Master Thesis

Master's degree in Industrial Engineering (MUEI)

Key Indicators for a Sustainable Building within Hilti

REPORT

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Statutory Declaration in Lieu of an Oath

I hereby certify that I have done this work independently and without the use of any aids other than those specified. All parts which are taken literally or analogously from published and not published writings of others are marked as such. The work has not yet been submitted in the same or similar form as an examination paper.

Schaan, 19th of January 2022

ETSEIB

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Abstract

Hilti is one of the world's leaders in power tools, accessories, and services for the construction industry. It may not seem obvious, but the global share of buildings and construction industry energy demand ascends to 36% of all the global energy production, which makes it the sector with the highest energy consumption rate worldwide. It is worth mentioning that having this significant energy demand leads the building sector to a direct and indirect carbon footprint of 37% of all CO_2 yearly global emissions [1]. Hence, it has become a focus of interest for Hilti's corporate sustainability strategy to aim for more sustainable buildings within the organization's assets.

This study aims to define a set of Sustainability Performance Indicators (SPIs), for a better assessment of Hilti's building portfolio, which will help to understand better what would be a sustainable building within Hilti and to define feasible targets from the selected SPIs thresholds aiming for a better implementation of improvement measures.

In this thesis, a theoretical framework about Hilti's sustainability strategy is introduced with an emphasis on the sustainability in buildings, current state problems are exposed, and research questions are presented. A methodology is followed to obtain a meaningful and impactful set of sustainability performance indicators, which will be then clustered, analyzed, and prioritized by relevance, feasibility, measurability, and area of application among others.

The findings of the project will provide guidelines to help focus the attention on the most relevant areas of interest to improve existing facilities or to assist the construction of new sustainable facilities.

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ACA: Adaptive Control Algorithm

AHP: Analytical Hierarchy Process

AQG: Air Quality Guidelines

B2B: Business to Business

BIM: Building Information Modelling

BREEAM: Building Research Establishment's Environmental Assessment Method

C2C: Cradle to Cradle

DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen

FAHP: Fuzzy Analytical Hierarchy Process

GBCs: Green Building Certifications

GBRS: Green Building Rating Systems

GHG: Green House Gases

HAG: Hilti Aktiengesellschaft or Hilti AG

HVAC: Heating, Ventilation, and Air Conditioning

IAQ: Indoor Air Quality

IEP: Indoor Environmental Parameters

IEQ: Indoor Environmental Quality

IWBI: International WELL Building Institute

KSU: *Hilti's* Corporate sustainability Department

LEED: Leadership in Energy and Environmental Design

MCDM: Multi-Criteria Decision-Making

NDC: Nationally Determined Contributions

NOB: North Office Building

PMV: Predicted Mean Vote

PPD: Predicted Percentage of Dissatisfied

RCP: Representative Concentration Pathway

SBS: Sick Building Syndrome

SDGs: Sustainable Development Goals

SPI: Sustainability Performance Indicator

SSP: Shared Socioeconomic Pathways

TC: Thermal Comfort

TVOC: Total Volatile Organic Compounds

USGBC: United States Green Building Council

VOC: Volatile Organic Compounds

WGBC: World Green Building Council

WHO: World Health Organization

1. Preface

1.1. Motivation

The topic for this master thesis was raised during my internship period with the Corporate Sustainability department at Hilti. This master thesis presents the highlight of a fascinating and challenging project which would help develop sustainable buildings within Hilti and possibly its customers.

During my time with the Corporate Sustainability team, I was involved in a project to provide a holistic statement that would include all types of facilities and Hilti's assets for a better understanding of what is a sustainable building. This study aims to provide the work and results achieved while answering the main research questions and adhering to Hilti's corporate strategy regarding sustainability.

1.2. Problem Statement

It has been proven by the scientific community during the last decades that climate change is a fact, and it is raising awareness not only from individuals but also from policymakers and especially from large companies, such as Hilti.

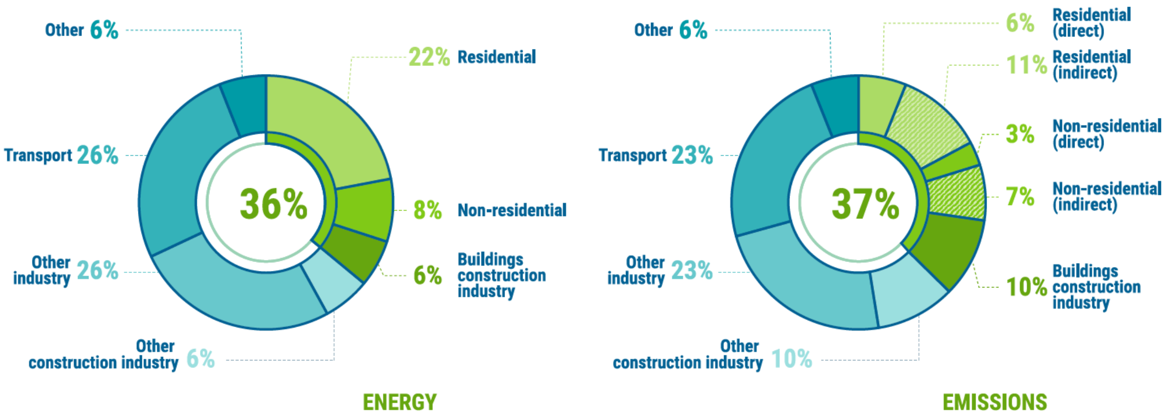


Figure 1.2.1: Global share of buildings and construction final energy and emissions, 2020 [1]

As stated in the last 2021 global status report for buildings and construction, all buildings and the building construction industry (Building's construction industry is the estimated portion of overall industry devoted to manufacturing building construction materials such as steel, cement, and glass around the world consume up to the 36% of energy production worldwide and produce 37% of indirect emissions from power generation and commercial heating). For this reason, it has been decided within Hilti that actions should be taken to become a more sustainable corporation especially being a market leader in the construction sector [1].

1.3. Previous requirements

One of the main requirements to carry out this thesis is to gain a better understanding of how a sustainable building can be certified as such and gain a better knowledge of all the sustainable building certifications available nowadays. Thanks to a collaboration between the KSU department and Lenum AG, a consultancy company specialized in bringing sustainability to buildings as a part of their core business, I have been able to leverage the knowledge and background from the synergy of these two groups of talented and experienced professionals by their workshops and cross-collaboration events.

2. Introduction

2.1. Objectives and scope of the project

This thesis mainly focuses on the process of establishing a foundation of various sustainability performance indicators within Hilti to have a better overview of the company's current status regarding sustainability within its facilities. This framework will help assess these facilities in the imminent future and will give guidelines to the company as to what should be optimized or improved and in what facilities or locations. However, providing a generic statement will be challenging, as those SPIs could vary along with Hilti's diverse type of facilities and their different locations worldwide.

The thesis at hand starts with a theoretical framework to remark the significance of sustainability in different sectors, more notably in construction, to help tackle climate change and its side effects. Once the basic concepts are defined in this first part, the second part of the thesis introduces the different types of labels available nowadays for certifying sustainable buildings, analyzing the most relevant criterion of these labels to assess buildings. The aim is to select SPIs that will help steer Hilti into a more sustainable way of managing and constructing buildings. The results expected are a selection of SPIs, out of which a deeper analysis will be performed on the most impactful ones to implement changes along Hilti's facilities.

2.2. Research Questions

As mentioned before, this master thesis aims to provide a better understanding of how to implement a theoretical framework to assess Hilti's facilities and to provide a good overview of the company's current status, answering these driving questions:

RQ1. What is the definition of a sustainable building within Hilti's assets?

(a) What performance indicators can be used to measure it?

(b) How can it be tracked?

RQ2. How to make it scalable within the Hilti Group?

3. Fundamentals and research background

In this chapter, the reader is introduced to the construction industry and more in detail to Hilti, a Liechtenstein multinational company that develops and manufactures products for the construction industry. The understanding of how the industry deals with the current situation regarding sustainability and climate crisis is imperative to better define Hilti's corporate strategy and willingness to become an active player in the topic. Because of this, this chapter will give a profound overview addressing important details that enhance common understanding for upcoming parts of the thesis.

3.1. Overview of the company

As mentioned before, Hilti is a Liechtenstein multinational company that develops, manufactures, and markets products for the construction, building maintenance, manufacturing, and energy industry, especially for professional end-users. The company was founded in 1941 in Schaan, Liechtenstein, by brothers Eugen and Martin Hilti. All company shares are in the possession of the Martin Hilti Family Trust, which ensures the long-term continuity of the Hilti family values by sustainably creating value through market leadership and differentiation [2].

With a workforce of 30.000 employees present in 120 countries around the world, Hilti is present in all the key markets in the world. Hilti is defined as a sales-driven company, as roughly 2/3 of its employees are dedicated to sales or engaging with the customer. This fact leads to 250.000 individual customer contacts each day, which is why ideas for improvement are often developed directly on construction sites while talking to customers and making Hilti market leader in certain products and services provided to the customer [2]. Hilti's products and services can be clustered by the following business areas:

- Anchor Systems
- Measuring Systems
- Power Tools and Accessories
- Tool Services
- Direct Fastening & Screw Fastening
- Fastening & Protection Solutions
- Firestop Systems
- Installations Systems
- Diamond Systems

3.2. Sustainable Development Goals (SDGs)

Nowadays, any ongoing initiative regarding sustainability or future upcoming initiative is linked to the Sustainable Development Goals (SDGs), which were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people will be able to enjoy peace and prosperity.

It is a system of 17 SDGs that are integrated and correlated amongst each other's, as acting in one area will affect the outcome in another area, and the overall development of all areas must balance social, economic, and environmental sustainability [3].

Figure 3.2.1 : Overview of the Sustainable Development Goals System [3]

It has been more than a year since the global pandemic first hit. The social and economic toll has been unprecedented, but recovery efforts have been insufficient to get our society back into achieving sustainable development. This global pandemic crisis is threatening years of development progresses, delaying the urgent transition to a greener, more inclusive economies, and throwing SDG's development gains even further off track.

This is one of the reasons why from big companies such as Hilti, there has been a strong call for action to help drive this sustainable development, not only as active players but also as role models for their employees, partners, and customers.

3.3. Hilti's Sustainability Corporate Strategy

To provide a better definition of Hilti's sustainability strategy, it was needed to identify what were the issues that were material to the Hilti Group. That is why a materiality analysis was performed on many potentially relevant topics, which came from initiatives such as the UN Global Compact, the already mentioned SDGs, various studies, and the survey and analysis of responses from both internal and external experts and stakeholders.

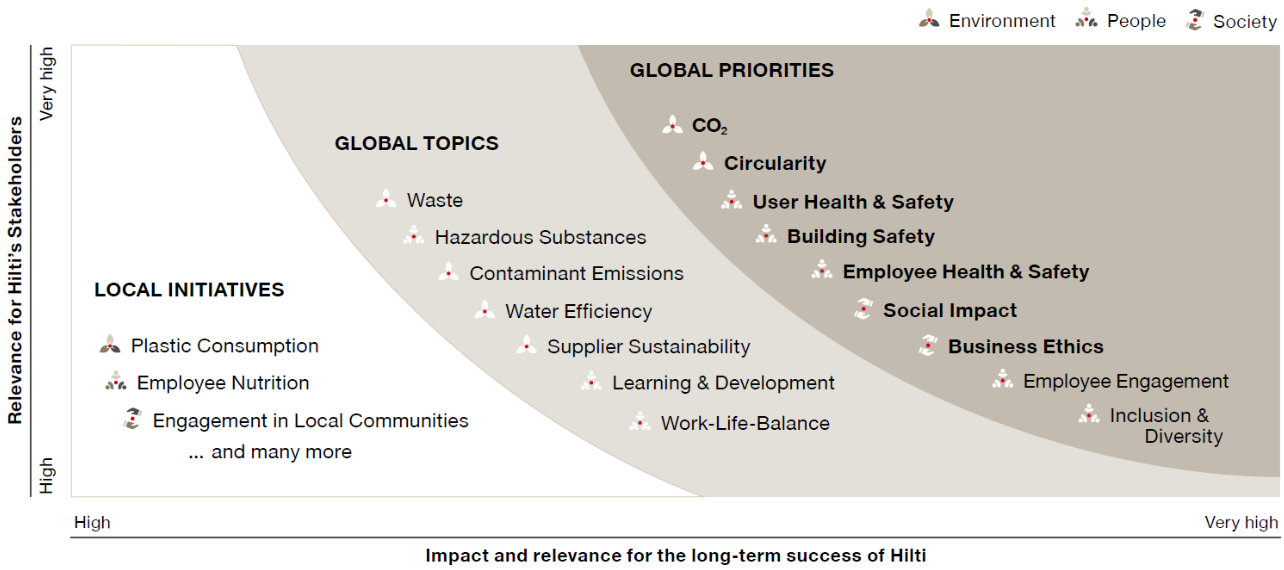


Figure 3.3.1: Hilti's Sustainability Materiality Matrix [4]

The most relevant topics regarding business success and its positive impact on society and the environment were selected. For each globally relevant topic, targets were defined. For achieving these targets and to anchor sustainability organizationally, in 2020 Hilti established a Corporate Sustainability Team (KSU) that reports directly to the CEO of the company, which is an effective structure to implement changes and to drive sustainability across the company. KSU acts as an interface for all relevant parties and supports the implementation of measures. The advisory body for KSU's activities is the Sustainability Council, which provides strategic advice and support on cross-functional issues but does not act as a decision-making body, but more as a sounding board to provide guidance and a broad strategic view.

It is chaired by the CEO and includes the heads of two of the largest regions and business units, as well as of the legal, human resources, logistics, and communications departments. As seen in *Figure 3.3.2*, the three main pillars of Hilti's sustainability strategy are the **environment**, **people,** and **society**.

Clustering by these main pillars, the key goals of Hilti's sustainability strategy are:

- **Environment**
  - Become CO_2 neutral by 2023
  - Lead the industry in circularity
- **People**
  - Differentiate through user-health & safety and building safety
  - Lead in employee health & safety
- **Society**
  - Create social impact at scale
  - Uphold Hilti and the industry to the highest standards in business ethics

Figure 3.3.2: Prioritized SDGs by strategic action field [4]

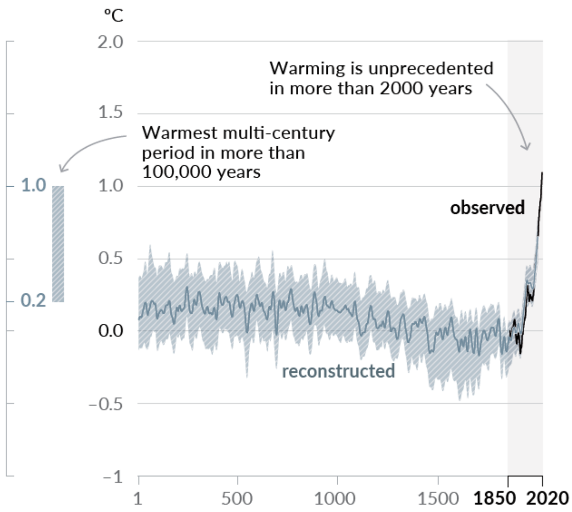
As Hilti is strongly linked to the construction industry, it is clear from a sustainability point of view, that due to the actual climate crisis and the sector's negative impact, those actions need to be taken. This is why, Hilti is willing to become a role model to better assess their customers and partners in the construction and real estate industry, by understanding what would be a sustainable building for the organization, to have a clear overview of the current status of its assets, and to contribute to this sustainable development by upgrading their facilities to Hilti's sustainability standards. The chosen approach to drive this change from KSU is to holistically improve the company's facilities from all aspects to contribute to each strategic action field.

3.4. Climate Change

It has been proven by the scientific community during the last decades, that climate change was a fact and a dynamically evolving risk for humankind. In the following points, the current situation of climate change and an overview of the possible climate futures will be introduced.

3.4.1. Current situation

It is indisputable that the evolution of humankind during the last centuries has risen earth's temperatures at unprecedented rates, mostly due to the emission of Green House Gases (amongst other pollutants) into the environment. An observed increase mix of GHG since 1750 is unequivocally associated with human activities [5], which led since then to rapid, widespread, and dynamic changes in the atmosphere, oceans, cryosphere, and biosphere.

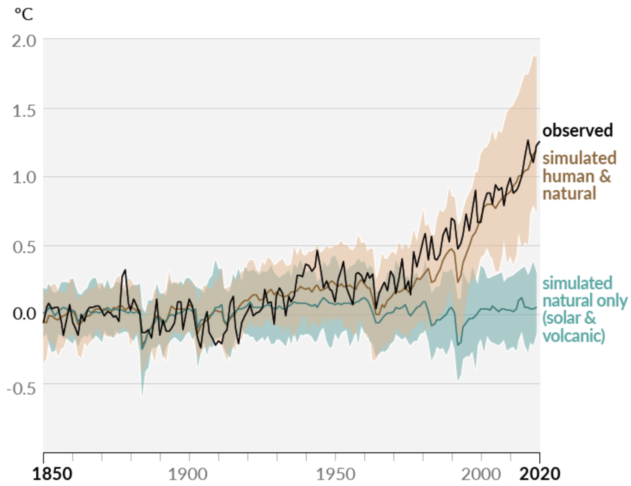


*<u>Graph 3.4.1.1:</u> Change in global surface temperature (decadal average) as reconstructed (1-2000) and **observed** (1850-2020)* [5]

The biggest influencer in global warming from the mix of GHG emitted to the atmosphere by human activities is CO_2. It also has been estimated that the global temperature increased by 1.07 °C since 1850 [5]. These two factors combined, have induced the following side-effects:

- Temperature rise of the upper layer of the ocean (0-700 m of depth)
- Global acidification of the surface open ocean
- Reduction of oxygen levels in many upper ocean regions
- Melting of glaciers and arctic poles, which correlates with a salinity modification of the oceans and a global sea-level rise of 0.2 m between 1901 and 2018[5]

- Radicalization, strengthening, and displacement of weather phenomena and extreme natural events, causing an alteration of precipitation patterns



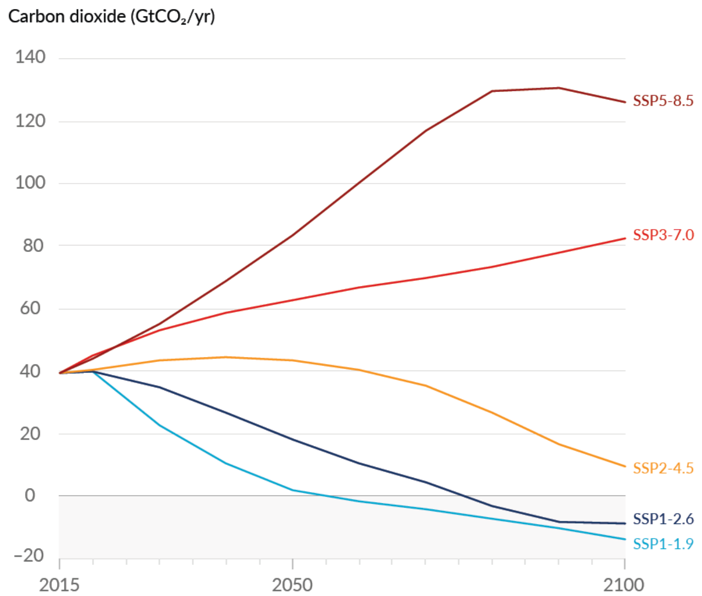
*Graph 3.4.1.2: Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)* [5]

Hence, planet earth is reacting to the harm inflicted by humankind, which translates to a more unpredictable and dynamically changing environment. This might lead to more developed strategies, for example, whilst searching for building locations during the design phase or in many other topics during other phases of the life cycle of a building, as meteorological and natural phenomena will need to be considered even more.

3.4.2. Possible climate futures

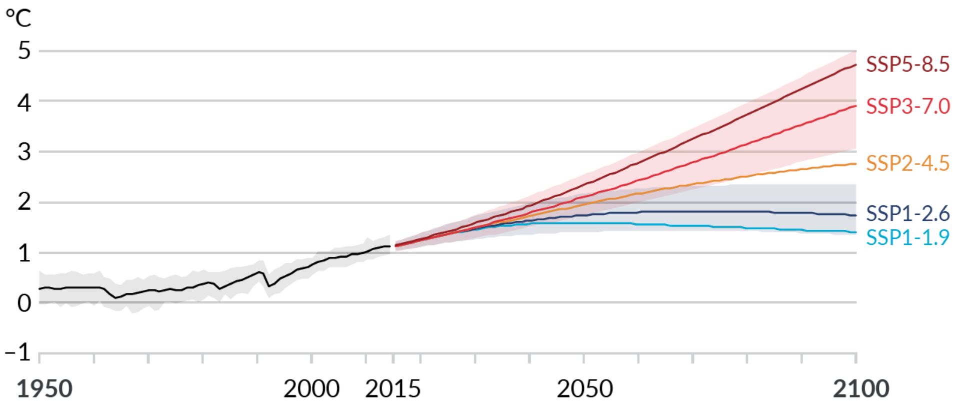
Undoubtedly, providing an exact prediction of global warming and its side effects is not an easy task, mainly because it is in mankind's hands to modify its behavior towards the environment and the quantity of GHG emissions discharged into the atmosphere. For this main reason, the best way to provide a forecast is by establishing different scenarios of GHG emissions trends for the upcoming years that will have a direct repercussion on global surface temperature rise.

It is worth mentioning that due to COVID-19, global fossil CO_2 emissions have decreased approximately by 2 $GTCO_2$ in 2020 to 31.5 $GTCO_2$ [6-8]. Because of the global pandemic, global GHG emissions and mainly CO_2 emissions dropped for the first time in decades because of the cease of activities from various industries and significantly from the prohibition of movement for all individuals during lockdowns. These lockdown periods shifted the energy demand to indoor spaces and residential buildings explicitly.



Graph 3.4.2.1: Future annual emissions of CO_2 with the different scenarios [5]

Unfortunately, after these restrictive periods terminated and normal activities began to take place again, have made that in 2021 global energy-related CO_2 emissions have grown and rebounded to 4.8% as demand for coal, oil and gas rebounded with the economy. This growth translates to a global emission of 33 $GTCO_2$ [8,9], which value opens the possibility to the first three Shared Socioeconomic Pathways (SSP) or scenarios from *figure 3.4.2.1* (SSP1-1.9, SSP1-2.6, SSP2-4.5).



Graph 3.4.2.2: Global surface temperature change relative to 1850–1900 [5]

As seen in *graph 3.4.2.2,* the most optimistic surface temperature rise from the possible scenarios with the actual emissions of CO_2 will be a rise of 1.5 °C. As mentioned before, this increase will directly affect widespread ecosystems and regions, inducing the following forecasted changes by the IPCC report [5]:

- Polar Ice sheets: Irreversible loss of Greenland's ice sheet and instabilities in the Arctic ice sheet, rising sea level, and its temperature.
- Sea level rise: Global mean sea-level change of approximately +0.5 m by 2100.
- Acidity and oxygen levels of oceans: Ocean acidity increased by 17% [10] by 2050 due to higher concentrations of carbon dioxide, decreasing oxygen levels and creating more "dead zones" where marine life cannot survive.
- Flooding, low-lying areas, Islands, and coastal: Sea level rise, will directly affect all low-lying areas next to the sea leading to freshwater stress, more extreme storms, flooding, and a loss of low-lying properties and economies.

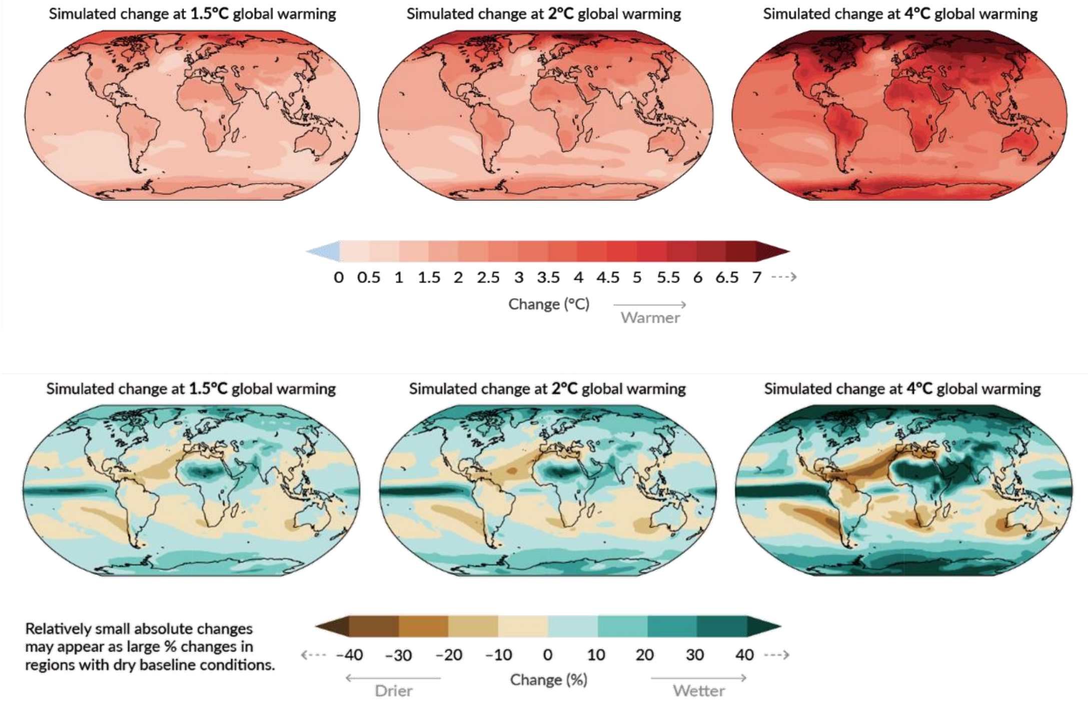


Figure 3.4.2.1: Annual mean precipitation change (%) and annual mean temperature change (°C) relative to 1850-1900 [5]

- Heatwaves: 14% of the world population will be exposed to extreme heat and heatwaves, which will cause severe droughts, freshwater stress, increased forest wildfires (up to 41% in the Mediterranean areas [11]) which will bring to deforestation, loss of biodiversity and ecosystems as side-effects.
- Food security: It will be reduced with the largest risks emerging in the African Sahel, the Mediterranean, Central Europe, the Amazon, and Western and Southern Africa. Crops will be displaced; less nutritive crops will be available and 7-10% of livestock will be lost.
- Water availability, droughts, and extreme precipitation: As seen in *figure 3.4.2.1,* there will be strong changes in the precipitation patterns worldwide, as it is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over the parts of the subtropics and in limited areas of the tropics. This scenario will induce water scarcity and severe droughts. Precipitation will become less frequent but more extreme, such as all the natural events or phenomena becoming a danger for the upcoming years.

