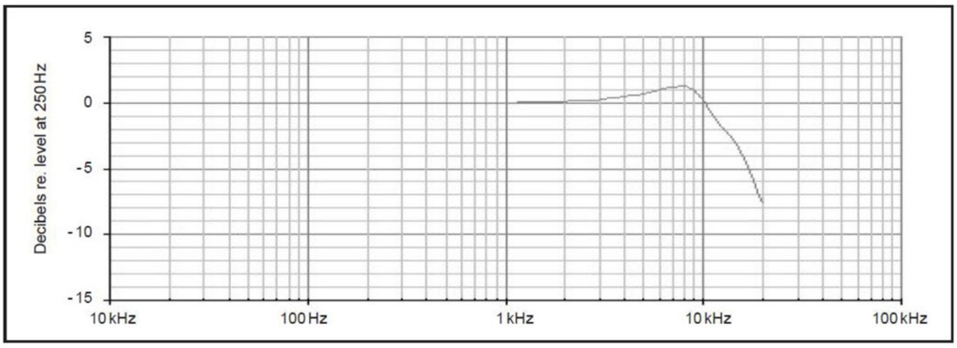
Frequency range (±1 dB)	Hz	12.5 to 7.5 k
Frequency range (±2 dB)	Hz	3.15 to 10 k
Dynamic range lower limit (microphone thermal noise)	dB(A)	16
Dynamic range lower limit with G.R.A.S. preamplifier	dB(A)	18
Dynamic range upper limit	dB	148
Dynamic range upper limit with G.R.A.S. preamplifier @ +28 V / ±14 V power supply	dB	142
Dynamic range upper limit with G.R.A.S. preamplifier @ +120 V / ±60 V power supply	dB	148
Dynamic range upper limit with G.R.A.S. CCP preamplifier	dB	138
Open-circuit sensitivity @ 250 Hz (±2 dB)	mV/Pa	50
Open-circuit sensitivity @ 250 Hz (±2 dB)	dB re 1V/Pa	-26
Resonance frequency	kHz	14
Microphone cartridge capacitance, typ.	pF	20
Microphone venting		Rear
Temperature range, operation	°C / °F	-40 to 120 / -40 to 248

G.R.A.S.
SOUND & VIBRATION

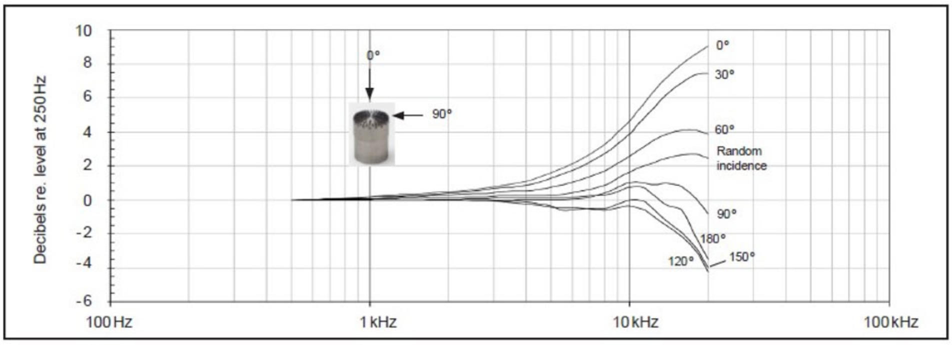
G.R.A.S. 40AD 1/2" Prepolarized Pressure Microphone, High Sensitivity
Date 18-03-2017.

Temperature range, storage	°C / °F	-40 to 85 / -40 to 185
Temperature coefficient @250 Hz	dB/°C / dB/°F	-0.01 / -0.006
Static pressure coefficient @250 Hz	dB/kPa	-0,014
Humidity range non condensing	% RH	0 to 100
Humidity coefficient @250 Hz	dB/% RH	0,001
Influence of axial vibration @1 m/s²	dB re 20 µPa	62
CE/RoHS compliant/WEEE registered		Yes / Yes, Yes
Weight	g / oz	9 / 0,317

G.R.A.S. Sound & Vibration reserves the right to change specifications without notice.



Typical frequency response



Free-field corrections for different angles of incidence

G.R.A.S.
SOUND & VIBRATION

Headquarters Skovlytoften 33 • DK-2840 Holte • Denmark • Tel: +45 45 66 40 46 • Fax: +45 45 66 40 47 • E-mail: gras@gras.dk • www.gras.dk