It can be observed in *figure 3.4.2.1* that with the commented rise of 1.5 °C global warmings, high latitude areas such as the arctic pole, will be the most harmed ones by this scenario. This event is already occurring, and it is the main reason why the arctic poles are melting faster than expected.

3.5. Overview of the building sector status

Like many other sectors, during 2020 the building sector got hit by the global pandemic affecting not only the cease of construction operations due to various lockdowns around the globe but also the financial part of the construction sector and its supply chain. In addition, the building sector suffered an abrupt transition in its occupancy and the way buildings were used until COVID-19 hit, from a work-place based type of employment to remote working arrangements. This quick transition left commercial and retail buildings empty or even abandoned, the shutdown of public services and buildings, and increased demand in warehousing, logistics, and delivery to keep up with the new imposed market and economic structure [12].

The most noticeable side-effect of this transition has been that in 2020 the direct and indirect emissions from building operations plunged to approximately 9 Gt of CO_2. This is mainly due to the lower activity in the lower activity from the service sector. Even though the power sector has leveraged the opportunity of lower activity and closures of buildings to boost its decarbonization, there is an expected rebound of emissions for the year 2021. This fact will interpose in the buildings sector target from the Paris agreement in 2015 to being fully decarbonized by 2050. To meet this target, all new buildings and 20% of the existing ones will have to be zero-carbon-ready by soon as 2030 [13].

The signing of the Paris Agreement in 2015 was a milestone in the path of addressing climate change, as one of the main goals of the agreement was to maintain global warming below 2°C and limit carbon dioxide emissions for the upcoming years. The building sector is key for achieving these goals, which will require a triple strategy to achieve them: reduce energy demand while increasing energy efficiency, decarbonize the energy system and address the embodied carbon dioxide in building[1] materials.

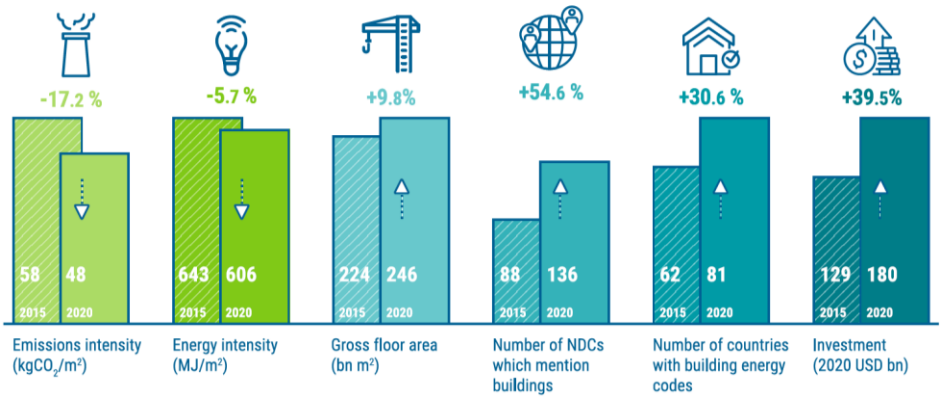


Figure 3.5.1: Key changes in buildings sector between 2015 and 2020 [1]

Since then, all efforts from policymakers, constructors, investors, and other relevant stakeholders have started to make an impact. As observed in *figure 3.5.1,* emissions and energy intensity of the sector have been reduced significantly whilst increasing the built gross floor

[1] Embodied CO_2: Emissions of CO_2 associated to the building materials and construction processes during the whole life cycle of the building, which includes all the activities that the material went through (manufacturing, transport to the site and installation)

area (which is expected to double by 2060 [1]). At the same time, the number of NDCs[2] has significantly raised the same as the number of countries which have developed building energy codes, which are tightening the minimum performance standards. But most importantly, global investments in green and sustainable buildings have also increased which means that the transformation of the sector has already started, and it is gaining more adherents.

3.5.1. Sustainability in the construction sector

Usually, the building sector (which includes all residential, public and commercial buildings) and the construction sector (including all the companies and their operations that are required to construct a building) are considered as one. But it is worth remarking that the construction sector by itself demands a 12% share of all global energy production. Although it only represents 9% of the global GDP, it consumes up to 40% of the planet's resources while causing almost 40% of all the waste produced by the economy and being responsible for 20% of all CO_2 yearly emissions [1].

The construction sector, which is strongly linked to Hilti, has also started the transformation to adopt more sustainable practices for being able to meet the goals from the Paris agreement and becoming a more environmentally friendly sector. To impulse this transformation, the sector has focused on the following initiatives as key drivers of sustainable practices implementation [14,15]:

- Digital planning: Fostering collaborative work methodologies such as Building Information Modelling (**BIM**), for creating and managing construction projects. Its main objective is centralizing all the information of the building in a digital information model created by all the stakeholders. It is the evolution of traditional design systems including geometric information (3D), time (4D), costs (5D), environmental (6D), and maintenance (7D). The use of BIM goes further than the main design phase, scoping the execution of the project and all the life cycle of the building. This holistic solution helps to reduce waste, improve traceability of materials, improve flexibility, adaptability, and resilience of the building whilst lowering operational costs.

[2] Nationally Determined Contributions: NDCs are non-binding national plans which highlight climate related targets, actions, measures and policies that governments aim to implement in response to climate change

- Prefabrication and modular construction: This construction method is based on a centralized production of building modules which are finally assembled on the construction site. It uses high-end planning and designing solutions such as BIM, combined with a highly qualified workforce. The result is a method of construction very precise and almost error-free, which reduces construction costs, reduces waste in the construction site, and reduces discomfort to the society surrounding the construction site due to a less time-consuming process of assembling modules versus constructing a building from scratch on the site. It is one of the best examples of Lean[3] construction.

- Green building certifications: These certifications are a very useful tool for investors, constructors, and policymakers to make buildings more sustainable by giving guidelines of improvement in different areas during the complete life cycle of the building. These labels help reduce the impact on the environment, reduce resource and energy consumption and create a positive impact in the surroundings of a building and mostly on its occupants.

- Circular construction: It is a method that applies principles and concepts of circular economy to the construction sector. Its framework applies these three principles: Eliminate waste and pollution, keep products and materials in use and regenerate natural systems. The main aim is to keep the materials in a closed-loop within the construction sector reducing extraction and resource consumption. Two tools are worth remarking which help the construction sector to incorporate circularity in its practices:
  - **Cradle to Cradle (C2C) certification:** This certification mainly focuses in improve the traceability of products during all its life cycle. It also helps track the embodied carbon in the construction products.

[3] Lean Methodology: It is a methodology which aims to optimize efforts and resources invested in a process towards creating value for the customer, whilst understanding what the customer is willing to pay for the offered product or service.

– **Material passport:** It acts basically as an inventory of materials used during a building's construction and components embedded in its structure.

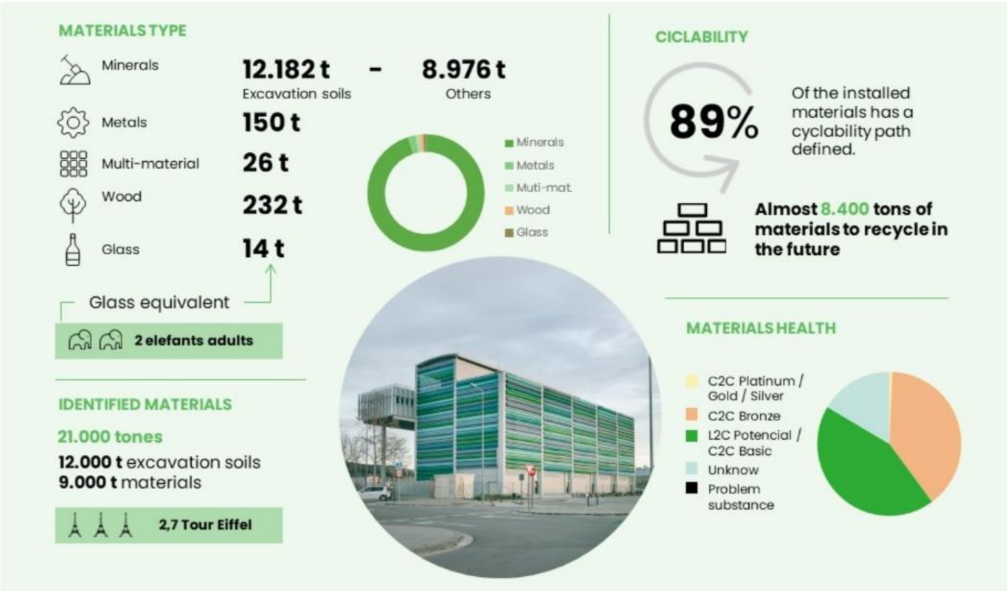


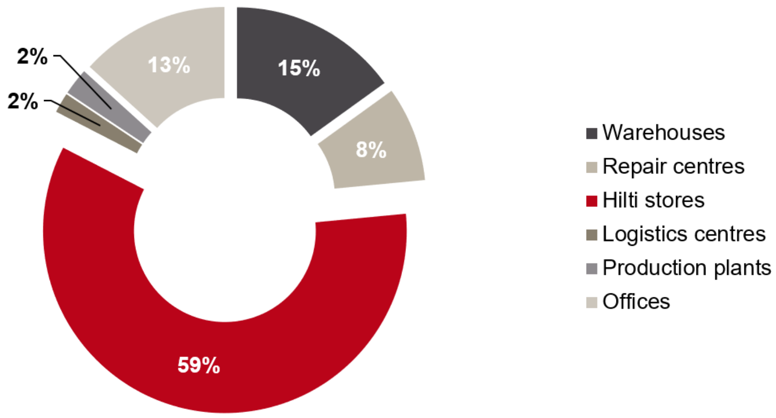
Figure 3.5.1.1: Example of a material passport, from Gonsi Sócrates bio-building [16]

The main concept behind this type of building identification or inventorying is that in the close future buildings will act as small quarries or sources of materials and components for new buildings, which will create a positive impact as no waste will be generated. It also eases recovery decisions, therefore the building's investment will maintain its value over time, as with this passport there is evidence of the amount of raw material that can be reused in another building.

As seen in *figure 3.5.1.1*, an example of a building passport is provided. In this specific case, the constructed building's passport acts as an overview of the quantity of the materials embedded in the building which will provide the value at the end of the building's life cycle. Adding to the passport, as seen there is an 89% of the installed materials have a cyclability path [16].

3.6. Clustering of Hilti's facilities

As stated in previous points, Hilti is a sales-driven company, meaning that its business model is focused mainly on selling products and services to constructors and other entities from the energy or industrial sectors (B2B). This business strategy directly reflects on the building assets that Hilti Group owns, rents, or outsources. If clustered by building use purpose, the number of facilities that are dedicated to direct sales to the customer (B2B) or Hilti stores as seen in *graph 3.6.1* ascends to almost 60% of the facilities. This ratio of facilities is very similar and aligns with the ratio of employees which integrate Hilti's salesforce (approximately 20.000 employees or 66% of Hilti's total workforce).



Graph 3.6.3.5.11: Distribution of Hilti's facilities by type of building or type of use

Although clustering by number might be misleading, as the smallest shares of facilities for example production plants, may also be the big players when concerning sustainability. Therefore, the SPIs framework that needs to be defined should be inclusive and provide a general statement of sustainable building with all the different types of facilities included in *Hilti's* assets.

It is also worth mentioning, that there will be more freedom of action regarding the implementation of sustainability measures or initiatives with owned assets rather than with rented or outsourced facilities, as more stakeholders will be included in the decision-making scheme.

4. Green Building Certifications and Methodology

A methodology is followed to achieve the problem's solution. In this chapter, all the analyzed Green Building Certifications (GBCs) are introduced. Their criteria are analyzed, assessed, prioritized, and clustered by the sustainability pillar to present a preselection of criteria.

4.1. Introduction to GBCs

The green building movement started decades ago with the increases in oil prices from the 1970s, which combined with the early beginnings of the environmental movements from the 1960s led to a spur in significant research and activities to improve energy efficiency and find renewable energy sources. In this early stage, the first experiments of the contemporary green building concept started to take place. Green buildings started reaching more awareness in the early 2000s, but it was a mindset for those architects and engineers that went above and beyond the norm to make buildings more energy-efficient and sustainable, as their norms back at the time were loose in the restrictions [17].

As stated in previous points, due to climate change and that the topic of sustainability has gone mainstream and many stakeholders expect some level of sustainability in their buildings, now the topic of sustainability has become a must-have instead of an above and beyond the topic. As the topic reached the deeper level of norms and policymakers' mindset, there was the need for specific entities which could assess the level of integration of sustainability within buildings, and it was when green building certifications and organizations were born.

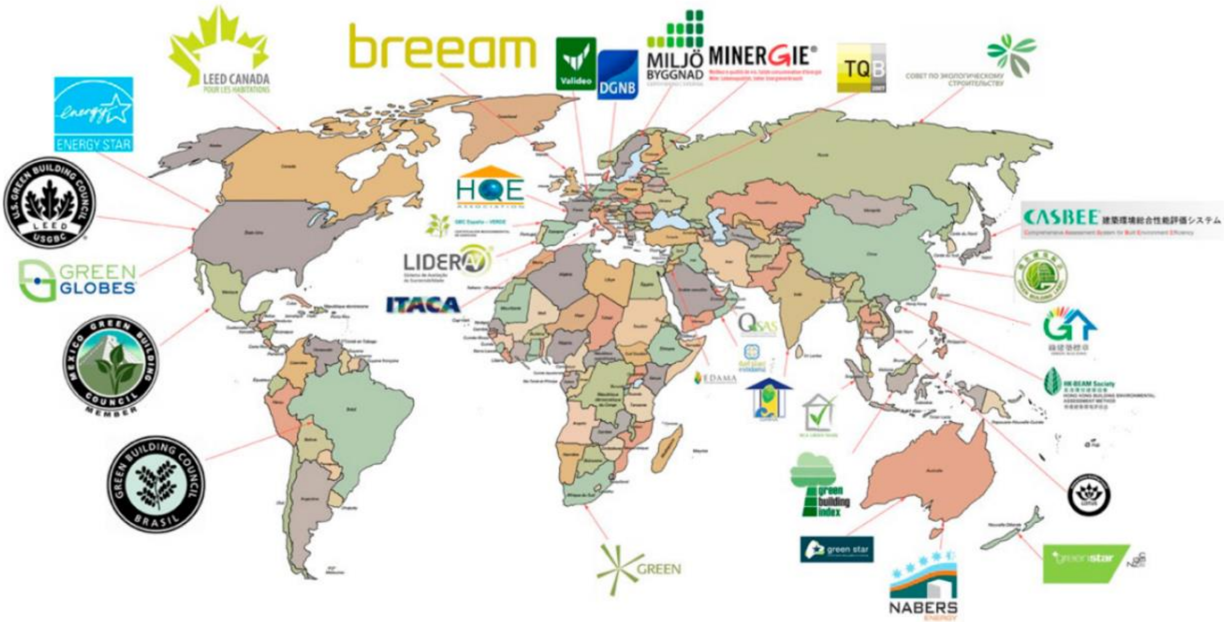


Figure 4.1.1: Overview of the existing green building labels worldwide [17]

As it can be seen in *figure 4.1.1,* the number of labels assessing sustainability in buildings is substantial and depending on the region or country it might be better to abide by the certification developed by the nearest organization, as it would be most aligned with the local and regional norms.

Every label has its main areas of interest as seen in *figure 4.1.2,* which can be clustered into three main pillars: Social aspects, environmental aspects, and economic aspects.

Out of these three pillars, there are a specific number of criteria with their respective performance indicators that the assessed buildings are required to fulfill. Then every label has its rating system which provides a quantitative result of the assessment and depending on the building's performance it can be awarded different certification levels or ranks.

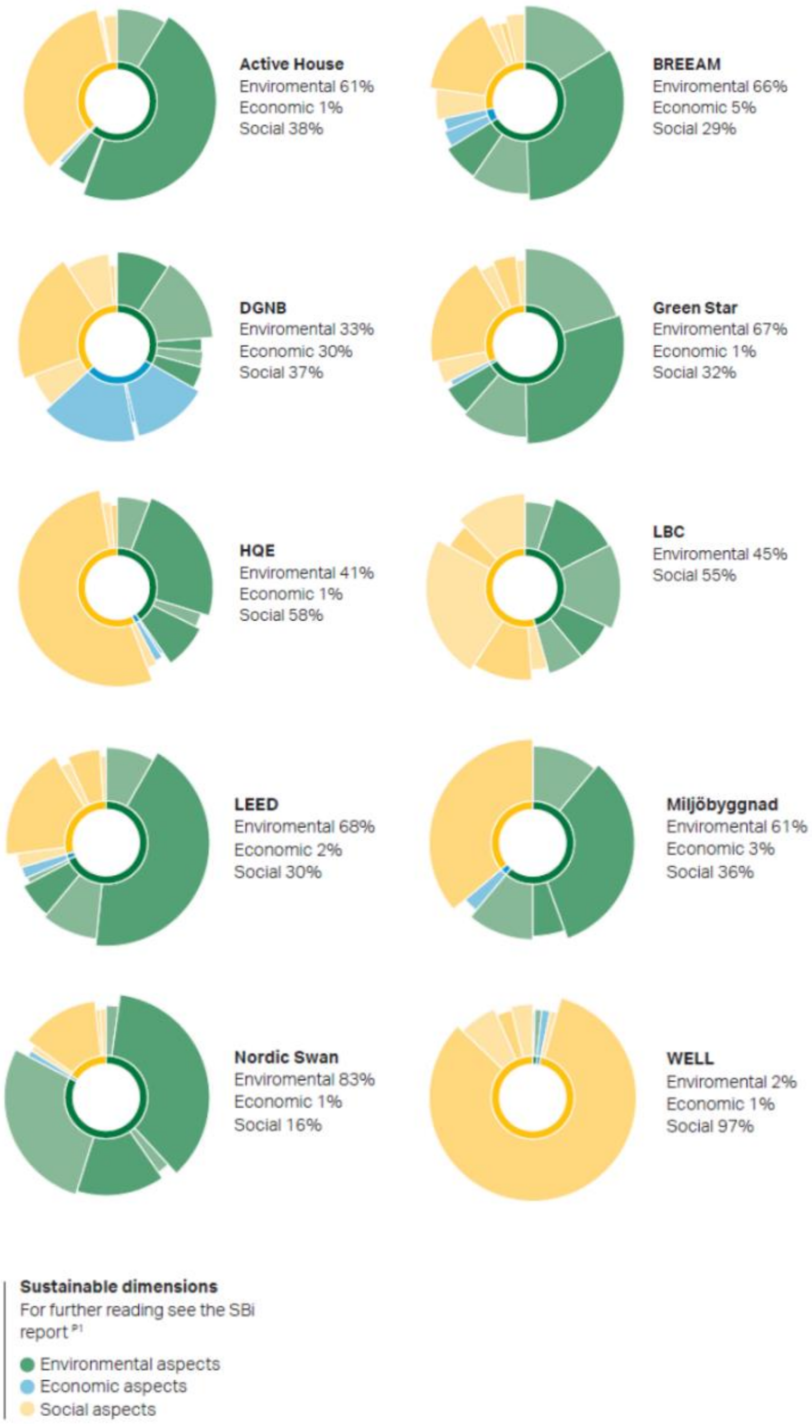


Figure 4.1.2: Overview of the most recognized sustainability assessment systems for buildings [18]

Hence, the initial methodology to follow for this study is to cluster by relevance the existing certification systems which assess sustainability in buildings, for later analyzing the key topics of interest of every label. The main aim of this methodology is to deeply understand what the perfect definition of a sustainable building would be from the most recognized labels, by analyzing the assessment's criterion and their respective weights in the overall assessment process. Once the ranking of criterion will be done, a preselection of their respective performance indicators will follow, leading to a SPIs final selection which will constitute Hilti's framework of SPIs. As a summary, a funneling approach will be followed from the bigger picture of the labels down to a specific set of SPIs, with the final target of selecting the most impactful SPIs for Hilti's facilities and defining their thresholds.

4.2. Label selection and Introduction

For the following points and during this thesis study, it must be said that the DGNB certification will be used as a guideline and reference over the other certifications for two main reasons: as seen in *figure 4.1.2* it is the most balanced certification along the three pillars of sustainability making it the most holistic one, and also because this certification aligns significantly with the company's sustainability strategy.

Moreover, to add more value to the certification comparison, three more certifications will be considered due to their recognition and extended use around the world, but also because these certifications will be a good supplement for the overall framework. These three labels are LEED, BREEAM, and WELL Standard. LEED and BREEAM will be a good addition to the environmental pillar and the WELL Standard will provide valuable inputs for the social pillar.

4.2.1. Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)

DGNB	Description
Country of origin	Germany
Year	2007
Managing organization	German Sustainability Council
Applications	• New construction • Commercial interiors • Renovations • Existing Buildings • Urban areas
Areas of focus	• Environmental quality • Economic quality • Sociocultural and functional quality • Technical quality • Process quality • Site quality
Logic of the award	DGNB system uses performance indices to grade buildings. Being awarded a final total performance index, buildings can be rated: • Platinum: ≥80 % • Gold: ≥65 % • Silver: ≥50 % • Bronze: ≥35 %

Table 4.2.1.1: Overview of DGNB certification system [19]

As said before, the DGNB has been selected as a guideline for this study due to its holistic approach regarding sustainability, placing equal emphasis on the environment, people, and commercial viability. Since 2007, it has been primarily used in Germany and its German-speaking neighboring countries, and because of its flexibility, it has been adopted in various types of buildings. The label's organization also fosters innovation by focusing its attention on good technical quality and the architectural processes involved. High quality is also ensured by a minimum performance index for each award: platinum 65%, gold 50%, and silver 35% [19,20].

4.2.2. Building Research Establishment's Environmental Assessment Method (BREEAM)

BREEAM	Description
Country of origin	United Kingdom
Year	1990
Managing organization	BRE Global
Applications	• New construction • In-Use • Refurbishment & Fit Out (interiors) • Communities • Infrastructure
Areas of focus	• Energy • Health & Well-being • Transport • Water • Materials • Waste • Land use & Ecology • Management • Pollution
Logic of the award	BREEAM system rating benchmarks to grade buildings: • Outstanding: ≥85 % • Excellent: ≥70 % • Very good: ≥55 % • Good: ≥45 % • Pass: ≥30 % • Unclassified: <30 %

Table 4.2.2.1: Overview of BREEAM certification system [21]

BREEAM certification system was the first label in the world that assessed and certified the sustainability of buildings, which is one of the main reasons it is still very popular. As seen in *figure 4.1.2* its focus of interest remains in the environmental pillar (66 %) and social pillar (29 %), leaving the economic aspects far behind on 2% of its awardable dimensions or criterion [21].

4.2.3. Leadership in Energy and Environmental Design (LEED)

LEED	Description
Country of origin	United States of America
Year	1998
Managing organization	United States Green Building Council
Applications	• New construction • Existing buildings, Operations & Maintenance • Commercial Interiors • Core & Shell • Neighborhood Development
Areas of focus	• Sustainable sites • Water efficiency • Energy & Atmosphere • Material & Resources • Indoor Environmental Quality (IEQ) • Locations & Linkages • Awareness & Education • Innovation in Design • Regional Priority
Logic of the award	LEED system uses a credit-granting in the areas of interest to achieve a certification level of the following: • Platinum Level: ≥ 80 points • Gold Level: 60 – 79 points • Silver Level: 50 – 59 points • LEED Certified: 40 – 49 points

Table 4.2.3.1: Overview of LEED certification system [22]

Having as a reference the overview of certifications of *figure 4.1.2*, LEED's distribution along the pillars of sustainability is also very focused on the environmental pillar and the social pillar. It can be considered as the American equivalent and successor of BREEAM, but it is one of the largest certification systems and the most widely used around the world [17]. Regarding the rating system, all the topics of the main areas of focus have prerequisites or mandatory practices and credits or recommendations. When these standards are met, credits or points are granted to the total building score up to a maximum of 110 points [22].

4.2.4. WELL Building Standard

WELL	Description
Country of origin	United States of America
Year	2014
Managing organization	International WELL Building Institute (IWBI)
Applications	• New construction • Existing Buildings • Interiors • Renovations • Urban Areas or neighborhoods
Areas of focus	• Air • Water • Nourishment • Light • Fitness • Comfort • Mind
Logic of the award	The WELL certification uses a point granting system per concept to assess buildings and to certify these as: • WELL Platinum: ≥ 80 points (min. points/concept: 3) • WELL Gold: ≥ 60 points (min. points/concept: 2) • WELL Silver: ≥ 50 points (min. points/concept: 1) • WELL Bronze: ≥ 40 points (min. points/concept: 0)

Table 4.2.4.1: Overview of WELL certification system [23]

As mentioned previously, the WELL certification focuses mainly on the occupant's health and well-being, up to 97 % of the weight of the certification being awarded to topics related to the social pillar of sustainability, placing human health and well-being at the center of the design, construction, and operations of a building. Alike other labels, WELL certification has several prerequisites in the different areas of interest and recommendations of which credits can also be added to the building's score up to 100 points in total or no more than 12 points per concept. Extra credits can be granted per concept over the 12 points maximum by submitting features or parts not already pursued within those concepts as innovations [23].

4.3. Prioritization of label's assessment criterion

Consecutively, after having a clear overview of what are the main areas of interest of the selected certifications [18-26], the next step for the selection process is to analyze more into detail the different criterion included in every area of study of the labels. As mentioned previously, green building certifications and labels that assess buildings' sustainability depend on various factors or criteria. Hence, a common practice performed by previous studies on the topic is to assess sustainability indicators by using a multi-criteria decision-making approach (MCDM) [27-31], in particular Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP).

In the case of this study, as one of the main aims is to provide a comprehensive answer of what a sustainable building is, a deep understanding of the GBRSs needs to be acquired first of all by leveraging and benchmarking the selected labels' criterion weighting system. Hereinafter, a priority management process will be followed, specifically a Pareto analysis of the criterion weighting systems of the labels; Therefore the "Critical Few" categories or most impactful criterion will be separated from the "Trivial Many". By following this approach, an avoidance of biased results from experts' surveys from MCDM approaches is expected [32] and performing an impartial analysis, as the topic of sustainability in buildings is still fuzzy and the results could vary depending on the pool of experts that would need to be selected in case of following an MCDM approach.

4.3.1. Priority management analysis of criterion

The expected outcome of the Pareto analysis of the labels' criterion is a ranked list of elements by the given weight of the certification system, to classify the ones which have the major relevance from the labels' point of view.

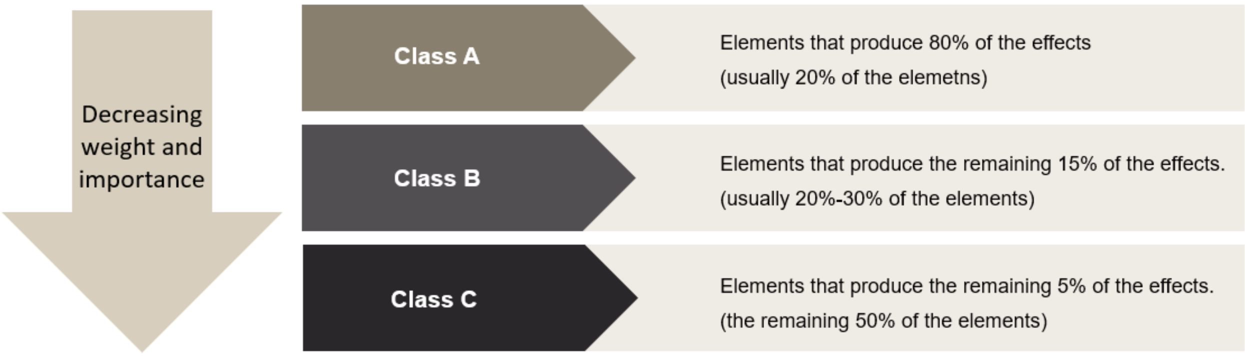


Figure 4.3.1.1: Pareto law elements classification by outcome effect [33]

By running a Pareto analysis over the certifications weighting tables, which can be seen in *appendix A,* a ranked list of criteria's weights can be obtained as a result:

- **DGNB:** Regarding the DGNB criterion weighting, as it can be seen in *table A.1 in appendix A*, there are different weightings awarded in the 4 different types of buildings that Hilti has in its assets. For the DGNB Pareto analysis, 4 different analyses have been performed by each type of building as seen in *table 4.3.1.1*. As for all the building types, the most relevant criterions are related to a comprehensive assessment of the building's life cycle, its environmental impact, and the flexibility and adaptability of the building for future changes in functionality.

  It can be said that along with the top 10 most impactful criterion, there are small differences in including criteria which apply more significantly to the building type rather than from a general building perspective. This is why a general inclusive statement of relevant criterion from the DGNB certification can be developed. The criterion which are included in all building types as commonalities will be included in the merged top 10 criterion, and for the outliers, *Hilti's* facilities distribution is considered to select those which will influence the major number of facilities worldwide.

Top 10	Criterion	Description	Offices
1	**ECO1.1**	Life cycle cost	**10%**
2	**ENV1.1**	Building life cycle assessment	**10%**
3	**ECO2.1**	Flexibility and adaptability	8%
4	**SOC1.2**	Indoor air quality	5%
5	**ECO2.2**	Commercial viability	5%
6	**ENV1.2**	Local environmental impact	5%
7	**SOC1.1**	Thermal comfort	4%
8	**SOC2.1**	Design for all	3%
9	**SOC1.4**	Visual comfort	3%
10	**TEC1.6**	Ease of recovery and recycling	3%

Top 10	Criterion	Description	Logistics
1	**ECO1.1**	Life cycle cost	**10.0%**
2	**ENV1.1**	Building life cycle assessment	**9.5%**
3	**ECO2.1**	Flexibility and adaptability	7.5%
4	**SOC1.2**	Indoor air quality	5.4%
5	**SOC1.6**	Quality of indoor and outdoor spaces	5.4%
6	**ECO2.2**	Commercial viability	5.0%
7	**ENV1.2**	Local environmental impact	4.7%
8	**SOC1.7**	Safety and security	4.3%
9	**SOC1.1**	Thermal comfort	4.3%
10	**SOC1.4**	Visual comfort	3.2%

Top 10	Criterion	Description	Stores
1	**ECO1.1**	Life cycle cost	**10.0%**
2	**ENV1.1**	Building life cycle assessment	**9.5%**
3	**ECO2.1**	Flexibility and adaptability	7.5%
4	**ECO2.2**	Commercial viability	5.0%
5	**ENV1.2**	Local environmental impact	4.7%
6	**SOC2.1**	Design for all	4.5%
7	**SOC1.1**	Thermal comfort	4.5%
8	**SOC1.2**	Indoor air quality	4.5%
9	**SOC1.4**	Visual comfort	3.4%
10	**TEC1.1**	Fire safety	2.9%

Top 10	Criterion	Description	Production
1	**ECO1.1**	Life cycle cost	**12.9%**
2	**ECO2.1**	Flexibility and adaptability	**9.6%**
3	**ENV1.1**	Building life cycle assessment	**9.5%**
4	**SOC1.2**	Indoor air quality	5.4%
5	**SOC1.6**	Quality of indoor and outdoor spaces	5.4%
6	**ENV1.2**	Local environmental impact	4.7%
7	**SOC1.1**	Thermal comfort	4.3%
8	**SOC1.7**	Safety and security	4.3%
9	**SOC1.4**	Visual comfort	3.2%
10	**TEC1.6**	Ease of recovery and recycling	2.7%

Table 4.3.1.1: Prioritized DGNB criteria by building type and weigh

- **BREEAM:** Unlike the DGNB, the BREEAM certification system provides a more general criterion weighting, not addressing a specific type of building at least from a rating point of view. As observed in *table 4.3.1.2,* the most impactful criterions in terms of rating are related to the environmental pillar and social pillar from a sustainability point of view which aligns with the previous assessment on label selection.

  The most awarded criterion assesses the building's environmental impact and occupant's or users' comfort and well-being.

Top 10	Criterion	Description	Weights
1	**Ene 01**	Reduction of energy use and carbon emissions	**8.1%**
2	**Mat 01**	Life cycle impacts	6.5%
3	**Hea 01**	Visual comfort	4.6%
4	**Mat 03**	Responsible sourcing of construction products	4.3%
5	**Pol 03**	Surface water run-off	3.8%
6	**Hea 02**	Indoor air quality	3.8%
7	**Wat 01**	Water consumption	3.5%
8	**Man 03**	Responsible construction practices	3.1%
9	**Pol 01**	Impact of refrigerants	3.1%
10	**Hea 05**	Acoustic performance	3.0%

Table 4.3.1.2: Prioritized BREEAM criterion by weight

- **LEED:** Similarly, the LEED weighting criteria focuses mainly on the environmental impact of the building and the impact in the vicinities of the building placement. But as seen in *table 4.3.1.3*, the LEED certification system also focuses on assessing if the assessed building will have a positive impact on its surroundings and the local area, by focusing the attention on how the building is supporting local communities, environmental projects in the area, if the addition of the building in the local area is providing access to quality transit and if there is enhanced commissioning after the construction process of the building.

  These top 10 criterion from LEED target a more comprehensive assessment as more stakeholders are considered, especially the building's neighbors and sustainable development of the operations of the building, aligning also with the SDGs.

Top 10	Criterion	Description	Weight
1	**Optimize energy performance**	Achieve increasing levels of energy performance	**14.3%**
2	**Neighborhood Development Location**	To avoid development on inappropriate sites.	**12.7%**
3	**Indoor water use reduction**	To reduce indoor potable water consumption.	4.8%
4	**Enhanced commissioning**	To further support the design, construction, and eventual operation of a project.	4.8%
5	**Access to quality transit**	To encourage development in locations shown to have multimodal transportation choices.	4.0%
6	**Renewable energy**	To reduce the environmental and economic harms associated with fossil fuel energy.	4.0%
7	**Building life-cycle impact reduction**	To encourage adaptive reuse and optimize the environmental performance of products and materials.	4.0%
8	**Surrounding density and diverse uses**	To conserve land and protect farmland and wildlife habitat by encouraging development in areas with existing infrastructure.	4.0%
9	**Innovation**	To encourage projects to achieve exceptional or innovative performance to benefit human and environmental health and equity.	4.0%
10	**Regional priority**	To provide an incentive for the achievement of credits that address geographically specific environmental, social equity, and public health priorities.	3.2%

Table 4.3.1.3: Prioritized LEED criterion by weight

- **WELL:** Unlike the previous criterion weighting, in the case of the WELL certification scorecard there are some differences in the rating structure. As it can be seen in *table A.3 in appendix A*, there are the requisites criterion of every category and the awardable criterion which can be given weight. The Pareto analysis has been done to the awardable criterion, which are the ones where a project can be given more points to improve its final score to obtain a better WELL Standard award. As it can be seen in *table 4.3.1.4* WELL certification values innovation along with the social and environmental aspects, which can lead to better, more efficient, environmental, and user-friendly solutions. The other criterion of the top 10, mainly focuses the attention on the user health and well-being, aligning with what has been stated previously about this certification. The requisites list as seen in *table B.1 in appendix B,* will be leveraged on the final SPIs selection, as the binary rating of the requisites (have/ don't have) will ease the selecting process for the must-have SPIs in the final framework.

Top 10	Criterion	Description	Weight
1	**I01**	Propose Innovations	**4.4%**
2	**I05.1**	Achieve Green Building Certification	2.2%
3	**S02.1**	Limit Background Noise Levels	1.3%
4	**C08.1**	Offer New Parent Leave	1.3%
5	**T02.1**	Survey for Thermal Comfort	1.3%
6	**I06ß.3**	Carbon Reduction	1.3%
7	**C12.1**	Promote Diversity and Inclusion	1.3%
8	**L03.1**	Meet Lighting for day-active People	1.3%
9	**I06ß.2**	Carbon Reduction Goal	1.3%
10	**X06.2**	Restrict VOC Emissions from Furniture, Architectural, and Interior Products	0.9%

Table 4.3.1.4: Prioritized WELL criterion by weight

By having performed the Pareto analysis, it has been emphasized the most significant and effectful criterion when it comes to a building assessment with the selected certifications. As seen in *Table 4.3.1.5,* an overview of these prioritized criterion clustered by certification and sustainability pillar is presented. With this overview, it is easier to assess the commonalities along with the main certifications and the outliers worthwhile incorporating in the framework. It is worth remarking, that the DGNB is still the most holistic and balanced certification with its top assessment criterion, whereas the other three labels focus mainly on environmental and social aspects. Hence, DGNB certification is still the guideline to follow.

Top 10	DGNB	BREEAM	LEED	WELL
1	Life cycle cost	Reduction of energy use and carbon emissions	Optimize energy performance	Propose Innovations
2	Building life cycle impact	Life cycle impacts	Neighborhood Development	Achieve Green Building Certification
3	Flexibility and adaptability	Visual comfort	Indoor water use reduction	Limit Background Noise Levels
4	Indoor air quality	Responsible sourcing of construction products	Enhanced commissioning	Offer New Parent Leave
5	Commercial viability	Surface water run-off	Access to quality transit	Survey for Thermal Comfort
6	Local environmental	Indoor air quality	Renewable energy	Carbon Reduction
7	Thermal comfort	Water consumption	Building life-cycle impact	Promote Diversity and Inclusion
8	Design for all	Responsible construction	Surrounding density and diverse	Meet Lighting for Day-Active People
9	Visual comfort	Impact of refrigerants	Innovation	Carbon Reduction Goal
10	Ease of recovery and recycling	Acoustic performance	Regional priority	Restrict VOC Emissions from Furniture, Architectural and Interior

Economic aspects Environmental aspects Social aspects

Table 4.3.1.5: Top 10 criterion clustered by certification and sustainability pillar

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5. SPIs Framework and Case Study

In this chapter, all the analyzed GBCs criterion and their respective performance indicators are selected, and a general SPI framework is defined for *Hilti's* facilities. A more detailed line of study is followed to analyze a small set of SPIs, which is believed to have the biggest impact following *Hilti's* sustainability strategy. The chapter is concluded with a case study and a value proposition regarding the selected SPIs.

5.1. Sustainability Performance Indicators Framework

After Pareto analyzing the labels criterion and prioritizing the most significant ones, the next step is to narrow down to a selection of performance indicators that will help assess and monitor sustainability within *Hilti's* facilities. This framework of SPIs needs to be comprehensive and relevant to track the progress of SDGs within the company's assets, but at the same time, a holistic approach is required to fulfill environmental, economic, and social aspects whilst aligning with the company's sustainability strategy.

After completing the criterion overview in *table 4.3.1.5*, a deeper analysis of the criteria is required to fully understand the concept behind them. A deeper understanding of the criteria will ease the merging process, as among the different certifications different nametags might be used to refer to the same concept. As it can be seen in *table C.1 in appendix C*, after merging all the common criteria and the most interesting outliers for *Hilti's* sustainability strategy, a final selection of the top 15 is established. Out of every criterion, a different number of performance indicators can track the progress and evolution of the specific assessed topic. For the selection of these SPIs, what has been assessed to include them in the framework is:

- **Sustainability pillar:** The SPI framework needs to be holistic and balanced, therefore there must be an even number of SPIs for every pillar.
- **Measurability:** The SPIs are required to be measurable and quantifiable, to assess progress and quantify sustainability levels within the company, easing the reporting phase.
- **Feasibility:** The SPIs included in the framework can be measured with existing *Hilti's* means or currently available technology unless a viable solution or future rollout strategy can be presented.

- **Building's life stage:** Like almost all facilities within *Hilti's* assets are operating buildings, SPIs should be applicable in existing buildings but also for new ones.
- **Modifiability:** The selected SPIs, can be used in a modifiable or actable environment in which the SPIs can help steer the building's parameters to obtain the most sustainable outcome.
- **Scalability:** The SPIs can be applied in all types of Hilti's facilities and any location.

For the above-mentioned reasons, the SPIs framework presented is the one in *table 5.1.1* hereunder.

Pillar	SPI	Measurement
Economic	Building-related costs (operating costs)	[€/m² GFA*a]
	Occupancy density / degree of utilization	[pers./m²], [%]
	Productivity	[output / building costs]
	Shortage of skilled workers	[%]
Environmental	Total resulting CO_2 emissions	[$kgCO_2/m^2$]
	Energy consumption by energy source (final energy)	[kWh/a]
	Impact of refrigerants as GHG	[DELC CO_{2e}] / [GWP]
	Drinking water consumption with share of reused / recycled water	[m³/person/a], [%]
Social	Indoor air quality (CO_2, TVOC, PM2.5)	[µg/m³], [ppm]
	Upper and lower temperature and humidity limits for operative period	[°C], [%]
	Acoustic performance	[dB]
	Visual comfort (luminous flux)	[lux]
	Distance travelled by employees and means of transportation	[km], [-]

Table 5.1.1: Proposed Sustainability Performance Indicators for Hilti's facilities

It is worth remarking, that the factors that contributed the most to the SPI selection are the building phase in which the SPI can be applied and the modifiability, as the selected framework is aimed to help monitor and steer change along all *Hilti's* facilities. As seen in *table 5.1.1* above presented, along the social SPIs almost all the selected ones are related to Indoor Environmental Quality (IEQ), which will help assess the actual IEQ to improve the occupant's surroundings within *Hilti*'s buildings. The selected framework complies with the international standards ISO 21929-1, ISO 21678, and ISO 20887.

5.2. Relevance of Social SPIs

One of the main pillars of the company's sustainability strategy is people and more specifically, one of the main goals of Hilti regarding the people pillar is to lead in employee's health, safety and well-being at all of its levels [4]. This is one of the main reasons, the target of this study will also be aligned with this willingness of improving the employees' health & well-being, by focusing on the social pillar SPIs to highlight which is the biggest lever of improvement for *Hilti's* facilities. It has also been stated in numerous studies the importance of IEQ in sustainable buildings, as there is the need of pursuing sustainable design which meets the requirements of safety and comfort [29].

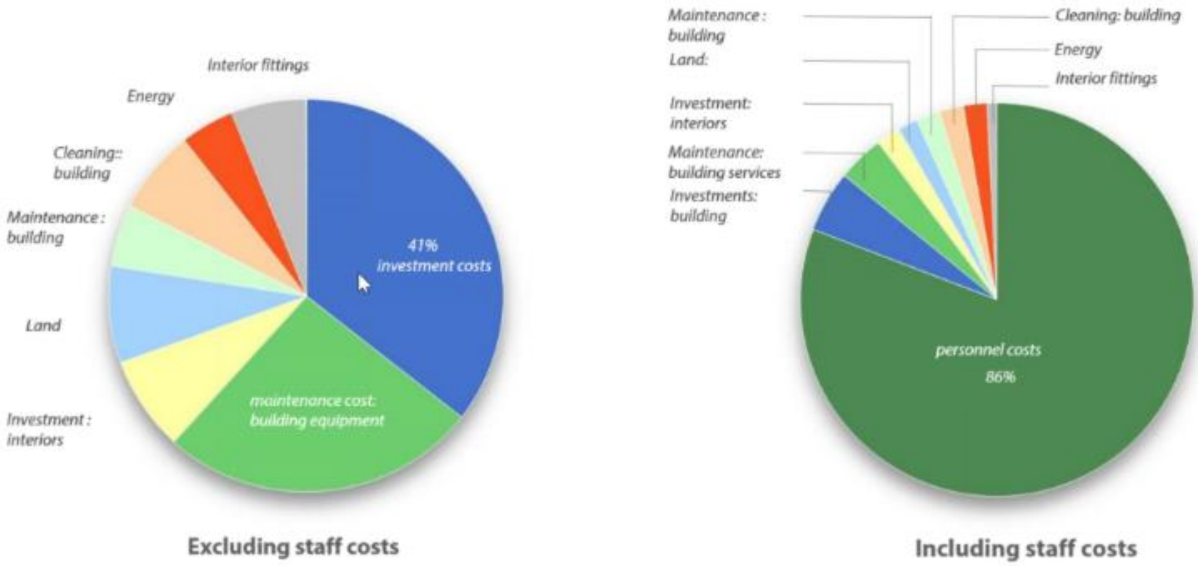


Figure 5.2.1: Distribution of costs over the life of a building [18]

Another reason to focus the attention on the social pillar SPIs is that as seen in *figure 5.2.1*, it is worth analyzing the overall costs of a building during its lifetime, which in this case is an office building during a lifespan of 20 years. If the occupant's costs or personnel costs of a building are included in the overall costs, these costs can represent approximately up to 86% of the complete cost of the building [18]. It can be seen that the biggest investment of a building is not the initial construction cost itself, but the investment in its occupants. This is why identifying the biggest lever of improvement within the social pillar SPIs (IEQ indicators especially), could lead to a more motivated, healthier, and productive workforce by avoiding the Sick Building Syndrome (SBS).

5.2.1. Sick Building Syndrome

The Sick Building Syndrome (SBS) is used to describe a set of symptoms or non-specific illnesses in which the occupants of a building experience the effects of a low Indoor Environmental Quality (IEQ) atmosphere, which also seems to be associated with the time spent in the building. The complainants may be localized in a particular room or zone or may be widespread throughout the building. These problems of health or symptomatology lead to occupants' discomfort, absenteeism, and low productivity.

There is a wide range of short-term symptoms associated with the SBS effects such as [34]:

- Headache
- Dizziness
- Nausea
- Eye irritation
- Nose irritation
- Throat irritation
- Dry cough
- Dry or itching skin
- Concentration loss
- Fatigue
- Odor sensitivity
- Increased asthma attacks
- Allergies
- Cold
- Flu-like symptoms
- Personality changes
- Hoarseness of voice

The above-mentioned symptoms are associated with short period stays in the affected building, which can be relieved by exiting the building, but a continuous and repeated stay in the affected building can lead to more serious long-term diseases such as cough, chest pain, shortness of breath on mild exertion, edema, palpitations, nosebleeds, cancers, pregnancy problems, and miscarriages. Extrinsic allergic alveolitis, Legionnaire's disease, humidifier fever, pneumonia, and occupational asthma are also known to occur [35].

The majority of these symptoms are caused by inadequate indoor air quality and thermal discomfort. By improving these two IEQ criteria from the social pillar of sustainability, employee's performance can be improved by up to 10% and reduce absenteeism [36], reverberating also in the economic and environmental pillar resulting in the holistic improvement approach that Hilti is aiming for its facilities.

5.2.2. Indoor air quality

Nowadays people spend more than 90% of their time indoors [19], and with the COVID-19 pandemic, this time has increased significantly. Despite some remarkable improvements in air quality, the global toll in deaths and lost years of healthy life has barely declined since the 1990s [37] and it will continue through this path as levels of pollution will still rise in the upcoming decades. This is why providing a good IEQ with healthy IAQ is a must-have for all companies which seek to take care of their employees and stakeholders, such as Hilti does with its people goals.

To provide healthy IAQ within Hilti's facilities, two main topics need to be assessed to develop a general statement with regards to air quality standards along with the different types of buildings that Hilti has in its assets: ventilation and filtration.

- **Ventilation:** Understanding ventilation as a forceful entry of outdoor air or airflow into a closed indoor system, it can be established a clear distinction between mechanical and natural ventilation. Ventilation in buildings is commonly used to supply occupants with fresh air, to provide adequate IAQ by removing and or diluting pollutants, and to provide adequate temperature for indoor air.

  - **Mechanical ventilation:** May be defined as the movement of air through a building using fan power; filtration and heating might also take place through Heating, Ventilation, and Air Conditioning (HVAC) systems. For optimal control of the parameters of the mechanical ventilation system, the building's airtightness or limitation of uncontrolled airflow exchange with the outdoor environment is required.
    A commonly used tool to assess the airflow needs of a facility is the air exchange rate, which varies depending on the activity of its occupants and the area of the building; to calculate it the following formula is used [38]:

$$\boldsymbol{q_{tot}}\,[\boldsymbol{l/s}] = \boldsymbol{n} \cdot \boldsymbol{q_p} + \boldsymbol{A} \cdot \boldsymbol{q_B} \qquad \text{(eq.1)}$$

q_P: ventilation rate per person [l/s · person^{-1}]

n: design value for the number of people in the room

q_B: ventilation rate from the building component [l/s · m^{-2}]

A: room floor area [m^2]

In *appendix D*, various tables can be found to calculate the necessary air exchange rate for a specific location. As recommended by CIBSE, a minimum of 8 l/s · person would be required to improve occupant's sensitivity to odors and comfort [40], which would reach a category II from the EN-15251 standards: Normal level of expectation from the building users and should be used for new buildings and renovations [39]. Also, a known factor for user comfort is a controlled airspeed of 0.1–0.3 m/s for delivering clean air to the indoor environment. Less than 0.1 m/s causes stuffiness and more than 0.3 m/s causes draughts [34]. A recommended value to avoid SBS symptoms would be having a total air supply between 4-6 air changes per hour [34].

- **Natural ventilation:** For natural ventilation through opening windows, documentation is possible via workplace regulation or a zonal flow simulation [19].

The requirements of workplace regulation A

System	Maximum permissible room depth in relation to the clear room height (h) [m]	Opening surface to ensure minimum air exchange	
		for continuous ventilation [m^2/present person]	for shock ventilation [m^2/10 m^2 floor area]
I one-sided ventilation*	Room depth = 2.5 x h (at h > 4 m: max. depth of space = 10 m) (assumed air speed in cross-section = 0.08 m/s)	0,35	1,05
II Cross ventilation*	Room depth = 5.0 x h (at h > 4 m: max. depth of space = 20 m) (assumed air speed in cross-section = 0.14 m/s)	0,20	0,60

System I: Single sided ventilation through external wall. System II: Transverse ventilation from external wall to wall or from external wall to roof.

Table 5.2.2.1: Natural ventilation through opening windows [19]

As seen in *table 5.2.2.1,* the DGNB standard states a minimum opening surface to ensure a minimum air exchange in naturally ventilated buildings. For this type of ventilation, an optimal additional resource would be a set of sensors that monitor pollutants to operate the windows as a result of an increase of pollutants levels.

It is worth mentioning that for both types of ventilation, it needs to be ensured that the quality of the exterior air is not contaminated to an impermissible level (by outgoing air from extraction or indoor air ventilation system, traffic, etc.) as ventilation without filtration could be detrimental.

- **Filtration:** It comprehends the process where air contaminants are prevented from entering the indoor environment of a building or facility by capturing the polluting particles before they are expelled out of the air ducts, but also comprehends the process of improving IAQ by filtering the existing indoor air whilst it is being recirculated and mixed with freshly filtered outside air (the process of air cleaning).

  Considering all the existing pollutants nowadays in the atmosphere might be overwhelming and counterproductive, as would overcomplicate the improvement process of IAQ. Instead, considering the symptomatology of different SBS diseases leads to the most common and dangerous pollutants that can be found in indoor environments (excluding the ones from specific industrial manufacturing processes) from human activity, building emissions, and atmospheric pollutants. A summary of the most important pollutants that need to be considered in IAQ monitoring and their thresholds can be seen in *table 5.2.2.2:*

	CO_2 [ppm] [19]	$PM_{2.5}$ [µg/m^3] [37]	TVOC [µg/m^3] [19]	Formaldehyde [µg/m^3] [19]
Maximum value	800	15	3000	100
Optimal	≤500	≤5	≤300	≤30

Table 5.2.2.2: Recommended maximum and optimal values of pollutants in indoor spaces

TVOCs and formaldehyde are organic compounds that can be emitted by construction materials such as floor coverings or other wooden products, adhesives, cleansers, aerosols, disinfectants moth repellents, and air fresheners which can decay at different rates. It is a very common indoor pollutant that can cause severe diseases affecting the respiratory and nervous systems, kidneys, and liver [41]. For this reason, it is important to monitor the levels of these pollutants, track the source, and neutralize or minimize their effects. The recommended values are aligned with ISO 16000-6, -3 standards and DGNB standards [19].