Sound card

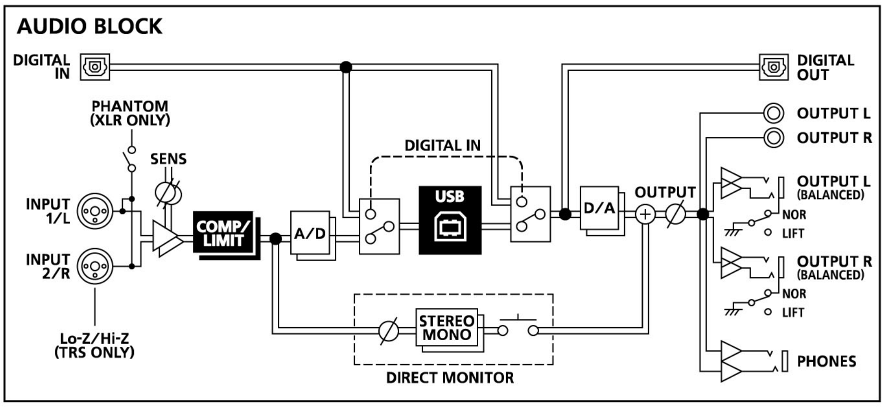
EDIROL by Roland

USB AudioCapture UA-25EX

24 bit 96 kHz

Owner's Manual

Before using this unit, carefully read the sections entitled: "USING THE UNIT SAFELY" and "IMPORTANT NOTES" (p. 2; p. 4). These sections provide important information concerning the proper operation of the unit. Additionally, in order to feel assured that you have gained a good grasp of every feature provided by your new unit, Owner's manual should be read in its entirety. The manual should be saved and kept on hand as a convenient reference.



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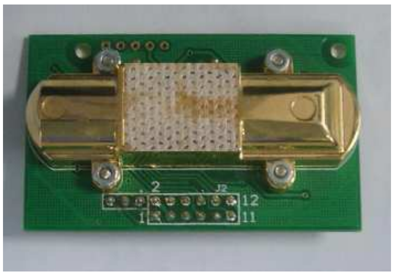
Carbon dioxide sensor

MH-Z14 CO2 Module

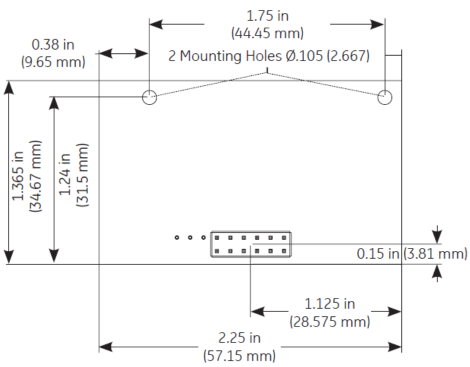


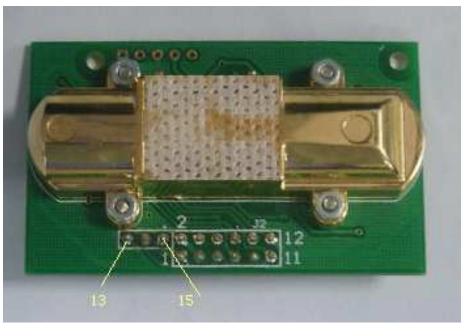
MH-Z14 NDIR Infrared gas module is a common type, small size sensor, using non-dispersive infrared (NDIR) principle to detect the existence of CO_2 in the air, with good selectivity, non-oxygen dependant, long life. Built-in temperature sensor can do temperature compensation; and it has digital output and analog voltage output. MH-Z14 NDIR Infrared gas module is applied in the HVAC, indoor air quality monitoring, industrial process, safety and protection monitoring, agricultrue and animal husbandry production process monitoring.

1. Technical specification:

Detection range	0～10000ppm（optional）
Resolution ratio	5ppm（0～2000ppm）
	10ppm（2000～5000ppm）
	20ppm（5000～10000ppm）
Accuracy	±50ppm±5%
Repeatability	±30ppm
Responsible time	<30S
Warm-up time	3min
Working temprature	0～50℃
Working humidity	0%～90%RH（No condensation）
Storage temprature	-20～60℃
Working voltage	4～6V
Working current	Max current <100mA，Average current <50mA
Usingage	>5year

2. Structure Dimension Chart





3. Signal output

Signal output：analog voltage output, PWM wave output, UART output.

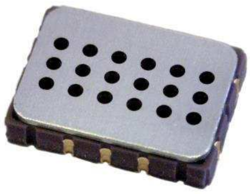
VOC sensor

Data Sheet | **MiCS-5524**
1084 rev 6

SGX SENSORTECH

The MiCS-5524 is a compact MOS sensor.

The MiCS-5524 is a robust MEMS sensor for indoor carbon monoxide and natural gas leakage detection; suitable also for indoor air quality monitoring; breath checker and early fire detection.