In the case of the particulate matter 2.5 or $PM_{2.5}$, it refers to the size of the particles of various pollutants which have a diameter less than 2.5 micrometers which remain suspended longer. These types of particles come from the combustion of different types of fuels, construction sites, motor vehicle traffic, and their exhaust gases. This type of pollutant is critical to be monitored, as its reduced diameter allows the particles to enter freely through the respiratory system reaching the circulatory system through the lungs (as their size is much smaller than the size of human alveoli) ending up in different locations of the human body being transported through the bloodstream. It mainly worsens asthma and heart diseases but is also associated with other respiratory and cardiovascular diseases [37]. The recommended values are aligned with WHO standards, as the optimal value is the annual average, allowing the upper limit values during a maximum period of 3-4 days per year.

Regarding CO_2 indoor levels, the optimal and maximum levels are aligned with the EN-15251 standards as the optimal indoor value should be ≤500 ppm [39]. It is worth mentioning, that the outdoor values of CO_2 are between 350-500 ppm [42,43], therefore the main aim of the HVAC system or the ventilation system is to provide a similar level of carbon dioxide in the interior compared to the exterior. It has been proven in various studies that high indoor CO_2 levels lead to lower concentration and decision-making performances of the building's occupants, which might cause health complaints to the occupants; it is also one of the main contributors to developing SBS in an indoor building environment [34,35].

In a previous study, a comparison of the performance of different subjects exposed to atmospheres with high values (1.000 ppm) of CO_2 versus normal levels (600 ppm) was carried out, in which performance levels in decision-making were significantly diminished [44]. Similar results were found in another study, where cognitive and concentration performances were assessed between indoor environments with high (2.000 ppm) and low (700 ppm) levels of CO_2. It was found that there was a minimum average decrease in the subject's performance of 5% in the results of the tests [45]. The size of the effects of having a bad IAQ in an office or productive environment on work performance appears to be as high as **6-10%** [46,47].

Therefore, by improving IAQ and especially decreasing CO_2 levels dissolved in indoor air, a performance improvement can be accomplished, impacting not only in the health and well-being of the building's occupants but also in economic aspects by improving employees' performance and the company's productivity. Also, if any investment is done with regards to IAQ improvement, the high cost of labor per unit floor area ensures that payback times will usually be as low as **1.4 - 2 years** [46,47].

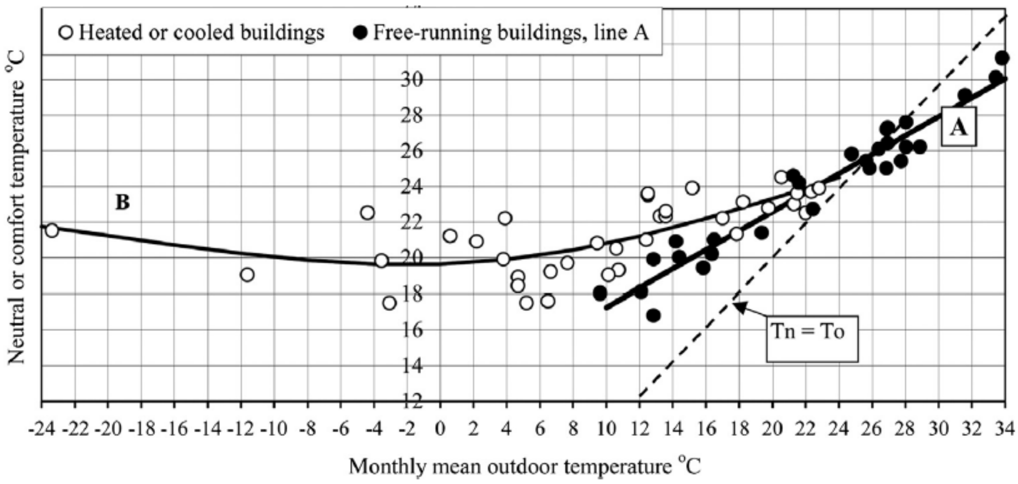
5.2.3. Thermal Comfort

From the selected social SPIs framework, thermal comfort has been selected as the one that can have the biggest and widest positive outcome to all the three pillars of sustainability; improving occupant's and users health & well-being, reducing the energy consumption of HVAC systems (whilst decreasing carbon footprint), and boosting productivity whilst reducing absenteeism. The focus of interest is the buildings with mechanical ventilation, as more control of the Indoor Environmental Parameters (IEP) system can be achieved. Thermal comfort has been defined as the "condition of mind that expresses satisfaction with the thermal environment", which ends up being a subjective evaluation of occupant's comfort with regards to IEQ; driven by outdoor parameters, IEP, and personal factors. [46]

- **Outdoor parameters:** One of the key parameters for indoor thermal comfort in a building depend on the outdoor atmospheric conditions of its placement. The geographic location of the building placement is the determining factor of which atmospheric conditions surround the building and its occupants. To classify these possible options, the most widely used classification until today has been the global Köppen climate zones, which cluster different areas around the globe by their atmospheric and meteorological conditions into A-Tropical climates, B-Dry climates, C-Mild temperate climates, D-Snow climates, and E-polar climates. In *appendix E*, information regarding the Köppen classification, main characteristics of the climate zones, and its localization in the globe are presented [48].

  As stated previously, due to climate change these climate zones will be displaced and shifted around the globe as seen in *appendix F*, which will affect specifically temperate zones but the temperature of every type of climate zone will increase progressively with the severity of the RCP [49]. These changes will affect the cooling and heating season during future years.

The most important parameter that influences in indoor thermal comfort of the occupants of a building is the mean outdoor air temperature. As seen in *graph 5.2.3.1*, Humphreys showed that indoor thermal comfort is a function of outdoor temperature [50].



Graph 5.2.3.1: Comfort temperature vs. Outside temperature [50]

Relative humidity and solar irradiance also have a relevant paper in the atmospheric conditions for the users, being factors to consider in the indoor parameters as the user transition from the outside to the inside should be unnoticed.

- **Indoor Environmental Parameters (IEP):** These are the set of parameters that help establish the adequate IEQ, which are the following:
  - **Air Temperature (t_a):** It is defined as the temperature of the air surrounding the occupant. It is worth mentioning that there are two types of air temperatures whilst studying thermal comfort: dry and wet bulb temperatures. The dry bulb temperature is the ambient temperature. The main difference with the wet-bulb temperature is a measure of the humidity of the air, as the wet-bulb essentially measures how much water vapor the indoor atmosphere can hold at current weather conditions.
  - **Relative Humidity (RH):** It is the ratio of the water vapor dissolved in the air compared to the water vapor dissolved in saturated air at the same atmospheric conditions. It quantifies the moisture of the air.
  - **Air Speed:** It is the rate of air movement at an indistinct point, without regard to its direction [51].

- **Mean Radiant Temperature (t_r):** It is a measure of the average temperature of the surfaces that surround a building occupant, with which it will exchange thermal radiation.
- **User Control:** It has been established that for occupants' thermal comfort it is necessary for them to have control over the IEP, to adjust the system to their thermal neutrality and satisfaction.

− **Personal factors:** These are the parameters that define the user's physiological characteristics and thermal needs, which vary from user to user due to the following parameters:
  - **Clothing Insulation**: It is the resistance to sensible heat transfer provided by a clothing ensemble [51]. The characteristics and amount of clothing will require different IEP to adjust every user's thermal satisfaction thresholds.
  - **Metabolic Rate**: It is described as the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism [51]. Every type of activity will require a different metabolic rate, as every task might have different energy demands.
  - **Thermal Sensitivity:** It is defined as the occupant's sensitivity to indoor temperature changes, interested in the overall body thermal sensitivity. This factor varies due to gender, age, and geographic origin of the user [52,61].

5.2.4. Operative IEP for adequate thermal comfort

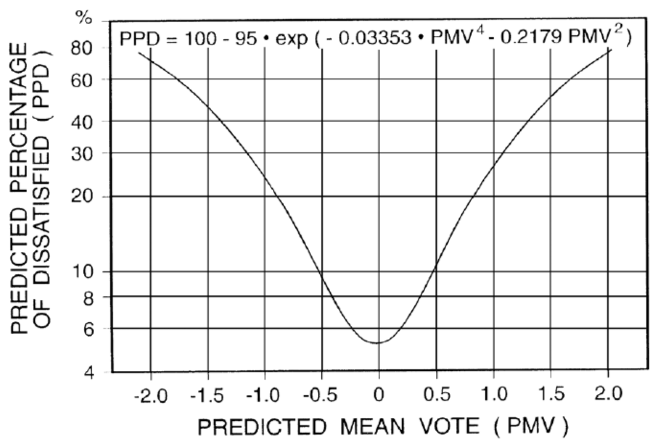
As the topic itself, thermal comfort and its development indices to find adequate IEP thresholds have evolved dynamically as during the last decades there have been more than 33 indices related to the topic [53]. For this reason, it is not a trivial task to establish general IEP thresholds for *Hilti's* facilities, as with upcoming findings these might have to be adjusted or modified.

To quantify the thermal sensation of users, surveys were used to obtain data about their perception of temperature in their working environments and subjects had to answer the ASHRAE or Bedford scale as seen in *table 5.2.4.1.* Out of these surveys, an average response of subjects along the mentioned scales is related to the previous thermal comfort factors mentioned above through the Predicted Mean Vote (PMV).

ASHRAE descriptor	Numerical equivalent	Bedford descriptor
Hot	3	Much too hot
Warm	2	Too hot
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cold
Cool	-2	Too cold
Cold	-3	Much too cold

Table 5.2.4.1: Descriptors for the ASHRAE and Bedford scale of thermal sensation [51]

Also, the Predicted Percentage of Dissatisfied (PPD) index is related to the PMV as defined in *figure 5.2.4.1*. It is based on the assumption that people voting +2, +3, -2, or -3 on the thermal sensation scale are dissatisfied and, on the simplification, that PPD is symmetric around a neutral or PMV [51].



Graph 5.2.4.1: Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV) [51]

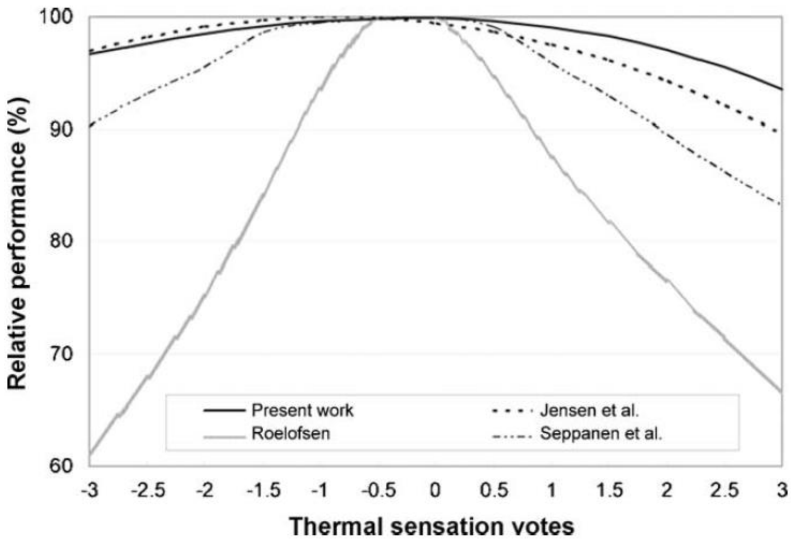
Using the PMV model to set an acceptable thermal sensation of the users, the different international standards set the following guidelines for the selected type of satisfaction along the users:

- **ISO 7730:** Category B, -0.5 < PMV <0.5
- **ASHRAE-55:** -0.5< PMV< +0.5; (PPD > 10)
- **EN 15251:** Category II, -0.5< PMV < 0.5

As it can be seen, following the percentage of satisfaction of 80% of the users, PMV should be between -0.5 (slightly cold) and +0.5 (slightly warm).

Also, it has been studied a direct impact on the PMV value and performance of workers, which as seen in *graph 5.2.4.2*, optimum performance is achieved when users feel slightly cool thereby it makes sense to set the PMV limits in workplaces in the range between -0.5 and 0 [55].

As it can be seen also in the same graph, it is worth remarking the negative influence on employees' performances as the PMV value rises on all performance studies [55-58].



Graph 5.2.4.2: Impact of thermal sensation on relative performance [55-58]

It is worth remarking that the type of building that the users are in, might lead to different ranges or thresholds of temperatures, as occupants of naturally ventilated buildings will be less sensitive to temperature changes (as they are more used to dealing with a wider range of temperatures) than occupants from air-conditioned or mix mode buildings (HVAC and operable windows) [52]. For this reason, the selected threshold will be for air-conditioned and mixed mode buildings, as are the ones which represent better the majority of *Hilti's* facilities.

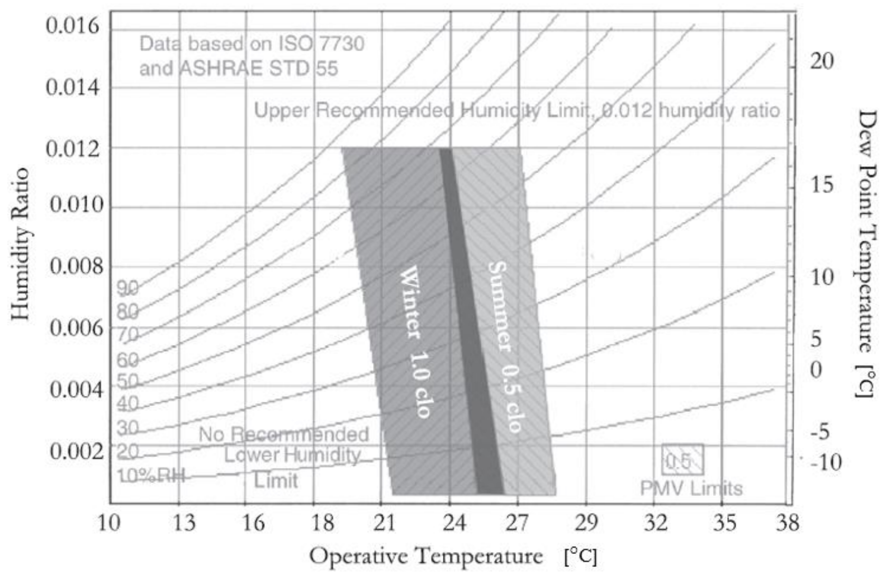
In the case of offices, department stores, and those facilities which require almost sedentary activities, the thresholds are set in *table 5.2.4.2*, complying with ASHRAE-55 and EN-16798 as the calculations have been made with airspeeds of 0.15 m/s (which avoids SBS symptoms as said before) and a general RH of 50% for air-conditioned buildings. It can also be seen that assumptions of average clothing insulation and metabolic rates have also been made to comply with the standards methodology.

The target of these calculations was to accomplish a negative PMV value, within the optimal performance values but at the same time minimizing PPD. The calculations have been done using the CBE Thermal Comfort Tool [59].

	Clothing insulation (clo)	Activity level (met)	Operative temperature range (°C)	Optimum operative temperature (°C)	PMV	PPD (%)
Winter	1	1.2	21-24	21.5	-0.20	6
Summer	0.5	1.2	24-27	25.5	-0.03	5

Table 5.2.4.2: Recommended thresholds for IEP in office /sedentary activities environments

If different values of RH need to be applied for another casuistic, either CBE Thermal Comfort Tool can be used with the desired values but aiming for similar values of PMV-PPD or graphically through *graph 5.2.4.3* (within 40-70% limits to avoid SBS symptoms) [40].



Graph 5.2.4.3: Acceptable range of operative temperature and humidity, with a maximum PPD of 10% [53]

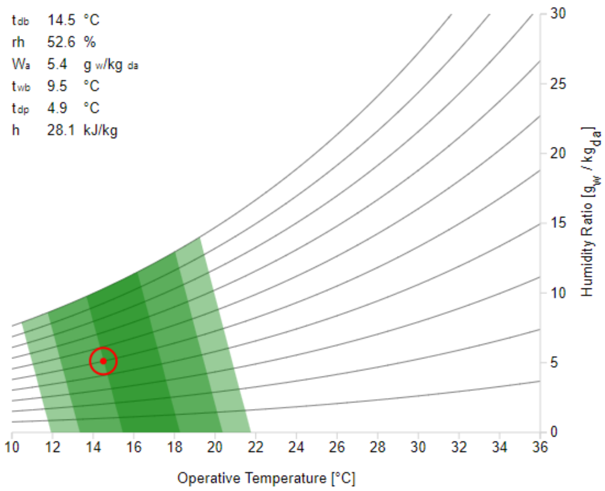
Conversely, for an air-conditioned industrial environment, different assumptions have been made as the type of activity developed by the employees and their needs are different, with a metabolic rate of 2.2 met, same general RH of 50%, same clothing insulation parameters for both winter and summer season as for the previous environment.

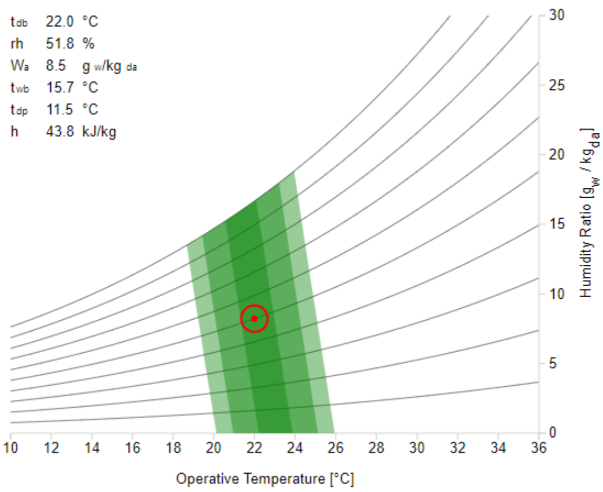
Different airspeeds supplies have been assumed, following the standards for industrial environments (an air maximum speed of 0.15 m/s during winter and 0.75 m/s during summer for soft work activities or light machine work) [60]. The same target of PMV-PPD values has been followed for these calculations using the same tool [59].

	Clothing insulation (clo)	Activity level (met)	Operative temperature range (°C)	Optimum operative temperature (°C)	PMV	PPD (%)
Winter	1	2.2	13-16	14.5	-0.20	6
Summer	0.5	2.2	20.5-23.5	22	-0.04	5

Table 5.2.4.3: Recommended thresholds for IEP in industrial or light machine work environments

If different values of RH need to be applied for another casuistic, either CBE Thermal Comfort Tool can be used with the desired values but aiming for similar values of PMV-PPD or graphically through *graph 5.2.4.4* (within 40-70% limits to avoid SBS symptoms) [40]. In both graphs, the red dot is the graphical representation on the psychrometric chart of the recommended values.





Graph 5.2.4.4: Psychrometric charts of industrial environments for a PPD lower than 10%, winter (left) and summer (right)

As stated before, providing a general and exact threshold of IEP for adequate thermal comfort for all *Hilti's* facilities is a complex task as many parameters from the building type, atmospheric and meteorological characteristics of its location, and the different activities taking place in the building requires an exact thermal comfort study for better and more comprehensive IEP thresholds. For this reason, a case study is proposed.

5.3. Thermal Comfort Case Study

To compare the applicability of the set thresholds for the different types of buildings within Hilti's facilities, the analysis of the IEP from a Hilti office building is proposed. The building, in particular, to be analyzed is the North Office Building (NOB) from Hilti's HQ Campus in Schaan, Liechtenstein. This particular building has been selected for this purpose for two main reasons:

- As it is a new construction building which has been recently inaugurated, it is easy to obtain data from its modern Building Management System (BMS). This BMS, controls its centralized HVAC system acting independently with the collected data from its sensors and the preset parameters. Screenshots of this system can be found in *appendix H.*
- The building's location in Hilti's HQ, makes the comprehension and physical analysis of its environment and surroundings much easier than any other building from Hilti's assets.

Figure 5.3.1: Picture of the North Office Building located in Hilti HQ in Schaan [62]

As it can be seen in *figure 5.3.1*, the building consists of a 4-story building mainly made of metal, glass, and concrete, and with external dimensions of 117 x 32 meters accommodating some 450 workstations along with all levels [62]. The spatial concept of the different floors has been designed to the latest findings and meet requirements for the digital workspace of the future, as open office areas promote communication and short distances ensure cross-collaboration along different teams and colleagues. The flexible desk principle has been implemented in these areas (and in other Hilti's facilities), which allows employees to choose their workplace according to their tasks and needs. The open office areas are complemented by meeting rooms and retreat areas that allow for focused work.

In terms of energy efficiency and comfort, the building has been certified with the Swiss Minergie-P Standard. For the building's heating, there is a heat recovery system from the close-by manufacturing plant. The exceeding heat from plant 1 is recovered in a heat exchanger, which heats a water circuit to transfer the thermal energy into the NOB's heating system as can be seen in *figure H.7* in *appendix H.* Heating in the NOB takes place by air through a network of five different HVAC systems, but also by radiation on floors and ceilings in specific areas. For instance, the basement has radiating floors as it is the coldest one. However, during the cooling season, the building relies mainly on HVAC.

5.3.1. IEP Outset Situation

As the building was started to be used by employees and other users in September 2021, there is not much data regarding past fluctuations of IEP due to atmospheric and meteorological events. As it is a new building also, it takes up to one year to adjust all the IEP. The only data available is from the current winter season and unfortunately, there is no data regarding the summer season. However, it is a great opportunity to analyze the actual thresholds, adjust them to the recommended levels and extract feedback from the building's occupants.

At the moment, due to technical limitations, IEP just has been set to steady-state values. Regarding the temperatures of the building, all rooms temperatures are set to 24 °C (open spaces and meeting rooms). In meeting rooms, the users can manually adjust the temperatures by +/- 1.5 °C if they want by physical actuators, meanwhile, in open spaces, users can request a temperature modification through a ServiceNow Ticket (Hilti's internal platform to manage requests). Regarding CO_2 levels (ppm), there is a preset value of 600 ppm where the ventilation system intervenes. The system maintains the CO_2 levels below the preselected values by itself. The humidity value for all areas is the same, as the fresh air is humidified in the ventilation system itself (a parameter that can be controlled in the HVAC centralized system but not in the monitored independent areas).

At first, glance, comparing the IAQ of the building to the recommended thresholds, levels of CO_2 are kept almost at the optimal values (≤500 ppm) as the system intervenes when the area monitored reaches a level of 600 ppm. Therefore, it can be stated that the air quality in the NOB is a good quality air that does not deplete performance neither induce symptomatology related to inadequate levels of carbon dioxide. No further analysis can be done regarding other pollutants that need to be monitored to avoid the SBS due to measuring limitations.

Evaluating RH, the average reading of RH is approximately 50%. This value is at the threshold of 40-70% which avoids SBS symptoms due to the level of moisture in the air [34].

Regarding temperature levels in the building, a differentiation needs to be done between open office spaces and meeting rooms. As commented previously, the temperature set for both spaces is 24 °C with user controllability through different means. At first look, this value is out of the recommended temperature threshold. However, if the preset value is compared to the average daily temperature readings of both spaces there is a significant difference (during the heating season). For open spaces along with all floors the average reading is 22.93 °C and for meeting rooms is 22.37 °C. This difference might be due to the thermal radiation of windows and the movement of users which induces air movement along with different spaces (such as outdoor air through building entrances). If calculated [59] with the reading values, the PMV values for both types of spaces would be respectively 0.13 for open spaces and -0.01 for meeting rooms. Both comply with the standards, but in the case of open spaces thermal sensation would feel slightly warm, which to boost productivity would have to be between -0.5 and 0.

As for the cooling season, there are no reading values yet, no further analysis can be performed.

5.3.2. Proposals for the North Office Building

After analyzing the current IEP of the building, it can be said that the HVAC system has been properly set at least for the heating season. However, by some literature review, some possible optimizations could be implemented and further tested in the building for both cooling and heating season. As identified by Guan [63] sensitivity of rooms to overheating might differ between floor levels and orientations. The high quality of the building and its airtightness allows better controllability of the IEQ by the HVAC system, as leaks of air and thermal energy have been minimized. For this reason, the stack effect[4] has been minimized and it can be observed in the temperature readings of every level of the building, which temperature does not increase with a height increase of the building. However, the orientation of the building to the sun has a relevant impact on indoor temperature through thermal radiation of the building. As seen in

[4] Stack Effect: Effect that occurs in buildings of more than one floor, when the outdoor temperature is significantly than the inside temperature. Hot indoor air rises and is buoyant and presses upward to exit the building through top floor openings.

appendix I, the sun cycles over the NOB are presented of all trajectories and their limits of June's and December's solstices.

As has been highlighted previously, one of the most complex tasks for providing thermal comfort to the building users is the adaptability of the system to the users' thermal needs and outdoor environmental phenomena. For this reason, the proposal, in this case, aims for user adaptability with a steady-state zone. Leveraging Hilti's flexible desk principles, the main proposal to bypass users' adaptability and to have a bigger rate of satisfaction among the occupants would be a creation of different climate zones on the different floors of the building. It would be the users, in this case, to move to the climatic zone of their thermal sensation preference.

As it can be seen in *figure 5.3.2.1,* climatic zones would be clustered mainly in two groups: slightly cold zones (1, 8, 7, 6) and slightly warm zones (2, 3, 4, 5). This distribution aims to leverage the sun's thermal radiation to improve occupant's thermal comfort and reducing energy consumption, especially during the cooling season.

<u>Figure 5.3.2.1:</u> Example off floor plan with climatic zones for NOB's level 2

In the floor map, zones 4 and 8 would be the warmest and the coldest respectively (accepted maximum and minimum threshold temperatures), meanwhile zones 1, 2, 3, 5, 6, 7 would be climatic transition zones with a ΔT of 0.75 °C.

5.4. Impact Discussion of Adequate Social SPIs Thresholds

IAQ and thermal comfort have been proved to be two of the most relevant and impactful criterion from social sustainability's social pillars, mainly due to their strong link with employee's perceived productivity, overall comfort and happiness. It is key, to improve IEQ as a holistic category because findings from different studies confirm the multidomain nature of how occupants perceive and report on their indoor conditions, what sets the basis for more research on facility management practices [65]. As improvements in IEQ and their long-term effects in users' health are difficult to track, the study of these improvements in SBS diseases is complex. Instead, it is believed that by minimizing short-term SBS symptomatology, it will decrease long-term SBS related diseases.

Regarding the NOB case study, a solution to bypass technical limitations of indoor conditions adaptation with mean outdoor temperature and phenomena has been proposed. By providing the users with the possibility of electing the climate zone that fits better to thermal needs every day, it is believed that user satisfaction and overall thermal comfort will rise. For the imminent future, with the digitalization of HVAC systems and implementation of IoT solutions, usability of predictive models or adaptive models for IEP adjustment to the outdoor conditions will increase.

As seen in *table 5.4.1*, the optimal solution would be to develop an adaptive control algorithm for every building's location, taking into consideration the local environmental and meteorological conditions to control better indoor temperatures utilizing the principles of adaptive comfort theory.

Country	**Adaptive control algorithm**	
	$T_{rm} \leq 10$ °C	$T_{rm} > 10$ °C
All	22.88 °C	$0.302 * T_{rm} + 19.39$
France	$0.049 * T_{rm} + 22.85$	$0.206 * T_{rm} + 21.42$
Greece	NA	$0.205 * T_{rm} + 21.69$
Portugal	$0.381 * T_{rm} + 18.12$	$0.381 * T_{rm} + 18.12$
Sweden	$0.051 * T_{rm} + 22.83$	$0.051 * T_{rm} + 22.83$
UK	$0.104 * T_{rm} + 22.85$	$0.168 * T_{rm} + 21.63$

Table 5.4.1: Adaptive comfort algorithms for individual countries [66]

5.5. Scalability of IEP thresholds implementation

One key factor for the long-term project's success is the scalability of the IEP thresholds implementation among the other Hilti's facilities around the globe. As highlighted in previous points, Hilti has different types of facilities in which a wide range of activities take place in them. By the type of activity, Hilti's facilities can be clustered in two main groups: sedentary or active facilities.

- **Sedentary facility**: Little or no physical activity is required on a daily work routine, tasks which have associated low metabolic rates or energy demand from the user (between 1-1.4 met). These type of facilities would include offices, Hilti stores, assembly lines in production plants and repair centers.
- **Active facility**: Moderate or heavy physical activity is demanded to perform a daily work routine, which have associated considerable metabolic rates or energy demand (between 2.2-4.8 met). These type of facilities would include logistics centers, warehouses and production plants.

For both type of facilities, indoor air quality thresholds would be applicable to all of them. The thresholds have been benchmarked along the different certifications and adjusted to prevent the users from SBS symptomatology. Therefore, the IAQ thresholds would be scalable to all Hilti's facilities.

Regarding the scalability of IEP for thermal comfort adjustment, for sedentary facilities the thresholds would be scalable as an average metabolic rate of 1.2 met of the users can be used, as the majority of sedentary tasks are performed the same way around the globe. In the case of active facilities, it is recommended to adjust the metabolic rate form the employees and recalculate the thermal comfort thresholds using the CBE comfort tool [59], as there might be bigger differences regarding metabolic rates assigned to the employee's tasks. Therefore, for sedentary facilities the recommended values can be used in many locations around the globe. However, for active facilities, it is recommended to adjust the values to enhance thermal comfort with the specific type of activity performed in the building, as the actual average metabolic rate of the activities performed in the location might differ significantly to the average used for the industrial facilities recommended thresholds.

It is worth mentioning that the lack of technical means and research, make the thresholds scalable, but the optimal process to follow would be to develop an adaptive model for every Hilti's Location to adjust the IEP to the mean outdoor temperature. By implementing adaptive models, users' tolerance to temperature adaptation would be improved as the indoor environment would adjust to the outdoor environment. As it has been stated previously, a weekly adjustment of IEP would enhance users' thermal comfort and minimize energy consumption. As seen in some cases, higher air speeds improve user's thermal sensitivity to high temperatures, technique that could be used to reduce energy consumption [67].

Finally, in many Hilti's locations, the implementation of IEQ sensors would be required to monitor and track the improvements or modifications regarding the IEP adjustments. This lack of sensors, data gathering, and display systems lead to users' unawareness of the quality of their indoor environment, that avoids any counteraction from them. A further and deeper study of the available sensing systems would be required locally in every location, as a general measuring solution would not apply to every location or facility.

6. Environmental impact

As commented during previous points, climate change will be a key factor of IEQ in the near future. Consumption of HVAC systems will increase due to the global temperature rise (minimum of 1.5 °C in the most optimistic scenario), as peak heating and cooling loads will be affected significantly by this rise and climate change effects. Peak heating loads are estimated to decrease by 40-100% and peak cooling loads are expected to increase by factor 1.3-2.6, which on average will have a direct impact on CO_2 emissions. CO_2 footprint is expected to be increased by 25% due to this situation [67]. For this reason, it is crucial to define and readjust IEQ to the dynamically changing environment whilst optimizing IEP to both reduce energy consumption and satisfy occupant's comfort expectations.

6.1. Energy savings from adequate social SPIs thresholds

It has been proved that providing occupants with an adequate IEQ by adjusting the IEP to a specific thresholds, not only it can improve productivity whilst reducing the potential diseases from SBS, but it can also decrease the energy consumption of buildings from HVAC systems. If the IEP are adjusted properly, occupants can avoid periods of overcooling or overheating that cause discomfort to building's occupants. It has been estimated, that by reducing 1 °C during the heating season or by increasing 1 °C during the cooling season, energy consumption from HVAC systems can be reduced by up to 10% [68].

As the recommended thresholds of IEP have not been implemented neither tested in the case of the NOB, there is not an exact value of the energy savings. However, by the modification of 1.5 °C in the case of the upcoming cooling season, savings of up to 15% are expected. In the case of the heating season instead, as the heating is recovered from exceeding heat from plant 1, no savings from heating are expected.

More energy savings for the other Hilti's facilities are expected, as by applying the recommended IEP thresholds more facilities would modify their energy consumption from all HVAC systems. Therefore, the room for improvement and the potential reduction of carbon footprint from HVAC energy savings are substantial.

7. Budget

For this section, an economic analysis of this master thesis is conducted by estimating the cost of this master thesis. An economic study of the impact on savings of the case study and the overall scalability of the project would have been very interesting, but due to the limited extent of the project, its timeline and lack of data from other Hilti's facilities it remained out of the scope of the project.

To develop this master thesis, a senior engineer and a junior engineer were involved. Senior engineer performed guidance and counseling tasks, advising the junior engineer on the course of the research and development of the thesis.

As seen in *table 7.1*, a summary of the overall costs of the thesis is presented.

Concept	Fare	Duration	Price (CHF)
ISO 20887	138 CHF	-	138
ISO 21929	158 CHF	-	158
ISO 21678	88 CHF	-	88
S. Engineer (counseling)	40 CHF/h	40h	1.600
J. Engineer (research)	2.000 CHF/month	4 months	8.000
VAT (12.5%)			1.248
TOTAL			11.232

Table 6.1: Summary table for the overall expenses of the master thesis

To conclude, the cost of this master thesis project ascends to eleven thousand two hundred and thirty-two Swiss francs.

8. Conclusions and Outlook

It has been proved along this master thesis that sustainability is a topic which is raising awareness in the construction and building sectors along its different pillars. Also, occupants' and users' health & well-being is gaining awareness among the sectors' main stakeholders.

One of the main aims of this thesis, was to study the different certifications that rate sustainability in buildings, from different points of view and areas of interest, and to select a framework of SPIs to analyze and track sustainability within Hilti's facilities. Also, it has been possible to narrow down the pillar and criterion which would positively impact the most along the three pillars of sustainability. The NOB case study has been useful to see the feasibility of the SPIs thresholds, possible solutions for existing Hilti buildings, and scalability of the implementation.

To conclude this master thesis, a response is given to the research questions that were proposed at the beginning of the study, based on the research that has been done.

RQ1: What is the definition of a sustainable building within Hilti's assets?

After analyzing in-depth, the selected certifications and understanding what the key criterion was to them, the best way to define what is a sustainable building is through a graphic representation as in *figure 8.1.*

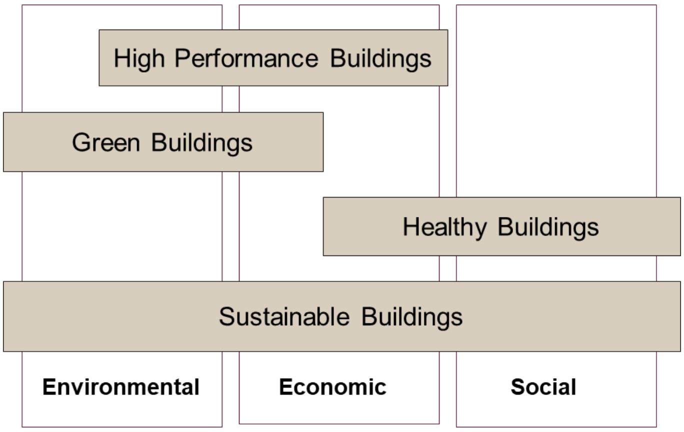


Figure 8.1: Graphic definition of a sustainable building

A sustainable building should be a comprehensive and holistic solution, overlapping the responsibilities of green, high performance and healthy building, aiming to cover the three pillars of sustainability: minimizing its environmental footprint, optimizing economic aspects, and maximizing its positive social impact on people but more important, in society.

A framework of SPIs has been proposed to assess, track and monitor sustainability along Hilti buildings. Its trackability, depends on mainly available data or accessible with small studies or implementation of small sensors systems.

RQ2: How to make it scalable within the Hilti Group?

As it has been proposed during the thesis, scalability of the SPIs is viable if implemented, developed and tracked locally, as data is much easier to obtain, analyze and monitor. Local knowledge is required to assess better the information collected for further adjustments and optimizations.

Limitations of the master thesis

The main three limitations that have been encountered during the development of this master thesis have been:

- The timeframe of the master thesis has not been sufficient to extract more detailed bases for all the SPIs framework and for developing more guidelines along the different pillars of sustainability. Also, due to time limitations there has been no possibility to implement and test any of the directions or guidelines recommended along the thesis to pursue more sustainable buildings within Hilti's facilities.

- Also, providing a general statement for specific SPIs has been a challenge. Assumptions have been made in order to provide these statements, but at the same time new directions for further investigations on the topic of sustainability on buildings have been encountered and will be proposed to improve Hilti's facilities and achieve a wider spectrum of SDGs.

- Limitations regarding the extent and the scope of the thesis have also been challenging, as it would have been very interesting to apply the recommended thresholds in more than one location and observe the real outcome and economic savings of the scalability of the project.

Directions for further research

Due to the limitations of this master thesis, new directions for further research have been discovered. Due to Hilti's approach of covering the topic of sustainable buildings holistically, it gives room for future studies on different fields of the construction and building management sectors.

There is the need to measure the improvements on the soft side effects on building's occupants of an improved IEQ within Hilti's facilities, applying the recommended thresholds within different type of building and measuring user satisfaction, happiness, productivity, improvements in health & well-being and absenteeism to validate the guidelines and quantify improvements in the social pillar of sustainability.

It is also recommended to develop further improvement strategies along the other two pillars of sustainability in buildings, specifically in the circularity and recyclability in existing and new buildings within Hilti's assets, studying the implementation of circularity tools such as C2C certifications and material passports for buildings.

Finally, it would be highly recommendable to pursue a more specific analysis regarding thermal comfort in a specific location of a Hilti building (such as Hilti's Headquarters) and to study the possibility of implementing an adaptive approach to thermal comfort, by developing an Adaptive Control Algorithm for the specific location and HVAC system. HVAC digitalization and merger with BMS, by including IoT solutions and predictive usage of spaces whilst adapting to the outdoor mean temperature with the ACA providing an optimal IEQ to its occupants.

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APPENDICES

APPENDIX A. CERTIFICATIONS WEIGHTINGS AND RATINGS

Table A.1. DGNB Weighting of the Criteria [19]

Topic	Criterion	Description	Office	Department store	Logistics	Production
ENV	ENV1.1	Building life cycle assessment	9.5%	9.5%	9.5%	9.5%
	ENV1.2	Local environmental impact	4.7%	4.7%	4.7%	4.7%
	ENV1.3	Sustainable resource extraction	2.4%	2.4%	2.4%	2.4%
	ENV2.2	Potable water demand and waste water volume	2.4%	2.4%	2.4%	2.4%
	ENV2.3	Land use	2.4%	2.4%	2.4%	2.4%
	ENV2.4	Biodiversity at the site	1.2%	1.2%	1.2%	1.2%
ECO	ECO1.1	Life cycle cost	10.0%	10.0%	10.0%	12.9%
	ECO2.1	Flexibility and adaptability	7.5%	7.5%	7.5%	9.6%
	ECO2.2	Commercial viability	5.0%	5.0%	5.0%	0.0%
SOC	SOC1.1	Thermal comfort	4.1%	4.5%	4.3%	4.3%
	SOC1.2	Indoor air quality	5.1%	4.5%	5.4%	5.4%
	SOC1.3	Acoustic comfort	2.0%	0.0%	0.0%	0.0%
	SOC1.4	Visual comfort	3.1%	3.4%	3.2%	3.2%
	SOC1.5	User control	2.0%	2.3%	0.0%	0.0%
	SOC1.6	Quality of indoor and outdoor spaces	2.0%	2.3%	5.4%	5.4%
	SOC1.7	Safety and security	1.0%	1.1%	4.3%	4.3%
	SOC2.1	Design for all	3.1%	4.5%	0.0%	0.0%
TEC	TEC1.1	Fire safety	2.5%	2.9%	2.7%	2.7%
	TEC1.2	Sound insulation	1.9%	0.0%	0.0%	0.0%
	TEC1.3	Quality of the building envelope	2.5%	2.1%	2.7%	2.7%
	TEC1.4	Use and integration of building technology	1.9%	2.1%	2.0%	2.0%
	TEC1.5	Ease of cleaning building components	1.3%	1.4%	1.4%	1.4%
	TEC1.6	Ease of recovery and recycling	2.5%	2.9%	2.7%	2.7%
	TEC1.7	Immissions control	0.6%	1.4%	1.4%	1.4%
	TEC3.1	Mobility infrastructure	1.9%	2.1%	2.0%	2.0%
PRO	PRO1.1	Comprehensive project brief	1.6%	1.6%	1.6%	1.6%
	PRO1.4	Sustainability aspects in tender phase	1.6%	1.6%	1.6%	1.6%
	PRO1.5	Documentation for sustainable management	1.1%	1.1%	1.1%	1.1%
	PRO1.6	Urban planning and design procedure	1.6%	1.6%	1.6%	1.6%
	PRO2.1	Construction site/construction process	1.6%	1.6%	1.6%	1.6%
	PRO2.2	Quality assurance of the construction	1.6%	1.6%	1.6%	1.6%
	PRO2.3	Systematic commissioning	1.6%	1.6%	1.6%	1.6%
	PRO2.4	User communication	1.1%	1.1%	1.1%	1.1%
	PRO2.5	FM-compliant planning	0.5%	0.5%	0.5%	0.5%
SITE	SITE1.1	Local environment	1.1%	1.1%	1.1%	1.1%
	SITE1.2	Influence on the district	1.1%	1.1%	1.1%	1.1%
	SITE1.3	Transport access	1.1%	1.1%	1.1%	1.1%
	SITE1.4	Access to amenities	1.7%	1.7%	1.7%	1.7%

Environmental Quality — Economic Quality — Sociocultural and Functional Quality — Technical Quality — Process Quality — Site Quality

Table A.2. BREEAM Rating of the Criteria [21]

Category	Weight (fully fitted, non residential)	Criterion	Description	Credits	Weight (non residential)
Management	11%	Man 01	Project brief and design	4	2.1%
		Man 02	Life cycle cost and service life planning	4	2.1%
		Man 03	Responsible construction practices	6	3.1%
		Man 04	Commissioning and handover	4	2.1%
		Man 05	Aftercare	3	1.6%
Health and wellbeing	19%	Hea 01	Visual comfort	6	4.6%
		Hea 02	Indoor air quality	5	3.8%
		Hea 03	Safe containment in laboratories	2	1.5%
		Hea 04	Thermal comfort	3	2.3%
		Hea 05	Acoustic performance	4	3.0%
		Hea 06	Accessibility	2	1.5%
		Hea 07	Hazards	1	0.8%
		Hea 08	Private space	1	0.8%
		Hea 09	Water quality	1	0.8%
Energy	20%	Ene 01	Reduction of energy use and carbon emissions	15	8.1%
		Ene 02a	Energy monitoring (metering systems, sub-meters)	2	1.1%
		Ene 02b	Energy monitoring (display devices)	2	1.1%
		Ene 03	External lighting	1	0.5%
		Ene 04	Low carbon design	3	1.6%
		Ene 05	Energy efficient cold storage	3	1.6%
		Ene 06	Energy efficient transport systems	3	1.6%
		Ene 07	Energy efficient laboratory systems	5	2.7%
		Ene 08	Energy efficient equipment	2	1.1%
		Ene 09	Drying space	1	0.5%
Transport	6%	Tra 01	Public transport accessibility	5	2.3%
		Tra 02	Proximity to amenities	2	0.9%
		Tra 03a,b	Alternative modes of transport	2	0.9%
		Tra 04	Maximum car parking capacity	2	0.9%
		Tra 05	Travel plan	1	0.5%
		Tra 06	Home office	1	0.5%
Water	7%	Wat 01	Water consumption	5	3.5%
		Wat 02	Water monitoring	1	0.7%
		Wat 03	Water leak detection and prevention	3	2.1%
		Wat 04	Water efficient equipment	1	0.7%
Materials	13%	Mat 01	Life cycle impacts	6	6.5%
		Mat 02	Hard landscaping and boundary protection	N/A	N/A
		Mat 03	Responsible sourcing of construction products	4	4.3%
		Mat 04	Insulation	N/A	N/A
		Mat 05	Designing for durability and resilience	1	1.1%
		Mat 06	Material efficiency	1	1.1%
Waste	6%	Wst 01	Construction waste management	3	1.8%
		Wst 02	Recycled aggregates	1	0.6%
		Wst 03a	Operational waste	1	0.6%
		Wst 03b	Operational waste	2	1.2%
		Wst 04	Speculative finishes	1	0.6%
		Wst 05	Adaptation to climate change	1	0.6%
		Wst 06	Functional adaptability	1	0.6%
Land use and ecology	8%	LE 01	Site selection	3	2.4%
		LE 02	Ecological value of site and protection of ecological f	2	1.6%
		LE 03	Minimizing impact on existing site ecology	N/A	N/A
		LE 04	Enhancing site ecology	3	2.4%
		LE 05	Long term impact on biodiversity	2	1.6%
Pollution	10%	Pol 01	Impact of refrigerants	4	3.1%
		Pol 02	NOx emissions	2	1.5%
		Pol 03	Surface water run-off	5	3.8%
		Pol 04	Reduction of night time light pollution	1	0.8%
		Pol 05	Reduction of noise pollution	1	0.8%
Innovation (additional)	10%	Extra			

Table A.3. LEED Rating of the Criteria [22]

Category	Criterion	Description	Credits	Weight
Integrative Process	Integrative process	To support high-performance, cost-effective, equitable project outcomes through an early analysis of the interrelationships among systems.	1	0.8%
Location and transportation	Neighborhood Development Location	To avoid development on inappropriate sites. To reduce vehicle distance traveled. To enhance livability and improve human health by encouraging daily physical activity.	16	12.7%
	Sensitive land protection	To cultivate community resilience, avoid the development of environmentally sensitive lands that provide critical ecosystem services and reduce the environmental impact from the location of a building on a site.	1	0.8%
	High priority site and equitable development	To build the economic and social vitality of communities, encourage project location in areas with development constraints and promote the ecological, cultural, and community health of the surrounding area while understanding the needs and goals of existing residents and businesses.	2	1.6%
	Surrounding density and diverse uses	To conserve land and protect farmland and wildlife habitat by encouraging development in areas with existing infrastructure. To support neighborhood and local economies, promote walkability, and low or no carbon transportation, and reduce vehicle distance traveled for all. To improve public health by encouraging daily physical activity.	5	4.0%
	Access to quality transit	To encourage development in locations shown to have multimodal transportation choices or otherwise reduced motor vehicle use, thereby reducing greenhouse gas emissions, air pollution, and other environmental and public health harms associated with motor vehicle use.	5	4.0%
	Bicycle facilities	To promote bicycling and transportation efficiency and reduce vehicle distance traveled. To improve public health by encouraging utilitarian and recreational physical activity.	1	0.8%
	Reduced parking footprint	To minimize the environmental harms associated with parking facilities, including automobile dependence, land consumption, and rainwater runoff.	1	0.8%
	Electric vehicles	To reduce pollution by promoting alternatives to conventionally fueled automobiles.	1	0.8%
Sustainable sites	Site assessment	To assess site conditions, environmental justice concerns, and cultural and social factors, before design to evaluate sustainable options and inform related decisions about site design.	1	0.8%

	Protect or restore habitat	To conserve existing natural areas and restore damaged areas to provide habitat and promote biodiversity.	2	1.6%
	Open space	To create exterior open space that encourages interaction with the environment, social interaction, passive recreation, and physical activities.	1	0.8%
	Rainwater management	To reduce runoff volume and improve water quality by replicating the natural hydrology and water balance of the site, based on historical conditions and undeveloped ecosystems in the region to avoid contributing to flooding downstream in frontline communities.	3	2.4%
	Heat island reduction	To minimize inequitable effects on microclimates and human, especially frontline communities, and wildlife habitats by reducing heat islands.	2	1.6%
	Light pollution reduction	To increase night sky access, improve nighttime visibility, and reduce the consequences of development for wildlife and people.	1	0.8%
Water efficiency	Outdoor water use reduction	To reduce outdoor potable water consumption and preserve no and low-cost potable water resources.	2	1.6%
	Indoor water use reduction	To reduce indoor potable water consumption and preserve no and low-cost potable water resources.	6	4.8%
	Optimize process water use	To conserve low cost potable water resources used for mechanical processes while controlling corrosion and scale in the condenser water system.	2	1.6%
	Water metering	To conserve low cost potable water resources and support water management and identify opportunities for additional water savings by tracking water consumption.	1	0.8%
Energy and atmosphere	Optimize energy performance	To achieve increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic harms associated with excessive energy use that disproportionately impact frontline communities.	18	14.3%
	Enhanced commissioning	To further support the design, construction, and eventual operation of a project that meets the owner's project requirements for energy, water, indoor environmental quality, and durability.	6	4.8%
	Advanced energy metering	To support energy management and identify opportunities for additional energy savings by tracking building-level and system-level energy use	1	0.8%
	Renewable energy	To reduce the environmental and economic harms associated with fossil fuel energy and reduce greenhouse gas emissions by increasing the supply of renewable energy projects and foster a just transition to a green economy.	5	4.0%

	Enhanced refrigerant management	To eliminate ozone depletion and global warming potential and support early compliance with the Montreal Protocol, including the Kigali Amendment, while minimizing direct contributions to climate change.	1	0.8%
	Grid Harmonization	To increase participation in demand response technologies and programs that make energy generation and distribution systems more affordable and more efficient, increase grid reliability, and reduce greenhouse gas emissions.	1	0.8%
Materials and resources	Building life-cycle impact reduction	To encourage adaptive reuse and optimize the environmental performance of products and materials.	5	4.0%
	Environmental product declarations	To encourage the use of products and materials for which life-cycle information is available and that have environmentally, economically, and socially preferable life-cycle impacts. To reward project teams for selecting products from manufacturers who have verified improved environmental life-cycle impacts.	2	1.6%
	Sourcing of raw materials	To encourage the use of products and materials for which life cycle information is available and that have environmentally, economically, and socially preferable life cycle impacts. To reward project teams for selecting products verified to have been extracted or sourced in a responsible manner.	2	1.6%
	Material ingredients	To encourage the use of products and materials for which life-cycle information is available and that have environmentally, economically, and socially preferable life-cycle impacts. To reward project teams for selecting products for which the chemical ingredients in the product are inventoried using an accepted methodology and for selecting products verified to minimize the use and generation of harmful substances. To reward raw material manufacturers who produce products verified to have improved life-cycle impacts.	2	1.6%
	Construction and demolition waste management	To reduce construction and demolition waste disposed of in landfills and incineration facilities through waste prevention and by reusing, recovering, and recycling materials, and conserving resources for future generations. To delay the need for new landfill facilities that are often located in frontline communities and create green jobs and materials markets for building construction services.	2	1.6%
Indoor Environmental Quality (IEQ)	Enhanced indoor air quality strategies	To promote occupants' comfort, well-being, and productivity by improving indoor air quality	2	1.6%

	Low-emitting materials	To reduce concentrations of chemical contaminants that can damage air quality and the environment, and to protect the health, productivity, and comfort of installers and building occupants.	3	2.4%
	Construction indoor air quality management plan	To promote the well-being of construction workers and building occupants by minimizing indoor air quality problems associated with construction and renovation.	1	0.8%
	Indoor air quality assessment	To establish better quality indoor air in the building after construction and during occupancy to protect human health, productivity, and wellbeing.	2	1.6%
	Thermal comfort	To promote occupants' productivity, comfort, and well-being by providing quality thermal comfort.	1	0.8%
	Interior lighting	To promote occupants' productivity, comfort, and well-being by providing high-quality lighting.	2	1.6%
	Daylight	To connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.	3	2.4%
	Quality views	To give building occupants a connection to the natural outdoor environment by providing quality views.	1	0.8%
	Acoustic performance	To provide workspaces and classrooms that promote occupants' well-being, productivity, and communications through effective acoustic design.	1	0.8%
Innovation	Social equity within the supply chain	Encourage any and all members of the project team to promote and further social equity by integrating strategies that address identified social and community issues, needs and disparities among those affected by the project by: -Promoting fair trade, respect for human rights, and other equity practices among disadvantaged communities; -Creating more equitable, healthier environments for those affected by manufacturing of the materials created for the project.	1	0.8%
	Innovation	To encourage projects to achieve exceptional or innovative performance to benefit human and environmental health and equity. To foster LEED expertise throughout building design, construction, and operation and collaboration toward project priorities.	5	4.0%
	LEED accredited professional	To encourage the team integration required by a LEED project and to streamline the application and certification process.	1	0.8%
Regional priority	Regional priority	To provide an incentive for the achievement of credits that address geographically specific environmental, social equity, and public health priorities.	4	3.2%

Table A.3. WELL Weighting of the Criteria [23]