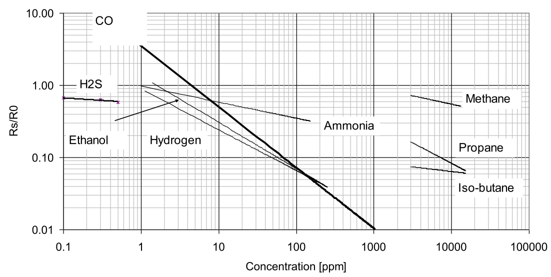


Features

- Smallest footprint for compact designs (5 x 7 x 1.55 mm)
- Robust MEMS sensor for harsh environments
- High-volume manufacturing for low-cost applications
- Short lead-times

Detectable gases

• Carbon monoxide	CO	1 – 1000ppm
• Ethanol	C_2H_6OH	10 – 500ppm
• Hydrogen	H_2	1 – 1000ppm
• Ammonia	NH_3	1 – 500ppm
• Methane	CH_4	>1000ppm



Continuous power ON, 25°C, 50% RH

For more information please contact:

info.em@sgxsensortech.com

SGX Sensortech, Courtils 1
CH-2035 Corcelles-Cormondrèche
Switzerland

www.sgxsensortech.com

5.Certification: products have passed CE/FCC/RoHS certification.

Scope of application

Detector of PM2.5;Purifier.

Working principle

Using laser scattering principle:

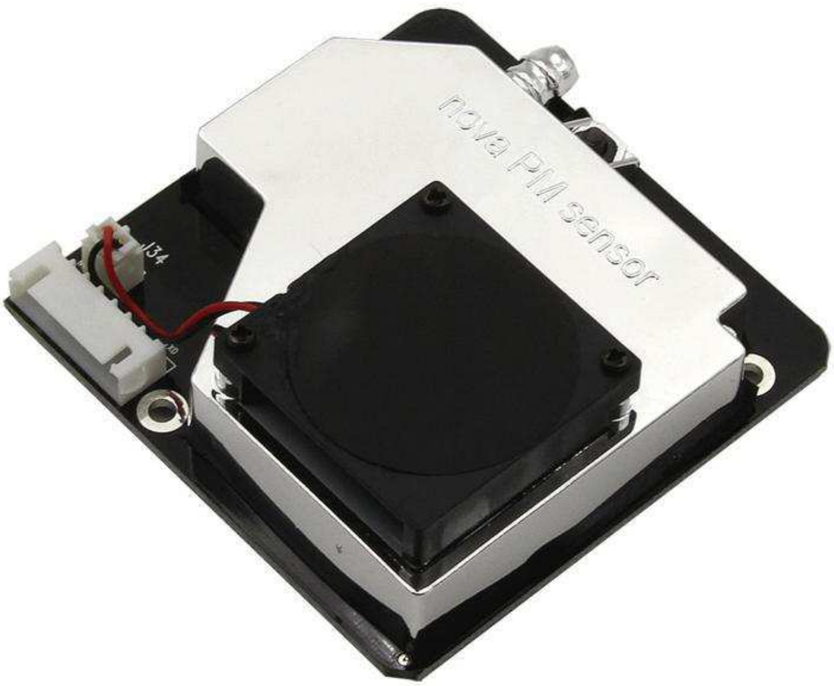
Light scattering can be induced when particles go through the detecting area. The scattered light is transformed into electrical signals and these signals will be amplified and processed. The number and diameter of particles can be obtained by analysis because the signal waveform has certain relations with the particles diameter.

Technical Parameters

No	Item	Parameter	Note
1	Measurement parameters	PM2.5,PM10	
2	Range	0.0-999.9 μg /m^3	
3	Rated voltage	5V	
4	Rated current	70mA±10mA	
5	Sleep current	<4 mA	Lase&Fan sleep
6	Temperature range	Storage environment：-20～+60℃	

Overview

The SDS011 using principle of laser scattering,can get the particle concentration between 0.3 to 10μm in the air. It with digital output and built-in fan is stable and reliable.



Characteristics

1. Accurate and Reliable: laser detection, stable, good consistency;

2. Quick response: response time is less than 10 seconds when the scene changes;

3. Easy integration: UART output (or IO output can be customized), fan built-in;

4. High resolution: resolution of 0.3 μ g/m^3;

		Work environment：-10～+50℃	
7	Humidity range	Storage environment：Max 90%	
		Work environment：Max 70%	
8	Air pressure	86KPa~110KPa	
9	Corresponding time	1s	
10	Serial data output frequency	1Hz	
11	Minimum resolution of particle	0.3 μm	
12	Counting yield	70%@0.3μm 98%@0.5μm	
13	Relative error	Maximum of ±15% and ±10μg/m³	25℃, 50%RH
14	Product size	71x70x23mm	
15	Certification	CE/FCC/RoHS	

Power requirement

Power Voltage：4.7~5.3V

Power supply：>1W

Supply voltage ripple：<20mV

Carbon monoxide sensor

Henan Hanwei Electronics Co., Ltd www.hwsensor.com

MQ-7 Semiconductor Sensor for Carbon Monoxide

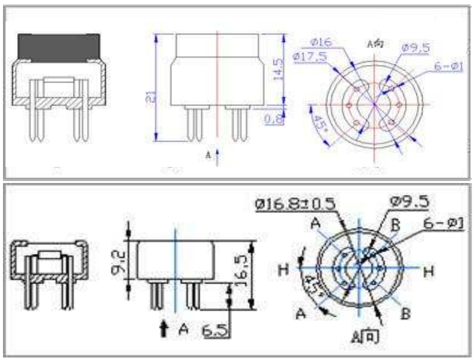
Sensitive material of MQ-7 gas sensor is SnO_2, which with lower conductivity in clean air. It make detection by method of cycle high and low temperature, and detect CO when low temperature (heated by 1.5V). The sensor's conductivity is more higher along with the gas concentration rising. When high temperature (heated by 5.0V), it cleans the other gases adsorbed under low temperature. Please use simple electrocircuit, Convert change of conductivity to correspond output signal of gas concentration.

MQ-7 gas sensor has high sensitity to Carbon Monoxide. The sensor could be used to detect different gases contains CO, it is with low cost and suitable for different application.

Character

*Good sensitivity to Combustible gas in wide range
* High sensitivity to Natural gas
* Long life and low cost
* Simple drive circuit

Configuration



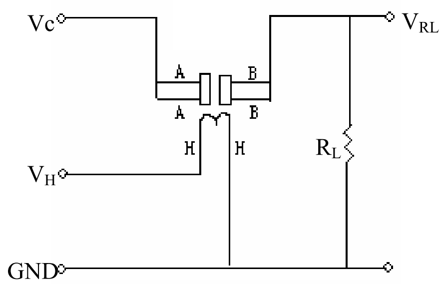
Application

* Domestic gas leakage detector
* Industrial CO detector
* Portable gas detector

Technical Data

Model No.			MQ-7
Sensor Type			Semiconductor
Standard Encapsulation			Plastic
Detection Gas			Carbon Monoxide
Concentration			10-10000ppm CO
Circuit	Loop Voltage	V_c	≤10V DC
	Heater Voltage	V_H	5.0V±0.2V ACorDC（High） 1.5V±0.1V ACorDC（Low）
	Heater Time	T_L	60±1S（High）90±1S（Low）
	Load Resistance	R_L	Adjustable
Character	Heater Resistance	R_H	31Ω±3Ω（Room Tem.）
	Heater consumption	P_H	≤350mW
	Sensing Resistance	R_s	2KΩ-20KΩ(in 100ppm CO)
	Sensitivity	S	Rs(in air)/Rs(100ppm CO)≥5
	Slope	α	≤0.6 (R_{300ppm}/R_{100ppm} CO)
Condition	Tem. Humidity		20℃±2℃；65%±5%RH
	Standard test circuit		Vc:5.0V±0.1V; V_H (High): 5.0V±0.1V; V_H (Low): 1.5V±0.1V
	Preheat time		Over 48 hours

Basic test loop



The above is basic test circuit of the sensor. The sensor need to be put 2 voltage, heater voltage（VH） and test voltage（VC）. VH used to supply certified working temperature to the sensor, while VC used to detect voltage (VRL) on load resistance （RL） whom is in series with sensor. The sensor has light polarity, Vc need DC power. VC and VH could use same power circuit with precondition to assure performance of sensor. In order to make the sensor with better performance, suitable RL value is needed:

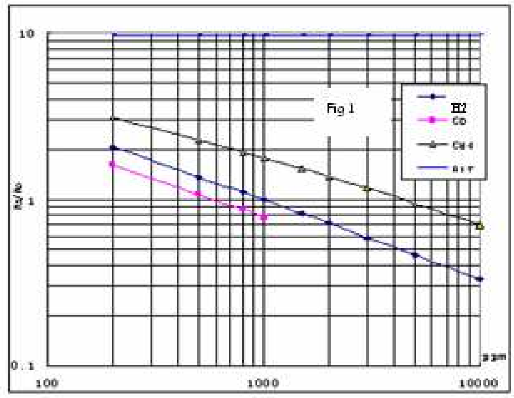
Power of Sensitivity body(Ps):

$Ps=Vc^2\times Rs/(Rs+RL)^2$

Tel: 86-371-67169070/80 Fax: 86-371-67169070 Email: sales@hwsensor.com

Resistance of sensor(Rs): Rs=(Vc/VRL-1)×RL

Sensitivity Characteristics



Influence of Temperature/Humidity

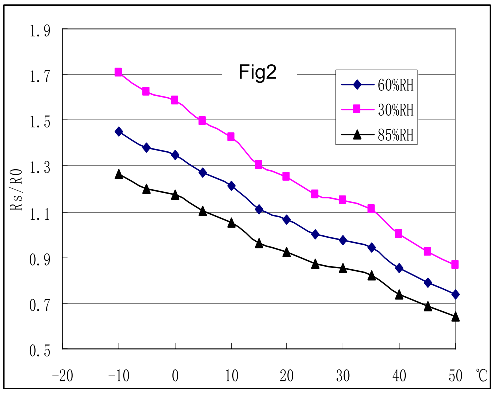
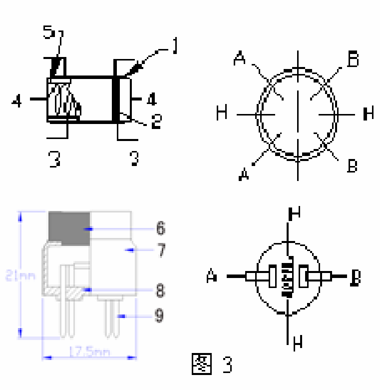


Fig.1 shows the typical sensitivity characteristics of the MQ-7, ordinate means resistance ratio of the sensor (Rs/Ro), abscissa is concentration of gases. Rs means resistance in different gases, Ro means resistance of sensor in 1000ppm Hydrogen. All test are under standard test conditions.