Category	Criterion	Description	Credits	Weight
Air	A01.1	Meet Thresholds for Particulate Matter	Required	N/A
	A01.2	Meet Thresholds for Organic Gases	Required	N/A
	A01.3	Meet Thresholds for Inorganic Gases	Required	N/A
	A01.4	Meet Thresholds for Radon	Required	N/A
	A01.5	Monitor Air Parameters	Required	N/A
	A02.1	Prohibit Indoor Smoking	Required	N/A
	A02.2	Prohibit Outdoor Smoking	Required	N/A
	A03.1	Ensure Adequate Ventilation	Required	N/A
	A04.1	Mitigate Construction Pollution	Required	N/A
	A05.1	Meet Enhanced Thresholds for Particulate Matter	2	0.89%
	A05.2	Meet Enhanced Thresholds for Organic Gases	1	0.44%
	A05.3	Meet Enhanced Thresholds for Inorganic Gases	1	0.44%
	A06.1	Increase Outdoor Air Supply	2	0.89%
	A06.2	Improve Ventilation Effectiveness	1	0.44%
	A07.1	Provide Operable Windows	1	0.44%
	A07.2	Manage Window Use	1	0.44%
	A08.1	Install Indoor Air Monitors	1	0.44%
	A08.2	Promote Air Quality Awareness	1	0.44%
	A09.1	Design Healthy Entryways	1	0.44%
	A09.2	Perform Envelope Commissioning	1	0.44%
	A10.1	Manage Combustion	1	0.44%
	A11.1	Manage Pollution and Exhaust	1	0.44%
	A12.1	Implement Particle Filtration	1	0.44%
	A13.1	Improve Supply Air	1	0.44%
	A14.1	Implement Ultraviolet Treatment for HVAC Surfaces	1	0.44%
Water	W01.1	Verify Water Quality Indicators	Required	N/A
	W02.1	Meet Chemical Thresholds	Required	N/A
	W02.2	Meet Thresholds for Organics and Pesticides	Required	N/A
	W03.1	Monitor Chemical and Biological Water Quality	Required	N/A
	W03.2	Implement Legionella Management Plan	Required	N/A
	W04.1	Meet Thresholds for Drinking Water Taste	1	0.44%
	W05.1	Assess and Maintain Drinking Water Quality	2	0.89%
	W05.2	Promote Drinking Water Transparency	1	0.44%
	W06.1	Ensure Drinking Water Access	1	0.44%
	W07.1	Design Envelope for Moisture Protection	1	0.44%
	W07.2	Design Interiors for Moisture Management	1	0.44%
	W07.3	Implement Mold and Moisture Management Plan	1	0.44%
	W08.1	Provide Bathroom Accommodations	1	0.44%

	W08.2	Enhance Bathroom Accommodations	1	0.44%
	W08.3	Support Effective Handwashing	1	0.44%
	W08.4	Provide Handwashing Supplies and Signage	1	0.44%
	W09ß.1	Implement Safety Plan for Non-Potable Water Capture and Reuse	2	0.89%
Nourishment	N01.1	Provide Fruits and Vegetables	Required	N/A
	N01.2	Promote Fruit and Vegetable Visibility	Required	N/A
	N02.1	Provide Nutritional Information	Required	N/A
	N02.2	Address Food Allergens	Required	N/A
	N02.3	Label Sugar Content	Required	N/A
	N03.1	Limit Total Sugars	1	0.44%
	N03.2	Promote Whole Grains	1	0.44%
	N04.1	Optimize Food Advertising	1	0.44%
	N05.1	Limit Artificial Ingredients	1	0.44%
	N06.1	Promote Healthy Portions	1	0.44%
	N07.1	Provide Nutrition Education	1	0.44%
	N08.1	Support Mindful Eating	2	0.89%
	N09.1	Accommodate Special Diets	1	0.44%
	N09.2	Label Food Allergens	1	0.44%
	N10.1	Provide Meal Support	1	0.44%
	N11.1	Implement Responsible Sourcing	1	0.44%
	N12.1	Provide Gardening Space	2	0.89%
	N13.1	Ensure Local Food Access	1	0.44%
	N14ß.1	Limit Red and Processed Meats	1	0.44%
Light	L01.1	Provide Indoor Light	Required	N/A
	L02.1	Provide Visual Acuity	Required	N/A
	L03.1	Meet Lighting for Day-Active People	3	1.33%
	L04.1	Manage Glare from Electric Lighting	2	0.89%
	L05.1	Implement Daylight Plan	2	0.89%
	L05.2	Integrate Solar Shading	2	0.89%
	L06.1	Conduct Daylight Simulation	2	0.89%
	L07.1	Balance Visual Lighting	1	0.44%
	L08.1	Enhance Color Rendering Quality	1	0.44%
	L08.2	Manage Flicker	2	0.89%
	L09.1	Enhance Occupant Controllability	2	0.89%
	L09.2	Provide Supplemental Lighting	1	0.44%
Movement	V01.1	Design Active Buildings and Communities	Required	N/A
	V02.1	Support Visual Ergonomics	Required	N/A
	V02.2	Provide Height-Adjustable Work Surfaces	Required	N/A
	V02.3	Provide Chair Adjustability	Required	N/A
	V02.4	Provide Support at Standing Workstations	Required	N/A
	V02.5	Provide Workstation Orientation	Required	N/A
	V03.1	Design Aesthetic Staircases	1	0.44%
	V03.2	Integrate Point-of-Decision Signage	1	0.44%

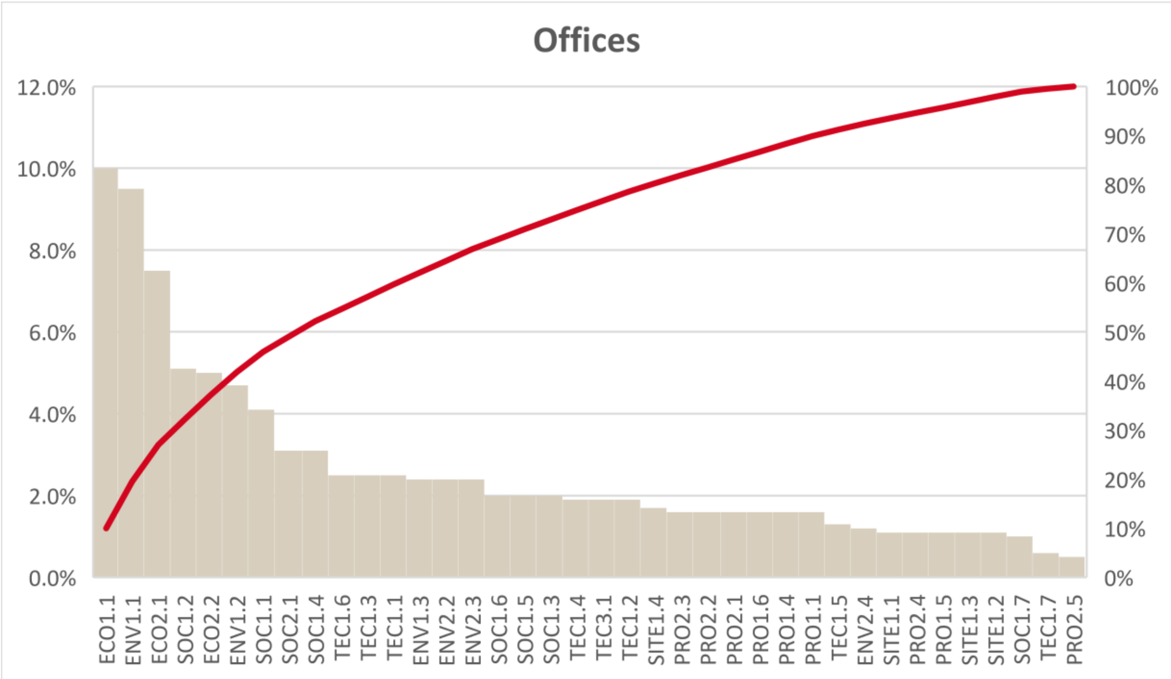
	V03.3	Promote Visible Stairs	1	0.44%
	V04.1	Provide Cycling Infrastructure	2	0.89%
	V04.2	Provide Showers, Lockers and Changing Facilities	1	0.44%
	V05.1	Select Sites with Pedestrian-friendly Streets	2	0.89%
	V05.2	Select Sites with Access to Mass Transit	2	0.89%
	V06.1	Offer Physical Activity Opportunities	2	0.89%
	V07.1	Provide Active Workstations	2	0.89%
	V08.1	Provide Indoor Activity Spaces	1	0.44%
	V08.2	Provide Outdoor Physical Activity Space	1	0.44%
	V09.1	Offer Physical Activity Incentives	1	0.44%
	V10.1	Provide Self-Monitoring Tools	1	0.44%
	V11ß.1	Implement an Ergonomics Program	1	0.44%
	V11ß.2	Commit to Ergonomic Improvements	1	0.44%
	V11ß.3	Support Remote Work Ergonomics	1	0.44%
Thermal comfort	T01.1	Provide Acceptable Thermal Environment	Required	N/A
	T01.2	Monitor Thermal Parameters	Required	N/A
	T02.1	Survey for Thermal Comfort	3	1.33%
	T03.1	Provide Thermostat Control	2	0.89%
	T04.1	Provide Personal Cooling Options	1	0.44%
	T04.2	Provide Personal Heating Options	1	0.44%
	T04.3	Allow Flexible Dress Code	1	0.44%
	T05.1	Implement Radiant Heating	1	0.44%
	T05.2	Implement Radiant Cooling	1	0.44%
	T06.1	Monitor Thermal Environment	1	0.44%
	T07.1	Manage Relative Humidity	1	0.44%
	T08ß.1	Provide Windows with Multiple Opening Modes	1	0.44%
	T09ß.1	Manage Outdoor Heat	1	0.44%
	T09ß.2	Avoid Excessive Wind	1	0.44%
	T09ß.3	Support Outdoor Nature Access	1	0.44%
Sound	S01.1	Label Acoustic Zones	Required	N/A
	S01.2	Provide Acoustic Design Plan	Required	N/A
	S02.1	Limit Background Noise Levels	3	1.33%
	S03.1	Design for Sound Isolation at Walls and Doors	1	0.44%
	S03.2	Achieve Sound Isolation at Walls	2	0.89%
	S04.1	Achieve Reverberation Time Thresholds	2	0.89%
	S05.1	Implement Sound Reducing Surfaces	2	0.89%
	S06.1	Provide Minimum Background Sound	1	0.44%
	S06.2	Provide Enhanced Speech Reduction	1	0.44%
	S07ß.1	Specify Impact Noise Reducing Flooring	1	0.44%
	S07ß.2	Meet Thresholds for Impact Noise Rating	2	0.89%
	S08ß.1	Provide Enhanced Speech Intelligibility	1	0.44%
	S08ß.2	Prioritize Audio Devices and Policies	1	0.44%
	S09ß.1	Implement a Hearing Health Conservation Program	1	0.44%
Materials	X01.1	Restrict Asbestos	Required	N/A

	X01.2	Restrict Mercury	Required	N/A
	X01.3	Restrict Lead	Required	N/A
	X02.1	Manage Asbestos Hazards	Required	N/A
	X02.2	Manage Lead Paint Hazards	Required	N/A
	X02.3	Manage Polychlorinated Biphenyl (PCB) Hazards	Required	N/A
	X03.1	Manage Exterior CCA Hazards	Required	N/A
	X03.2	Manage Lead Hazards	Required	N/A
	X04.1	Assess and Mitigate Site Hazards	1	0.44%
	X05.1	Select Compliant Interior Furnishings	1	0.44%
	X05.2	Select Compliant Architectural and Interior Products	1	0.44%
	X06.1	Limit VOCs from Wet-Applied Products	2	0.89%
	X06.2	Restrict VOC Emissions from Furniture, Architectural and Interior Products	2	0.89%
	X07.1	Select Products with Disclosed Ingredients	1	0.44%
	X07.2	Select Products with Enhanced Ingredient Disclosure	1	0.44%
	X07.3	Select Products with Third-Party Verified Ingredients	1	0.44%
	X08.1	Select Materials with Enhanced Chemical Restrictions	1	0.44%
	X08.2	Select Optimized Products	1	0.44%
	X09.1	Implement a Waste Management Plan	1	0.44%
	X10.1	Manage Pests	1	0.44%
	X11.1	Improve Cleaning Practices	1	0.44%
	X11.2	Select Preferred Cleaning Products	1	0.44%
	X12ß.1	Reduce Respiratory Particle Exposure	1	0.44%
	X12ß.2	Address Surface Hand Touch	1	0.44%
Mind	M01.1	Promote Mental Health and Well-being	Required	N/A
	M02.1	Provide Connection to Nature	Required	N/A
	M02.2	Provide Connection to Place	Required	N/A
	M03.1	Offer Mental Health Screening	1	0.44%
	M03.2	Offer Mental Health Services	1	0.44%
	M03.3	Offer Workplace Support	1	0.44%
	M03.4	β Support Mental Health Recovery	1	0.44%
	M04.1	Offer Mental Health Education	1	0.44%
	M04.2	Offer Mental Health Education for Managers	1	0.44%
	M05.1	Develop Stress Management Plan	2	0.89%
	M06.1	Support Healthy Working Hours	1	0.44%
	M06.2	Provide Nap Policy and Space	1	0.44%
	M07.1	Provide Restorative Space	1	0.44%
	M08.1	Provide Restorative Programming	1	0.44%
	M09.1	Provide Nature Access Indoors	1	0.44%
	M09.2	Provide Nature Access Outdoors	1	0.44%
	M10.1	Provide Tobacco Cessation Resources	2	0.89%
	M10.2	Limit Tobacco Availability	1	0.44%
	M11.1	Offer Substance Use Education	1	0.44%
	M11.2	Provide Substance Use and Addiction Services	1	0.44%

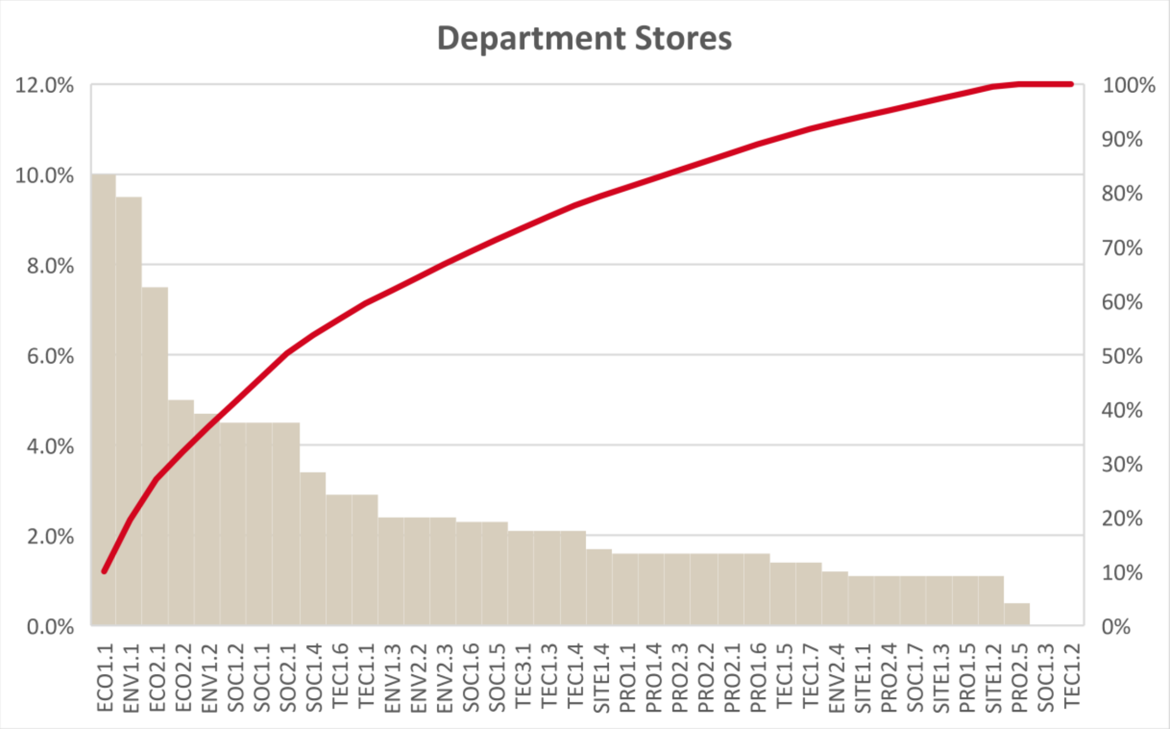
Community	C01.1	Provide WELL Feature Guide	Required	N/A
	C02.1	Facilitate Stakeholder Charrette	Required	N/A
	C02.2	Promote Health-Oriented Mission	Required	N/A
	C03.1	Develop Emergency Preparedness Plan	Required	N/A
	C04.1	Select Project Survey	Required	N/A
	C04.2	Administer Survey and Report Results	Required	N/A
	C05.1	Utilize Enhanced Survey	1	0.44%
	C05.2	Utilize Pre- and Post-Occupancy Survey	1	0.44%
	C05.3	Implement Action Plan	1	0.44%
	C05.4	Facilitate Interviews, Focus Groups and/or Observation	1	0.44%
	C06.1	Promote Health Benefits	1	0.44%
	C06.2	Offer On-Demand Health Services	1	0.44%
	C06.3	Offer Sick Leave	1	0.44%
	C06.4	Support Community Immunity	1	0.44%
	C07.1	Promote Culture of Health	1	0.44%
	C07.2	Establish Health Promotion Leader	1	0.44%
	C08.1	Offer New Parent Leave	3	1.33%
	C09.1	Offer Workplace Breastfeeding Support	1	0.44%
	C09.2	Design Lactation Room	2	0.89%
	C10.1	Offer Childcare Support	1	0.44%
	C10.2	Offer Family Leave	1	0.44%
	C10.3	Offer Bereavement Support	1	0.44%
	C11.1	Promote Community Engagement	1	0.44%
	C11.2	Provide Community Space	1	0.44%
	C12.1	Promote Diversity and Inclusion	3	1.33%
	C13.1	Integrate Universal Design	2	0.89%
	C14.1	Promote Emergency Resources	1	0.44%
	C14.2	Provide Opioid Response Kit and Training	1	0.44%
	C15ß.1	Promote Business Continuity	1	0.44%
	C15ß.2	Support Emergency Resilience	1	0.44%
	C15ß.3	Facilitate Healthy Re-entry	1	0.44%
	C15ß.4	Establish Health Entry Requirements	1	0.44%
	C16ß.1	Allocate Affordable Units	2	0.89%
	C17ß.1	Disclose Labor Practices	1	0.44%
	C17ß.2	Implement Responsible Labor Practices	2	0.89%
	C18ß.1	Support Victims of Domestic Violence	2	0.89%
Innovation	I01	Propose Innovations	10	4.44%
	I02.1	Achieve WELL AP	1	0.44%
	I03.1	Offer WELL Educational Tours	1	0.44%
	I04.1	Complete Health and Well-Being Programs	1	0.44%
	I05.1	Achieve Green Building Certification	5	2.22%
	I06ß.1	Carbon Inventory	2	0.89%
	I06ß.2	Carbon Reduction Goal	3	1.33%
	I06ß.3	Carbon Reduction	3	1.33%
	I06ß.4	Carbon Neutral	2	0.89%

APPENDIX B. CERTIFICATION'S PRIORITIZATION OF CRITERION

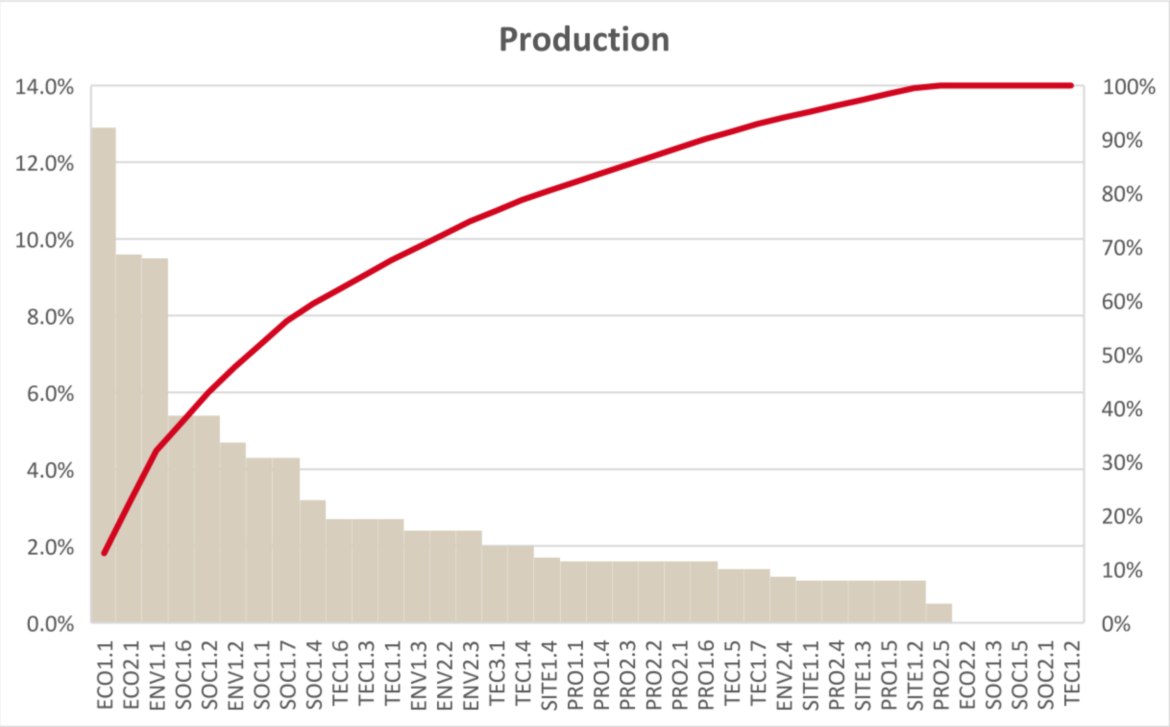
Graph B.1. DGNB Pareto chart Offices [19]



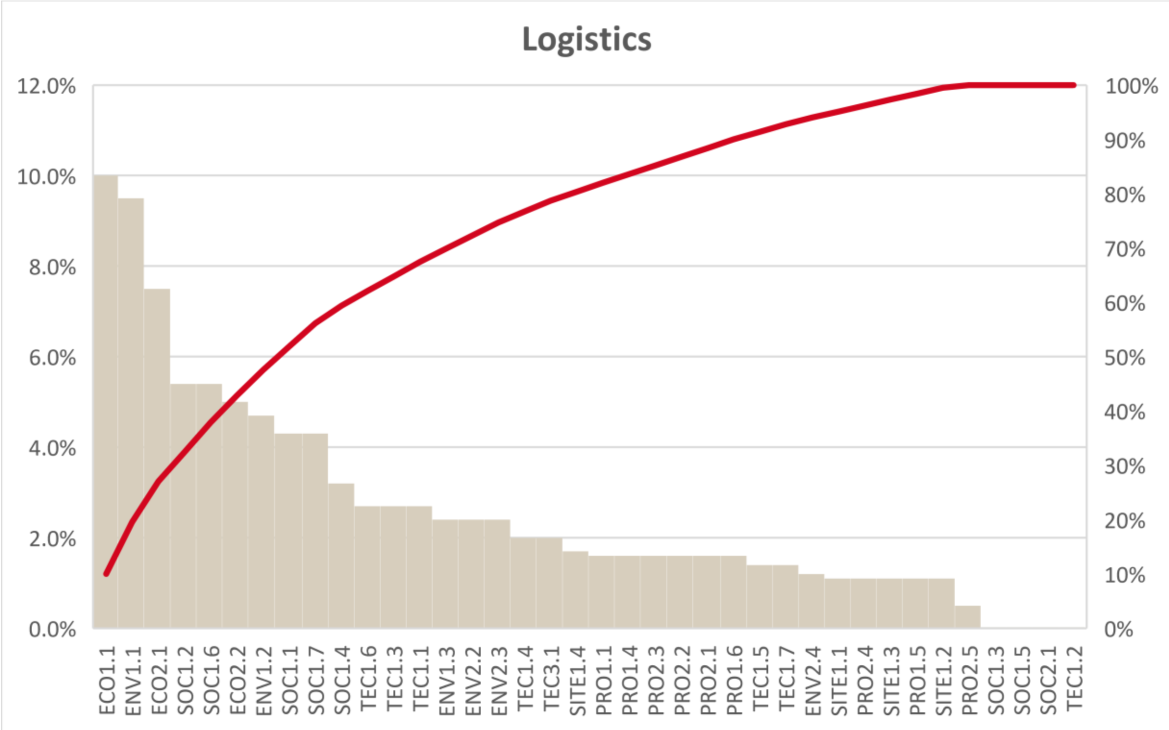
Graph B.2. DGNB Pareto chart Department Stores [19]

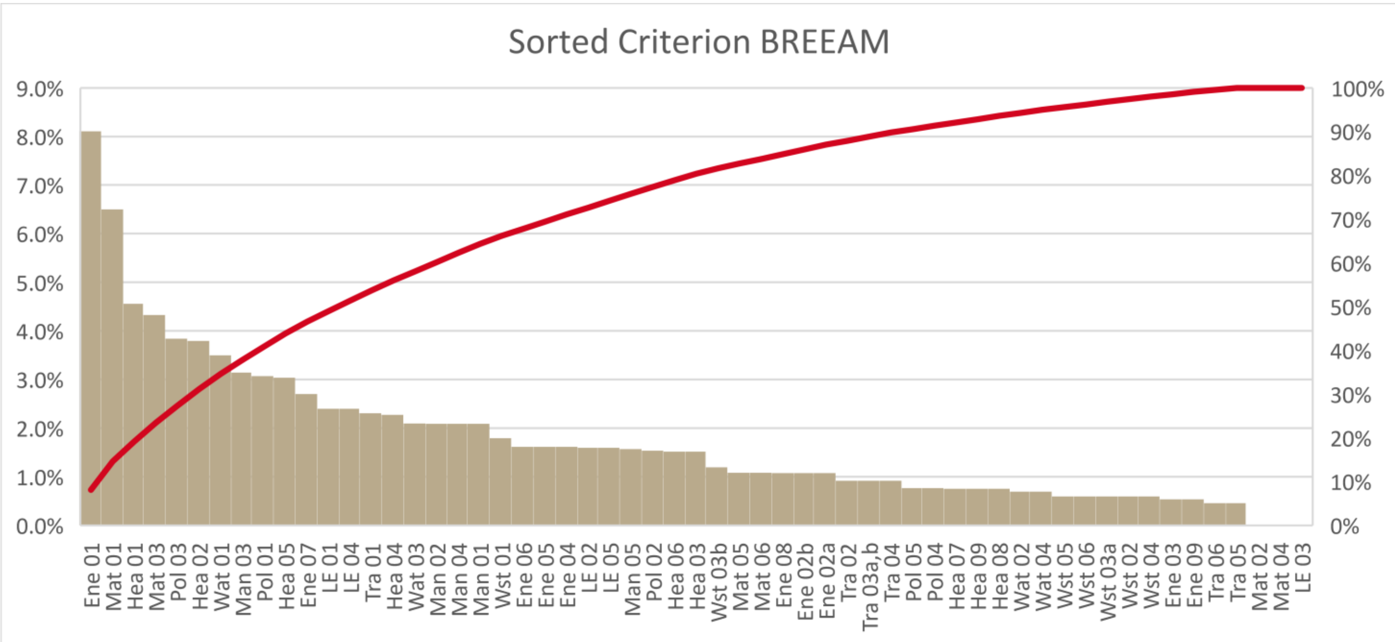


Graph B.3. DGNB Pareto chart Production [19]