Fig.2 shows the typical temperature and humidity characteristics. Ordinate means resistance ratio of the sensor (Rs/Ro), Rs means resistance of sensor in 100ppm CO under different tem. and humidity. Ro means resistance of the sensor in environment of 100ppm CO, 20℃/65%RH

Structure and configuration

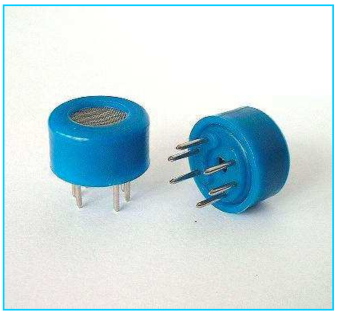


	Parts	Materials
1	Gas sensing layer	Sno2
2	Electrode	Au
3	Electrode line	Pt
4	Heater coil	Ni-Cr alloy
5	Tutlar ceramic	Al2O3
6	Filter	Active Carbon
7	Clamp ring	Ni-Cu
8	Resin Base	Bakelte
9	Tube Pin	Ni-Cu

Structure and configuration of MQ-7 gas sensor is shown as Fig. 3, sensor composed by micro AL2O3 ceramic tube, Tin Dioxide (SnO2) sensitive layer, measuring electrode and heater are fixed into a crust made by plastic and stainless steel net. The heater provides necessary work conditions for work of sensitive components. The enveloped MQ-7 have 6 pin, 4 of them are used to fetch signals, and other 2 are used for providing heating current.

Ozone sensor

TECHNICAL DATA MQ-131 GAS SENSOR



FEATURES

Fast response and High sensitivity
Stable and long life
Simple drive circuit
Wide detecting range

APPLICATION

They are used in air quality control equipments for buildings/offices, are suitable for detecting Of O_3 .

SPECIFICATIONS

A. Standard work condition

Symbol	Parameter name	Technical condition	Remarks
Vc	Circuit voltage	5V±0.1	AC or DC
V_H	Heating voltage	6V±0.1	AC or DC
R_L	Load resistance	Variable	
R_H	Heater resistance	31Ω±5%	Room Tem
P_H	Heating consumption	Less than 1100mw	

B. Environment condition

Symbol	Parameter name	Technical condition	Remarks
Tao	Using Tem	-10□-50□	
Tas	Storage Tem	-20□-70□	
R_H	Related humidity	Less than 95%RH	

C. Sensitivity characteristic

Symbol	Parameter name	Technical parameter	Remark 2
Rs	Sensing Resistance	100KΩ-200KΩ (50ppb O_3)	Detecting concentration scope□ 10ppb-2ppm O_3
α O_3 (100ppb/50ppb)	Concentration Slope rate	≤0.65	
Standard Detecting Condition	Temp: 20□±2□ Vc:5V±0.1 Humidity: 65%±5% Vh: 6V±0.1		
Preheat time	Over 24 hour		

D. Structure and configuration, basic measuring circuit

	Parts	Materials
1	Gas sensing layer	SnO_2
2	Electrode	Au
3	Electrode line	Pt
4	Heater coil	Ni-Cr alloy
5	Tubular ceramic	Al_2O_3
6	Anti-explosion network	Stainless steel gauze (SUS316 100-mesh)
7	Clamp ring	Copper plating Ni
8	Resin base	Bakelite
9	Tube Pin	Copper plating Ni

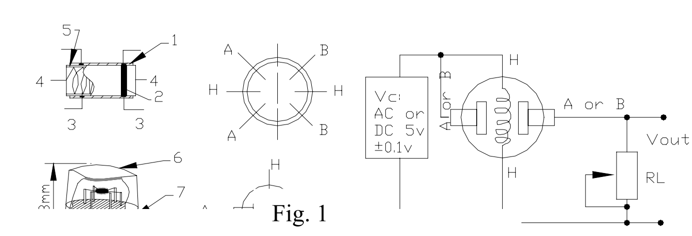
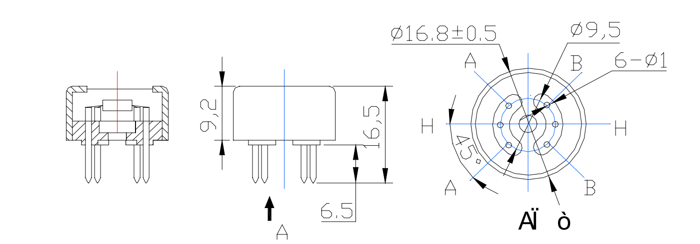


Fig. 1



Structure and configuration of MQ-131 gas sensor is shown as Fig.1, sensor composed by micro AL2O3 ceramic tube, Metal-oxide semiconductor sensitive layer, measuring electrode and heater are fixed into a crust made by nylon and stainless steel net. The heater provides necessary work conditions for work of sensitive components. The enveloped MQ-131 have 6 pin ,4 of them are used to fetch signals, and other 2 are used for providing heating current.