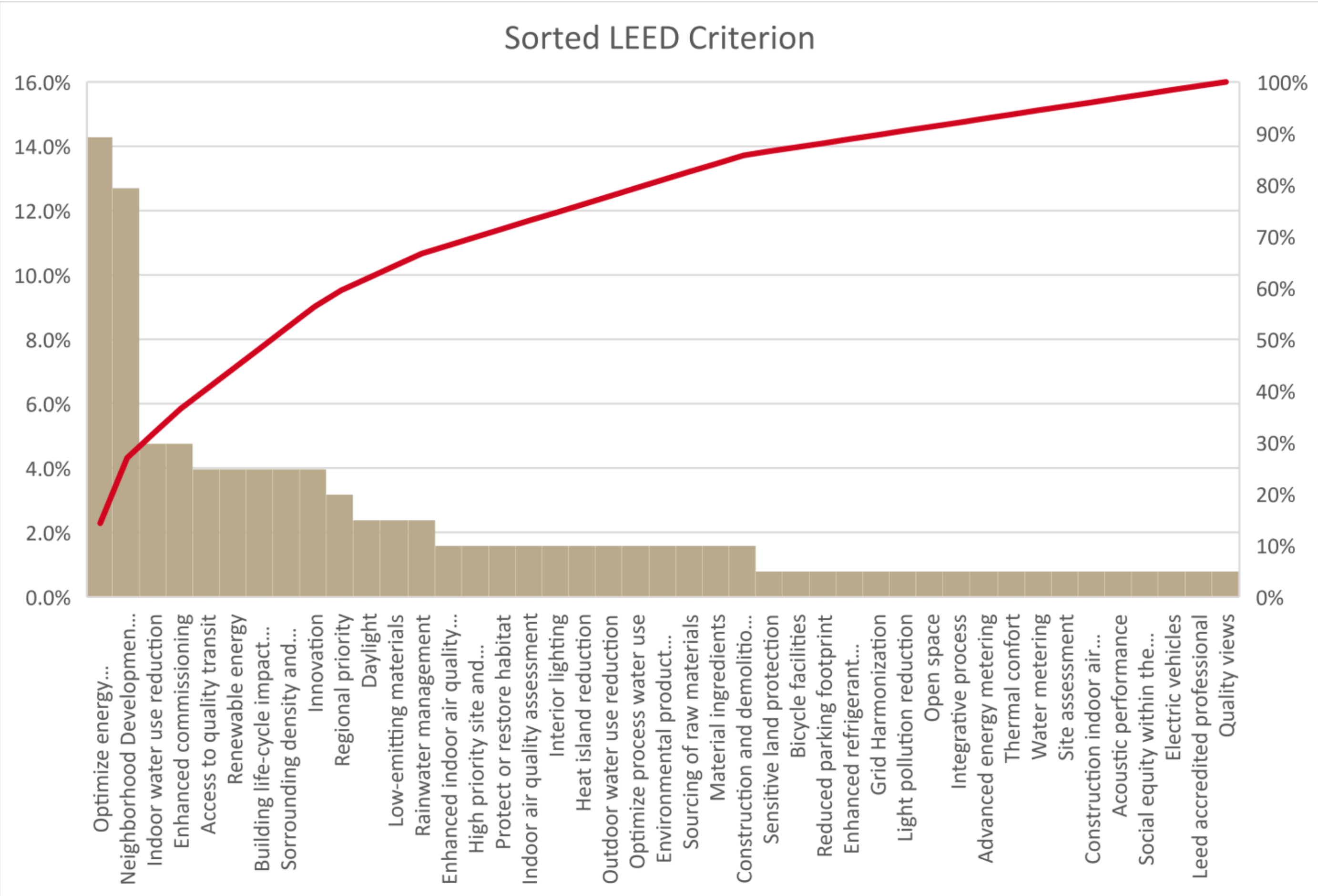
Graph B.4. DGNB Pareto chart Logistics [19]





Graph B.5. BREEAM Pareto chart [21]

Graph B.6. LEED Pareto chart [22]



Graph B.7. WELL Pareto chart [23]

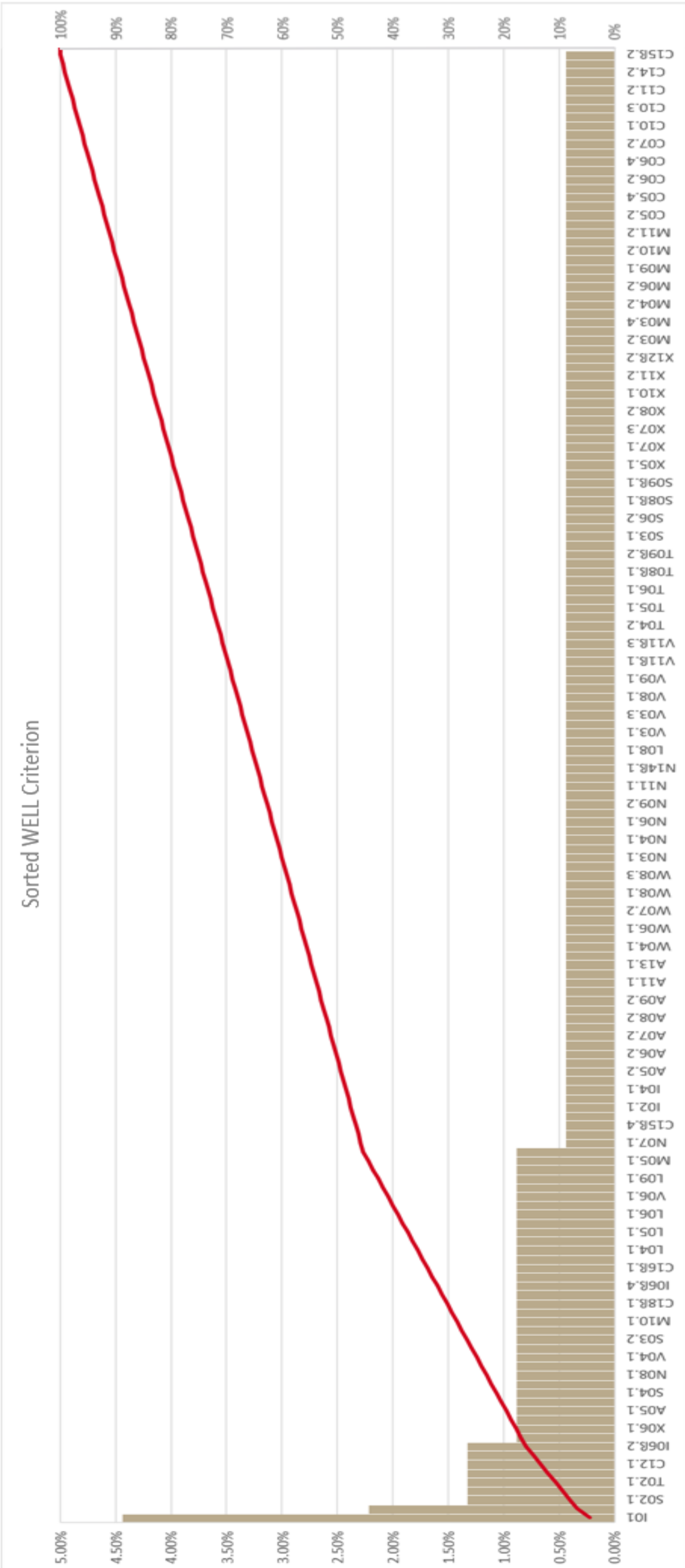


Table B.1. WELL Requisites analyzed by awardable category weight and requisite count [23]

Weight relevance (awarded extra)	Pre-requisites	Criterion	Description	Requisites count	Relevance of requisites
8.0%	**Air**	A01.1	Meet Thresholds for Particulate Matter	9	**18.75%**
		A01.2	Meet Thresholds for Organic Gases		
		A01.3	Meet Thresholds for Inorganic Gases		
		A01.4	Meet Thresholds for Radon		
		A01.5	Monitor Air Parameters		
		A02.1	Prohibit Indoor Smoking		
		A02.2	Prohibit Outdoor Smoking		
		A03.1	Ensure Adequate Ventilation		
		A04.1	Mitigate Construction Pollution		
6.2%	**Water**	W01.1	Verify Water Quality Indicators	5	10.42%
		W02.1	Meet Chemical Thresholds		
		W02.2	Meet Thresholds for Organics and Pesticides		
		W03.1	Monitor Chemical and Biological Water Quality		
		W03.2	Implement Legionella Management Plan		
7.1%	**Nourishment**	N01.1	Provide Fruits and Vegetables	5	10.42%
		N01.2	Promote Fruit and Vegetable Visibility		
		N02.1	Provide Nutritional Information		
		N02.2	Address Food Allergens		
		N02.3	Label Sugar Content		
8.0%	**Light**	L01.1	Provide Indoor Light	2	4.17%
		L02.1	Provide Visual Acuity		
9.3%	**Movement**	V01.1	Design Active Buildings and Communities	6	12.50%
		V02.1	Support Visual Ergonomics		
		V02.2	Provide Height-Adjustable Work Surfaces		
		V02.3	Provide Chair Adjustability		
		V02.4	Provide Support at Standing Workstations		
		V02.5	Provide Workstation Orientation		
7.1%	**Thermal comfort**	T01.1	Provide Acceptable Thermal Environment	2	4.17%
		T01.2	Monitor Thermal Parameters		
8.0%	**Sound**	S01.1	Label Acoustic Zones	2	4.17%
		S01.2	Provide Acoustic Design Plan		
8.0%	**Materials**	X01.1	Restrict Asbestos	8	**16.67%**
		X01.2	Restrict Mercury		
		X01.3	Restrict Lead		
		X02.1	Manage Asbestos Hazards		
		X02.2	Manage Lead Paint Hazards		
		X02.3	Manage Polychlorinated Biphenyl (PCB) Hazards		
		X03.1	Manage Exterior CCA Hazards		
		X03.2	Manage Lead Hazards		
8.4%	**Mind**	M01.1	Promote Mental Health and Well-being	3	6.25%
		M02.1	Provide Connection to Nature		
		M02.2	Provide Connection to Place		
17.3%	**Community**	C01.1	Provide WELL Feature Guide	6	12.50%
		C02.1	Facilitate Stakeholder Charrette		
		C02.2	Promote Health-Oriented Mission		
		C03.1	Develop Emergency Preparedness Plan		
		C04.1	Select Project Survey		
		C04.2	Administer Survey and Report Results		

The remaining 12.4 % of awardable points in the weight relevance column are from the innovation category, which is not included in this table because it has no requisites and all the criterion can be awarded as extra points.

APPENDIX C. SPIs SELECTION

Table C.1. WELL Requisites analyzed by awardable category weight and requisite count

Top 15	Hilti buildings	KPI	Measurement	Criterion	Source	Feasibility	Building Phase	Pillar
1	**Life cycle cost & impact**	Building-related costs	[€/m² GFA*a]	ECO1.1/Mat 01	DGNB/BREEAM	Feasible	Construction / Refurbishment	Eco
2	**Reduction of energy use and carbon emissions**	Building's heating and cooling energy demand	[MJ/m²]	Ene 01	BREEAM	Feasible	All	Env
		Building's primary energy consumption	[kWh/m²]			Feasible	All	Env
		Total resulting CO_2 emissions	[$kgCO_2/m^2$]			Feasible	All	Env
		Transition from fossil fuels to other sources	[%], [MJ/year]			Feasible	OPS/REF	Env
3	**Flexibility and adaptability**	Usable floor (UA) vs. Gross floor area (GFA)	[m2/m2]	ECO2.1	DGNB	Feasible	All	Eco
		Shell dimension	[m]			Feasible	All	Eco
		Building depth	[m]			Feasible	All	Eco
		Gross Floor Area/ #of building access cores	[m²GFA]			Feasible	All	Eco
		Flex for the user: pg. 291	[-]			Feasible	All	Eco
4	**Indoor air quality**	Measured value of TVOCs/rooms of measurement	[µg/m³]	SOC1.2 / Hea 02	DGNB/BREEAM/WELL	Feasible, but sensor needed	Operation	Soc
		Measured value for formaldehyde (with number/share of the rooms for which the measured values are applicable)	[µg/m³]			Feasible, but sensor needed	Operation	Soc
		Total ventilation rate (with number/share of the rooms for which the ventilation rate is applicable)	[l/s]			Feasible, if HVAC system allows	Operation	Soc
		Maximum CO2 concentration in 95% of the use time (with number/share of the rooms for which the maximum CO2 concentration is applicable)	[%]			Feasible, but sensor needed	Operation	Soc
5	**Commercial viability**	Car parking spaces allocated in the building	[PS/unit]	ECO2.2	DGNB	Feasible	All, relevant in design	Env
		Bicycle parking spaces allocated in building	[PS/unit]			Feasible	All, relevant in design	Env
		Capacity of car/ HGV parking space available to publ	[passenger car/HGV PS/Unit]			Feasible	All, relevant in design	Env
		Relationship between planned area and the existing buildings in the sub-market	[%]			Feasible	All, relevant in design	Eco
		Degree of utilization/occupancy rate	[%]			Feasible, data on attendance needed	Operation	Eco
		Year of construction of the building, the building's planned service life, building geometry, usable floor area, market segment in accordance with the BOMA classification	[-]			Feasible	All	Eco
6	**Thermal comfort**	Frequency of deviation of the operative temperature (heating and cooling period)	[%]	SOC1.1	DGNB/WELL	Feasible, monitoring system needed	Operation	Soc/Env/Eco
		Number or proportion of workstations where the specified frequency of deviation of the operative temperature (heating and cooling period) is	[%]			Feasible, measuring system needed	Operation	Soc/Env/Eco
		Upper and lower temperature limits for the operative temperature (heating and cooling period)	[°C]			Feasible, sensor needed	All	Soc/Env/Eco
		Maximum air velocities at the workstations (heating and cooling period)	[%]			Feasible, if HVAC system allows	All	Soc/Env/Eco
		Number of workstations where the specified air velocities is applicable	[%]			Feasible, if HVAC system allows	All	Soc/Env/Eco
		Maximum and minimum interior surface temperatures	[°C]			Feasible, sensor and network needed	All	Soc/Env/Eco
		Indoor humidity (maximum and minimum)	[%]			Feasible, sensor needed	All	Soc/Env/Eco
		Climate zone, and heating and cooling days also correspond to Level(s) basic data regarding the building	[zone] , [number]			Feasible	All	Soc/Env/Eco

7	**Water consumption**	Water consumption in the building	[m³/person/year]	Wat 01	BREEAM	Feasible	Operation	Env
8	**Impact of refrigerants**	Impact of refrigerants as GHG	[DELC CO_{2e}] / [GWP]	Pol 01	BREEAM	Feasible	All	Env
9	**Visual comfort**	**Daylight factor (DF) for 50% of the usable area**	[%]	SOC1.4 / Hea 01	DGNB/BREEAM/WELL		All, relevant in design	Soc/Eco
		Relative annual useful exposure	[%]			…	All, relevant in design	Soc/Eco
		Proportion of the roof surface area represented by translucent skylights	[%]			…	All, relevant in design	Soc/Eco
		Proportion of the rooms with direct visual link to the outside	[%]			Feasible	All, relevant in design	Soc/Eco
		Artificial light qualities: Color rendering index, illuminance and rate of adjustment, light color	[-]			…	All, relevant in design	Soc/Eco
		Color rendering index of the glazing	[%]			…	All, relevant in design	Soc/Eco
		Durations of exposure to daylight (17th January and at the equinox) and proportion of rooms to which this information applies	[h]			Feasible	All, relevant in design	Soc/Eco
10	**Ease of recovery and recycling**	Share of building components with materials selected for ease of recycling = sum of the shares of building components as a proportion of the corresponding reference value share in QL 2 or circular economy bonus – reuse or material	[% reference quantity share]	TEC1.6	DGNB	…	Construction / Refurbishment	Env
		Share of building components that are easy to recover = sum of the shares of building components as a proportion of the corresponding reference value share in QL 2.	[% reference quantity share]			…	Construction / Refurbishment	Env
		Intended recycling and recovery quota for the entire building structure =in accordance with the German Recycling Law (KrWG) (Section 14, 3), the percent by weight of the entire building structure that can be allocated to recycling paths 2, 3, 4, 5 and 7.	[% weight share]			…	Construction / Refurbishment	Env
11	**Access to quality transit**	Multimodal transportation choices	[# transport routes]		LEED	Feasible	All, relevant in design	Soc/Env
		Bicycle parking spaces allocated in building	[#]			Feasible	All, relevant in design	Soc/Env
		Electric vehicle charging stations	[#]			Feasible	All, relevant in design	Soc/Env
		Public transport stations	[#]			Feasible	All, relevant in design	Soc/env
12	**Neighborhood Development Location**	Distance traveled by employees	[km]		LEED	Feasible, survey needed	All, relevant in design	Soc/Env
13	**Renewable energy**	Portion of Renewable energy consumed	[%]		LEED	Feasible	All	Env
14	**Responsible sourcing of construction products**	Trackability of construction products	[-]	Mat 03	BREEAM	Feasible, but on development/construction phase	Construction / Refurbishment	Env
15	**Acoustic performance**	Evaluation in accordance with room acoustics classes	[s]	SOC1.3	BREEAM/DGNB	Feasible, measuring system needed	All, relevant in design	Soc
		Average value of the reverberation times (differentiated for different rooms)	[s]			Feasible, measuring system needed	All, relevant in design	Soc
		Average equivalent sound absorption area	[%]			Feasible, measuring system needed	All, relevant in design	Soc

APPENDIX D. PARAMETERS FOR VENTILATION AND FILTRATION

Table D.1. Ventilation rates (q_p) required to limit CO_2 concentration for differing activities

Activity	Minimum ventilation requirement / (litre·s^{-1} per person)	
	0.5% CO_2 limit	0.25% CO_2 limit
Seated quietly	0.8	1.8
Light work	1.3–2.6	2.8–5.6
Moderate work	2.6–3.9	N/A
Heavy work	3.9–5.3	N/A
Very heavy work	5.3–6.4	N/A

[40]

Table D.2. Description of the applicability of the categories used [39]

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

Table D.3. Classification of buildings pollution level [39]

Source	Low emitting products for low polluted buildings	Very low emitting products for very low polluted buildings
TVOC (as in CEN/TS 16516)	<1.000 µg/m^3	<300 µg/m^3
Formaldehyde	<100 µg/m^3	<30 µg/m^3
Any C1A or C1B classified carcinogenic VOC	<5µg/m^3	<5µg/m^3

Table D.4. Ventilation rates (q_p, q_B) for the building emissions [39]

Type of building or space	Cate-gory	Floor area m²/per-son	q_p	q_B	q_{tot}	q_B	q_{tot}	q_B	q_{tot}	Add when smoking
			l/s, m² for occupancy	l/s,m² for very low-polluted building		l/s,m² for low-polluted building		l/s,m² for non-low polluted building		l/s,m²
Single office	I	10	1,0	0,5	1,5	1,0	2,0	2,0	3,0	0,7
	II	**10**	**0,7**	**0,3**	**1,0**	**0,7**	**1,4**	**1,4**	**2,1**	**0,5**
	III	10	0,4	0,2	0,6	0,4	0,8	0,8	1,2	0,3
Land-scaped office	I	15	0,7	0,5	1,2	1,0	1,7	2,0	2,7	0,7
	II	**15**	**0,5**	**0,3**	**0,8**	**0,7**	**1,2**	**1,4**	**1,9**	**0,5**
	III	15	0,3	0,2	0,5	0,4	0,7	0,8	1,1	0,3
Conference room	I	2	5,0	0,5	5,5	1,0	6,0	2,0	7,0	5,0
	II	**2**	**3,5**	**0,3**	**3,8**	**0,7**	**4,2**	**1,4**	**4,9**	**3,6**
	III	2	2,0	0,2	2,2	0,4	2,4	0,8	2,8	2,0
Auditorium	I	0,75	15	0,5	15,5	1,0	16	2,0	17	
	II	**0,75**	**10,5**	**0,3**	**10,8**	**0,7**	**11,2**	**1,4**	**11,9**	
	III	0,75	6,0	0,2	0,8	0,4	6,4	0,8	6,8	
Department store	I	7	2,1	1,0	3,1	2,0	4,1	3,0	5,1	
	II	**7**	**1,5**	**0,7**	**2,2**	**1,4**	**2,9**	**2,1**	**3,6**	
	III	7	0,9	0,4	1,3	0,8	1,7	1,2	2,1	

Table D.4. Recommended Air Quality Guideline levels and interim targets [37]

Pollutant	Averaging time	Interim target				AQG level
		1	2	3	4	
$PM_{2.5}$, µg/m³	Annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15
PM_{10}, µg/m³	Annual	70	50	30	20	15
	24-hour[a]	150	100	75	50	45
O_3, µg/m³	Peak season[b]	100	70	–	–	60
	8-hour[a]	160	120	–	–	100
NO_2, µg/m³	Annual	40	30	20	–	10
	24-hour[a]	120	50	–	–	25
SO_2, µg/m³	24-hour[a]	125	50	–	–	40
CO, mg/m³	24-hour[a]	7	–	–	–	4

[a] 99th percentile (i.e. 3–4 exceedance days per year).
[b] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

Table D.5. Air quality guidelines for nitrogen dioxide, sulfur dioxide and carbon dioxide (short averaging times) [37]

Pollutant	Averaging time	Air quality guidelines that remain valid
NO_2, µg/m³	1-hour	200
SO_2, µg/m³	10-minute	500
CO, mg/m³	8-hour	10
	1-hour	35
	15-minute	100

APPENDIX E. KÖPPEN CLASSIFICATION OF GLOBAL CLIMATE ZONES

Figure E.1. World Map of Köppen climate classification for 1901-2010 [48]

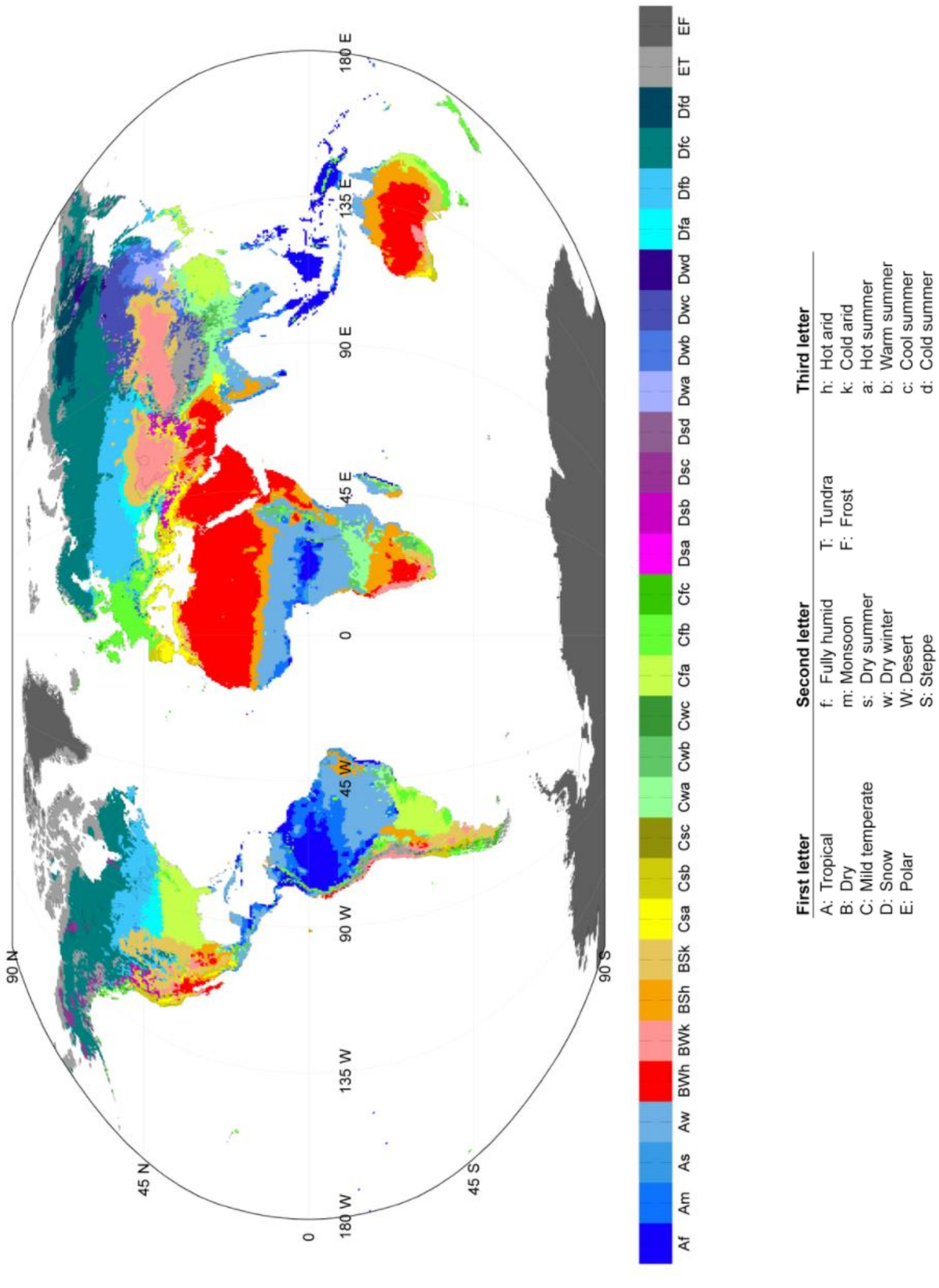


Table E.1. Köppen climate classification category overview first two letters [48]

Type	Description	Criteria
A	Tropical climates	Coldest month temperature is greater than or equal to +18 °C
Af	Tropical rain forest	Driest month precipitation is greater than or equal to 60 mm
Am	Tropical monsoons	Driest month precipitation is greater than or equal to 100 - (total annual precipitation in mm/25) mm
As	Tropical savanna with dry summer	Driest month precipitation in summer is less than 60 mm
Aw	Tropical savanna with dry winter	Driest month precipitation in winter is less than 60 mm
B	Dry climates	Total annual is less than 10 times the dryness threshold [5]
BW	Desert (arid)	Total annual precipitation is less than or equal to 5 times the dryness threshold [4]
BS	Steppe (semi-arid)	Total annual precipitation is greater than 5 times the dryness threshold [4]
C	Mild temperate	Coldest month temperature is greater than -3 °C and less than +18 °C
Cs	Mild temperate with dry summer	Driest month precipitation in summer is less than driest month in winter, wettest month precipitation in winter is more than 3 times the driest month precipitation in summer, and driest month precipitation in summer is less than 40 mm
Cw	Mild temperate dry winter	Wettest month precipitation in summer is more than 10 times the driest month precipitation in winter, driest month precipitation in winter is less than wettest month precipitation in summer
Cf	Mild temperate, fully humid	Not Cs or Cw
D	Snow	Coldest month temperature is less than or equal to -3 °C
Ds	Snow with dry summer	Driest month precipitation in summer is less than driest

[5] The dryness threshold is given in mm and depends on the annual mean temperature (T_{ann}) in °C. It is calculated as follows: if at least 2/3 of the annual precipitation occurs in winter, then the dryness threshold is $2 \times T_{ann}$; if at least 2/3 of the annual precipitation occurs in summer, then the dryness threshold is $2 \times T_{ann} + 28$; otherwise the dryness threshold is $2 \times T_{ann} + 14$.