Electric parameter measurement circuit is shown as above Fig.1.

E. Sensitivity characteristic curve

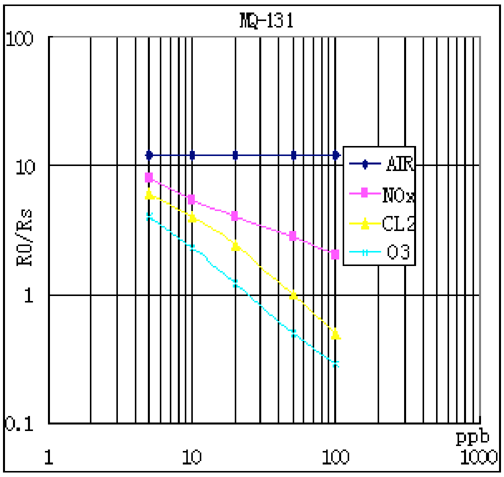


Fig.3 sensitivity characteristics of the MQ-131

Fig.3 is shows the typical sensitivity characteristics of the MQ-131 for several gases.
in their: Temp: 20℃
Humidity: 65%
O_2 concentration 21%
RL=20kΩ
Ro: sensor resistance in the clean air.
Rs: sensor resistance at various concentrations of gases.

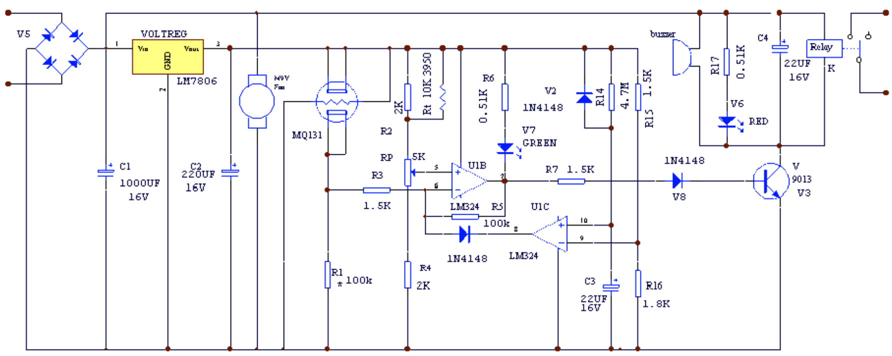
APPLICATION

Resistance value of MQ-131 is difference to various kinds and various

Concentration gases. When using this components, sensitivity adjustment is very necessary. we recommend that you calibrate the detector for 50ppb O_3 in air and use value of Load resistance that(R_L) about 100 KΩ(50KΩ to 200 KΩ). When accurately measuring, the proper alarm point for the gas detector should be determined after considering the temperature and humidity influence.

Noting: there are a round hole in the up and down side of the sensors, this design enable the sensor inner gas to exchange better with outside air, and the sensor shall has higher sensitivity, quicker response and resume time with a fan .

REFERENCE APPLICATION CIRCUIT:



Teperature & humidity sensor: initial choice

Datasheet SHT3x-DIS

SENSIRION THE SENSOR COMPANY

1 Sensor Performance

1.1 Humidity Sensor Performance

Parameter	Conditions	Value	Units
SHT30 Accuracy tolerance[1]	Typ.	±3	%RH
	Max.	Figure 2	%RH
SHT31 Accuracy tolerance[1]	Typ.	±2	%RH
	Max.	Figure 4	%RH
Repeatability[2]	Low	0.2	%RH
	Medium	0.15	%RH
	High	0.07	%RH
Resolution	Typ.	0.01	%RH
Hysteresis	at 25°C	±0.8	%RH
Specified range[3]	extended[4]	0 to 100	%RH
Response time[5]	$\tau_{63\%}$	8[6]	s
Long-term drift	Typ.[7]	<0.25	%RH/yr

Table 1 Humidity sensor specification

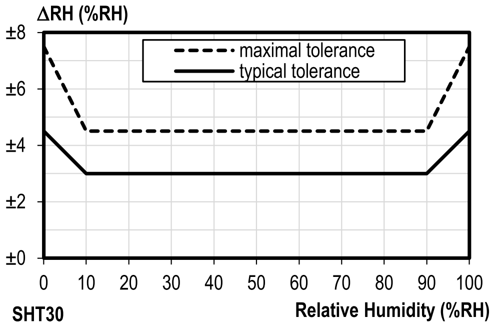


Figure 2 Tolerance of RH at 25°C for SHT30

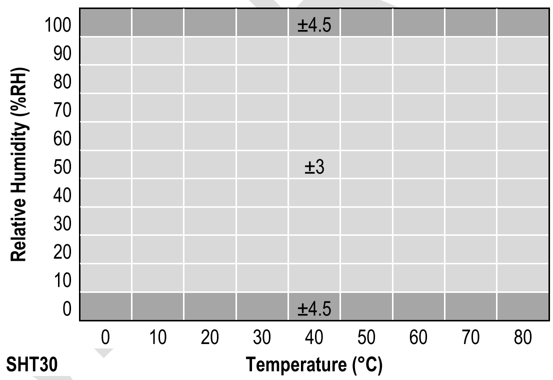


Figure 3 Typical tolerance of RH over T for SHT30

PRELIMINARY

[1] For definition of typical and maximum accuracy tolerance, please refer to the document "Sensirion Humidity Sensor Specification Statement".
[2] The stated repeatability is 3 times the standard deviation (3σ) of multiple consecutive measurements at the stated repeatability and at constant ambient conditions. It is a measure for the noise on the physical sensor output.
[3] Specified range refers to the range for which the humidity or temperature sensor specification is guaranteed.
[4] For details about recommended humidity and temperature operating range, please refer to section 1.3.
[5] Time for achieving 63% of a humidity step function, valid at 25°C and 1m/s airflow. Humidity response time in the application depends on the design-in of the sensor.
[6] With activated ART function (see section 4.7) the response time can be improved by a factor of 2.
[7] Typical value for operation in normal RH/T operating range, see section 1.3. Maximum value is < 0.5 %RH/yr. Value may be higher in environments with vaporized solvents, out-gassing tapes, adhesives, packaging materials, etc. For more details please refer to Handling Instructions.

1.2 Temperature Sensor Performance

Parameter	Condition	Value	Units
Accuracy tolerance[1]	Typ. 10 to +55	±0.3	°C
Repeatability[2]	Low	0.16	°C
	Medium	0.07	°C
	High	0.04	°C
Resolution	Typ.	0.015	°C
Specified Range	-	-40 to 125	°C
Response time [8]	$\tau_{63\%}$	>2	s
Long Term Drift	max	<0.03	°C/yr

Table 2 Temperature sensor specification

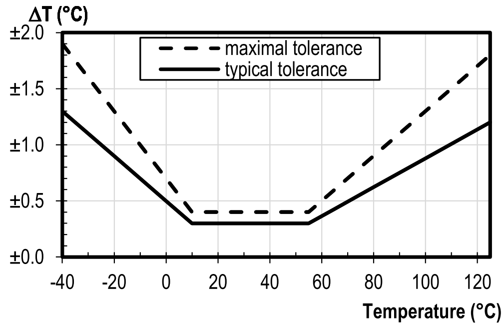


Figure 6 Tolerance of the temperature sensor in °C for SHT30 and SHT31

1.3 Recommended Operating Condition

The sensor shows best performance when operated within recommended normal temperature and humidity range of 5 – 60 °C and 20 – 80 %RH, respectively. Long term exposure to conditions outside normal range, especially at high humidity, may temporarily offset the RH signal (e.g.+3%RH after 60h at >80%RH). After returning into the normal temperature and humidity range the sensor will slowly come back to calibration state by itself. Prolonged exposure to extreme conditions may accelerate ageing. To ensure stable operation of the humidity sensor, the conditions described in the document "SHTxx Assembly of SMD Packages", section "Storage and Handling Instructions" regarding exposure to volatile organic compounds have to be met. Please note as well that this does apply not only to transportation and manufacturing, but also to operation of the SHT3x-DIS.

PRELIMINARY

[8] Temperature response times strongly depends on the design-in of the sensor in the final application. Minimal response time can be achieved when the thermalized sensor at T1 is placed on a well conducting surface with temperature T2.

Teperature & humidity sensor: IT students choice

SILICON LABS

Si7021-A20

I^2C HUMIDITY AND TEMPERATURE SENSOR

Features

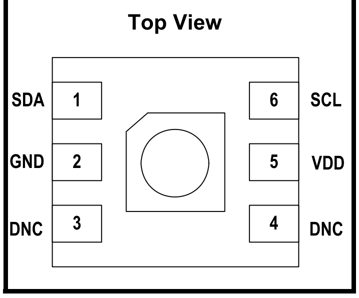
- Precision Relative Humidity Sensor
  - ± 3% RH (max), 0–80% RH
- High Accuracy Temperature Sensor
  - ±0.4 °C (max), –10 to 85 °C
- 0 to 100% RH operating range
- Up to –40 to +125 °C operating range
- Wide operating voltage (1.9 to 3.6 V)
- Low Power Consumption
  - 150 µA active current
  - 60 nA standby current
- Factory-calibrated
- I^2C Interface
- Integrated on-chip heater
- 3x3 mm DFN Package
- Excellent long term stability
- Optional factory-installed cover
  - Low-profile
  - Protection during reflow
  - Excludes liquids and particulates

Ordering Information:
See page 29.

Applications

- HVAC/R
- Thermostats/humidistats
- Respiratory therapy
- White goods
- Indoor weather stations
- Micro-environments/data centers
- Automotive climate control and defogging
- Asset and goods tracking
- Mobile phones and tablets

Pin Assignments



Patent Protected. Patents pending

Description

The Si7021 I^2C Humidity and Temperature Sensor is a monolithic CMOS IC integrating humidity and temperature sensor elements, an analog-to-digital converter, signal processing, calibration data, and an I^2C Interface. The patented use of industry-standard, low-K polymeric dielectrics for sensing humidity enables the construction of low-power, monolithic CMOS Sensor ICs with low drift and hysteresis, and excellent long term stability.

The humidity and temperature sensors are factory-calibrated and the calibration data is stored in the on-chip non-volatile memory. This ensures that the sensors are fully interchangeable, with no recalibration or software changes required.

The Si7021 is available in a 3x3 mm DFN package and is reflow solderable. It can be used as a hardware- and software-compatible drop-in upgrade for existing RH/ temperature sensors in 3x3 mm DFN-6 packages, featuring precision sensing over a wider range and lower power consumption. The optional factory-installed cover offers a low profile, convenient means of protecting the sensor during assembly (e.g., reflow soldering) and throughout the life of the product, excluding liquids (hydrophobic/oleophobic) and particulates.

The Si7021 offers an accurate, low-power, factory-calibrated digital solution ideal for measuring humidity, dew-point, and temperature, in applications ranging from HVAC/R and asset tracking to industrial and consumer platforms.

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Temperature sensor

DS18B20

Programmable Resolution
1-Wire Digital Thermometer

Absolute Maximum Ratings

Voltage Range on Any Pin Relative to Ground ....-0.5V to +6.0V
Operating Temperature Range .... -55°C to +125°C
Storage Temperature Range .... -55°C to +125°C
Solder Temperature ....Refer to the IPC/JEDEC J-STD-020 Specification.

These are stress ratings only and functional operation of the device at these or any other conditions above those indicated in the operation sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods of time may affect reliability.

DC Electrical Characteristics

(-55°C to +125°C; V_{DD} = 3.0V to 5.5V)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Supply Voltage	V_{DD}	Local power (Note 1)		+3.0		+5.5	V
Pullup Supply Voltage	V_{PU}	Parasite power	(Notes 1, 2)	+3.0		+5.5	V
		Local power		+3.0		V_{DD}	
Thermometer Error	t_{ERR}	-10°C to +85°C	(Note 3)			±0.5	°C
		-55°C to +125°C				±2	
Input Logic-Low	V_{IL}	(Notes 1, 4, 5)		-0.3		+0.8	V
Input Logic-High	V_{IH}	Local power	(Notes 1,6)	+2.2		The lower of 5.5 or V_{DD} + 0.3	V
		Parasite power		+3.0			
Sink Current	I_L	$V_{I/O}$ = 0.4V		4.0			mA
Standby Current	I_{DDS}	(Notes 7, 8)			750	1000	nA
Active Current	I_{DD}	V_{DD} = 5V (Note 9)			1	1.5	mA
DQ Input Current	I_{DQ}	(Note 10)			5		µA
Drift		(Note 11)			±0.2		°C

Note 1: All voltages are referenced to ground.
Note 2: The Pullup Supply Voltage specification assumes that the pullup device is ideal, and therefore the high level of the pullup is equal to V_{PU}. In order to meet the V_{IH} spec of the DS18B20, the actual supply rail for the strong pullup transistor must include margin for the voltage drop across the transistor when it is turned on; thus: $V_{PU\_ACTUAL} = V_{PU\_IDEAL} + V_{TRANSISTOR}$.
Note 3: See typical performance curve in Figure 1.
Note 4: Logic-low voltages are specified at a sink current of 4mA.
Note 5: To guarantee a presence pulse under low voltage parasite power conditions, V_{ILMAX} may have to be reduced to as low as 0.5V.
Note 6: Logic-high voltages are specified at a source current of 1mA.
Note 7: Standby current specified up to +70°C. Standby current typically is 3µA at +125°C.
Note 8: To minimize I_{DDS}, DQ should be within the following ranges: GND ≤ DQ ≤ GND + 0.3V or V_{DD} – 0.3V ≤ DQ ≤ V_{DD}.
Note 9: Active current refers to supply current during active temperature conversions or EEPROM writes.
Note 10: DQ line is high ("high-Z" state).
Note 11: Drift data is based on a 1000-hour stress test at +125°C with V_{DD} = 5.5V.