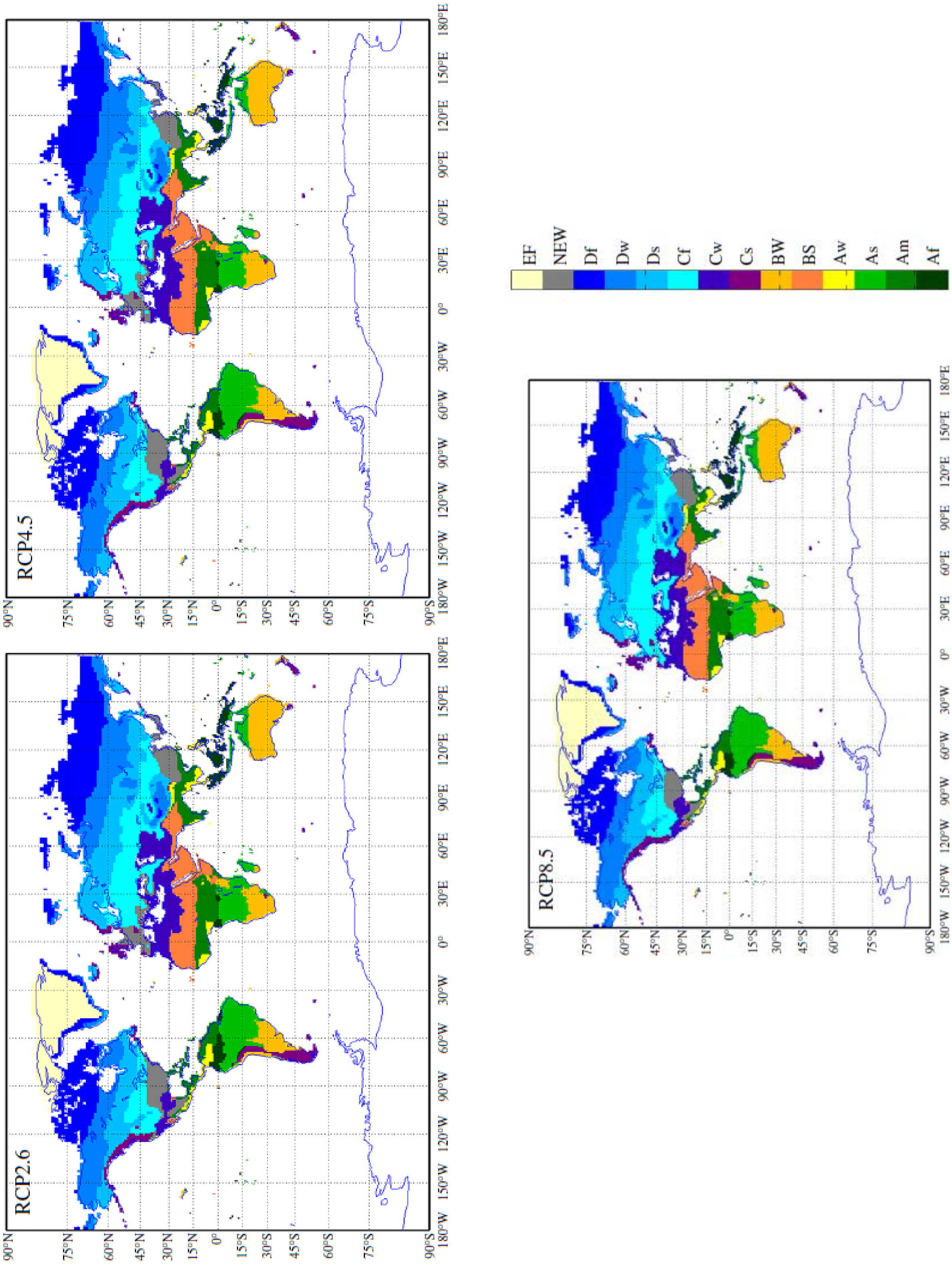
		month in winter, wettest month precipitation in winter is more than 3 times the driest month precipitation in summer, and driest month precipitation in summer is less than 40 mm
Dw	Snow with dry winter	Wettest month precipitation in summer is more than 10 times the driest month precipitation in winter, driest month precipitation in winter is less than wettest month precipitation in summer
Df	Snow, fully humid	Not Ds or Dw
E	Polar	Warmest month temperature is less than +10 °C
ET	Tundra	Warmest month temperature is greater than or equal to 0 °C
EF	Frost	Warmest month temperature is less than 0 °C

Table E.2. Köppen climate classification category overview third letter [48]

Type	**Description**	**Criteria**
h	Hot arid	Annual mean temperature is greater than or equal to +18 °C
k	Cold arid	Annual mean temperature is less than +18 °C
a	Hot summer	Warmest month temperature is greater than or equal to +22 °C
b	Warm summer	Warmest month temperature is less than +22 °C and at least 4 months with temperatures greater than or equal to +10 °C
c	Cool summer	Warmest month temperature is less than +22 °C, at least 4 months with temperatures less than +10 °C, and coldest month temperature is greater than -38 °C
d	Cold summer	Warmest month temperature is less than +22 °C, at least 4 months with temperatures less than +10 °C, and coldest month temperature is less than or equal to -38 °C

APPENDIX F. DISPLACEMENT OF CLIMATE ZONES FORECAST

Figure F.1. Different Scenarios of Current Emissions with Displaced Climate Zones [49]



APPENDIX G. CHARTS AND TABLES FOR IEP CALCULATION

Table G.1. Metabolic Rates for Typical Tasks [51]

Activity	Metabolic Rate		
	Met Units	W/m²	(Btu/h·ft²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Reading, seated	1.0	55	(18)
Writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0–2.0	60–115	(18–37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6–2.0	95–115	(29–37)
House cleaning	2.0–3.4	115–200	(37–63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0–2.4	115–140	(37–44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0–4.8	235–280	(74–88)
Miscellaneous Leisure Activities			
Dancing, social	2.4–4.4	140–255	(44–81)
Calisthenics/exercise	3.0–4.0	175–235	(55–74)
Tennis, single	3.6–4.0	210–270	(66–74)
Basketball	5.0–7.6	290–440	(90–140)
Wrestling, competitive	7.0–8.7	410–505	(130–160)

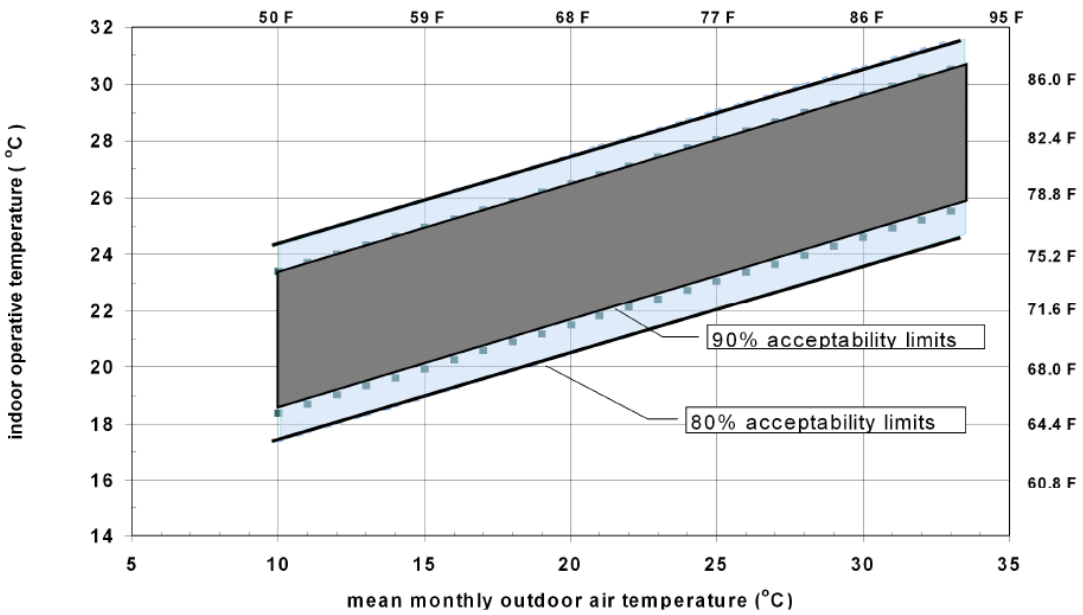
Table G.2. Clothing Insulation Values for Typical Ensembles [51]

Clothing Description	Garments Included†	I_{cl}, (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

* Data are from Chapter 9 in the 2009 *ASHRAE Handbook—Fundamentals*.[3]

† All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Figure G.1. Acceptable operative temperature ranges for naturally conditioned spaces [51]



APPENDIX H. HVAC BMS OF THE NORTH OFFICE BUILDING

Figure H.1. Ground floor North Office Building

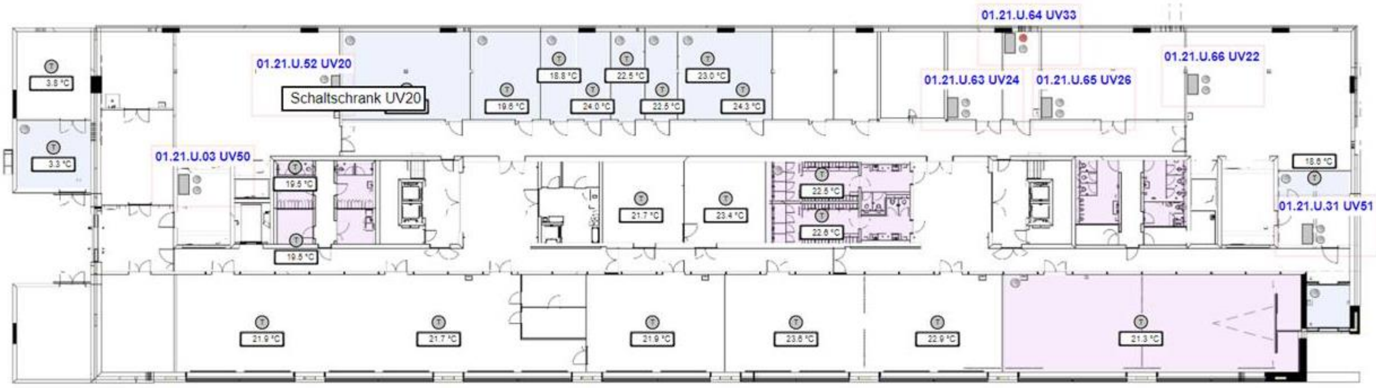


Figure H.2. Level 1 North Office Building

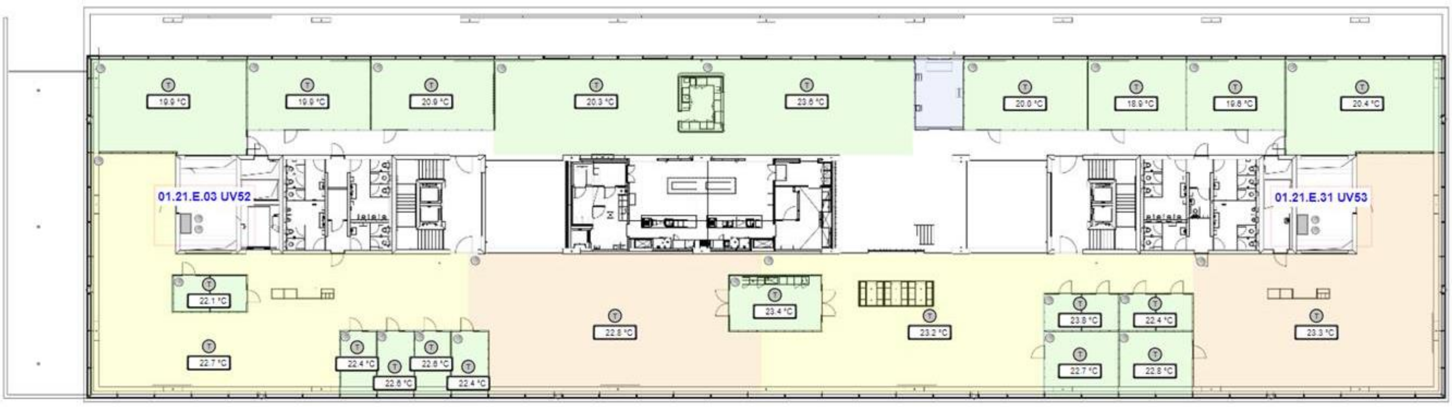


Figure H.3. Level 2 North Office Building

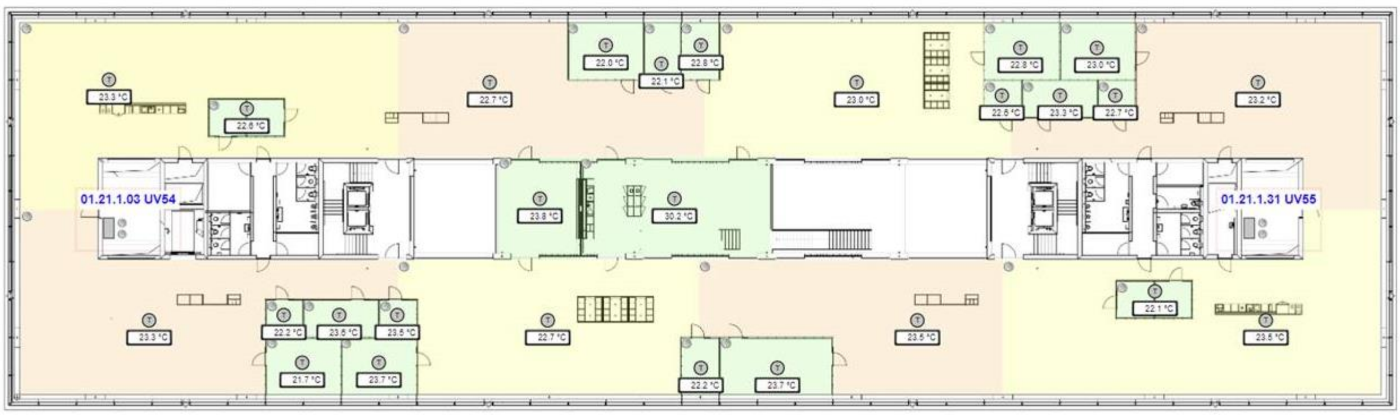


Figure H.4. Level 3 North Office Building

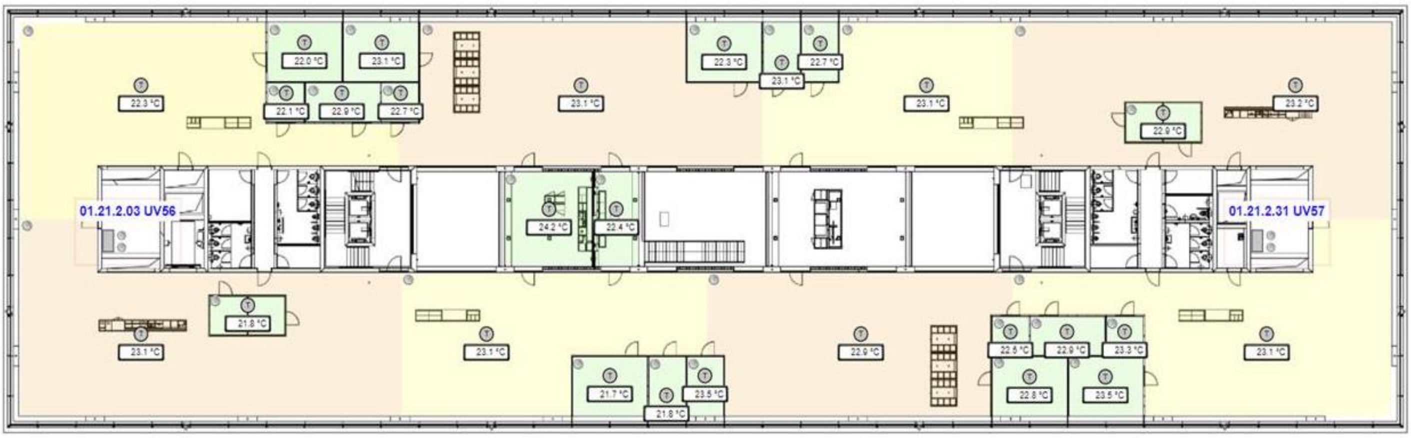


Figure H.5. Open space control interface

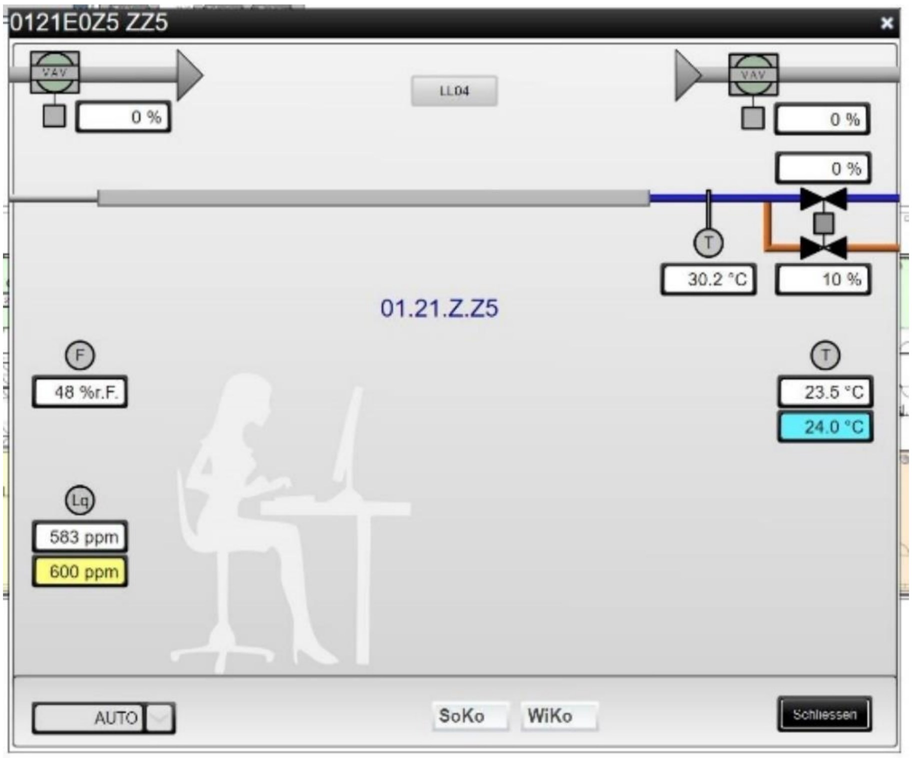


Figure H.6. Meeting room control interface

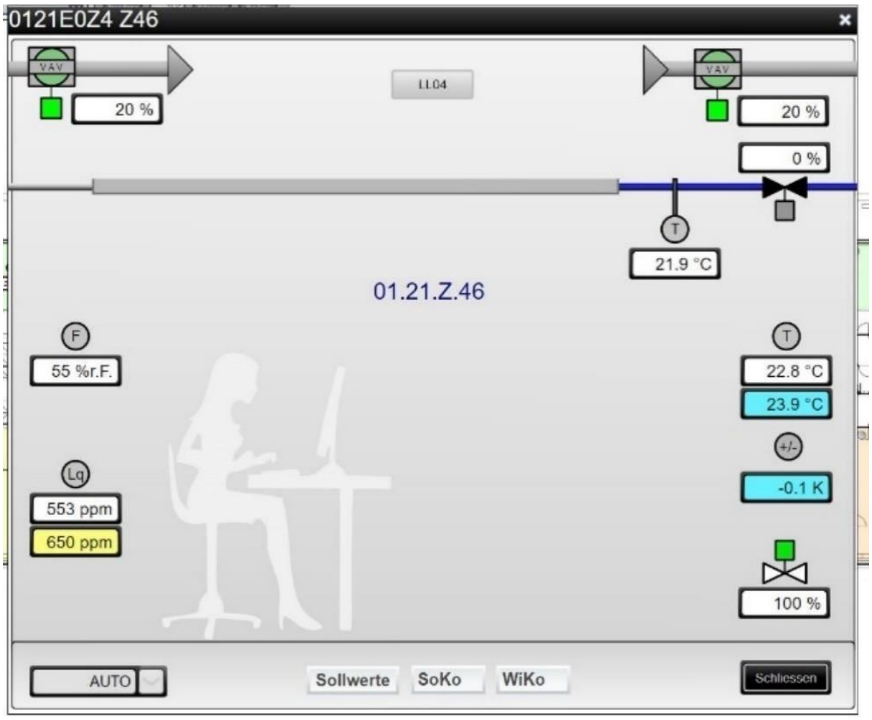


Figure H.7. Heat utilization and transfer from plant 1 to office North

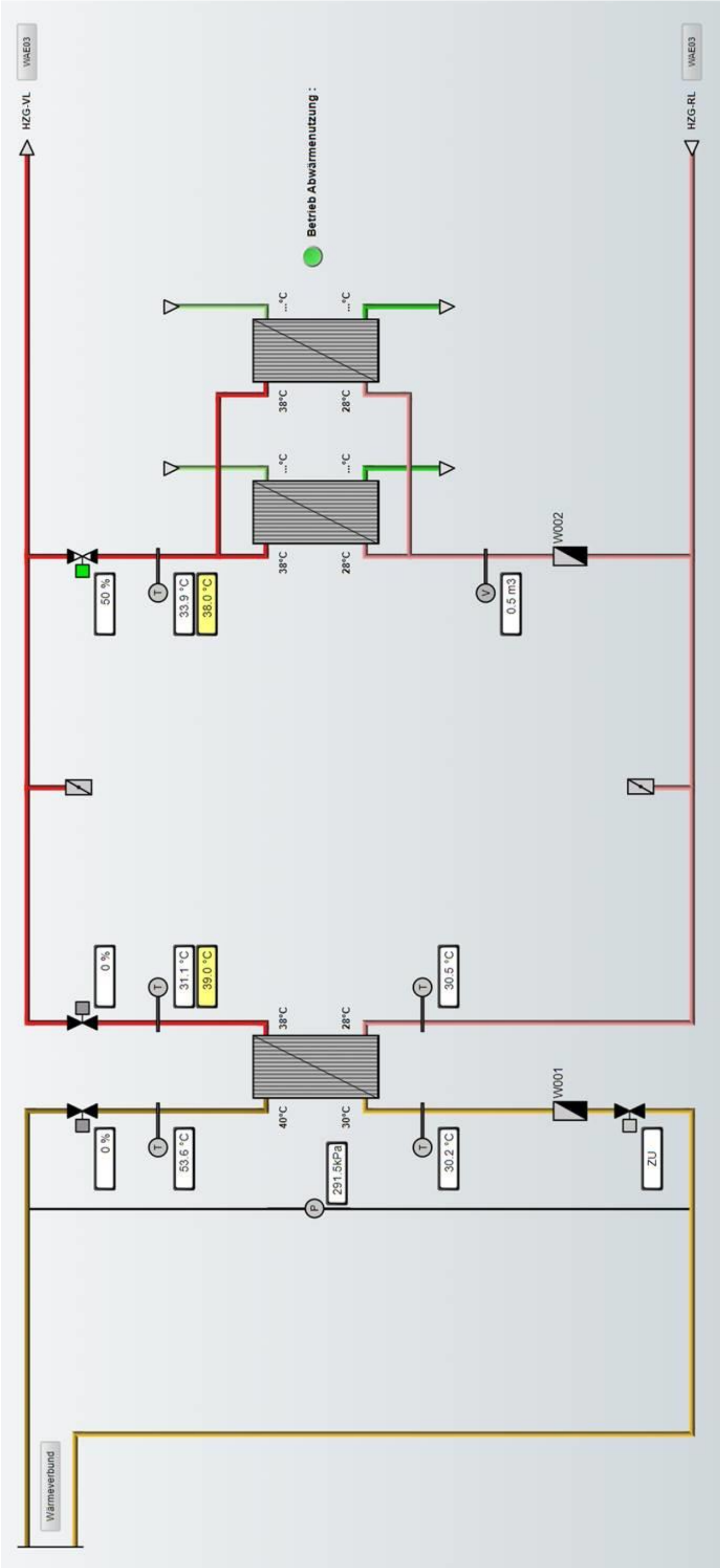
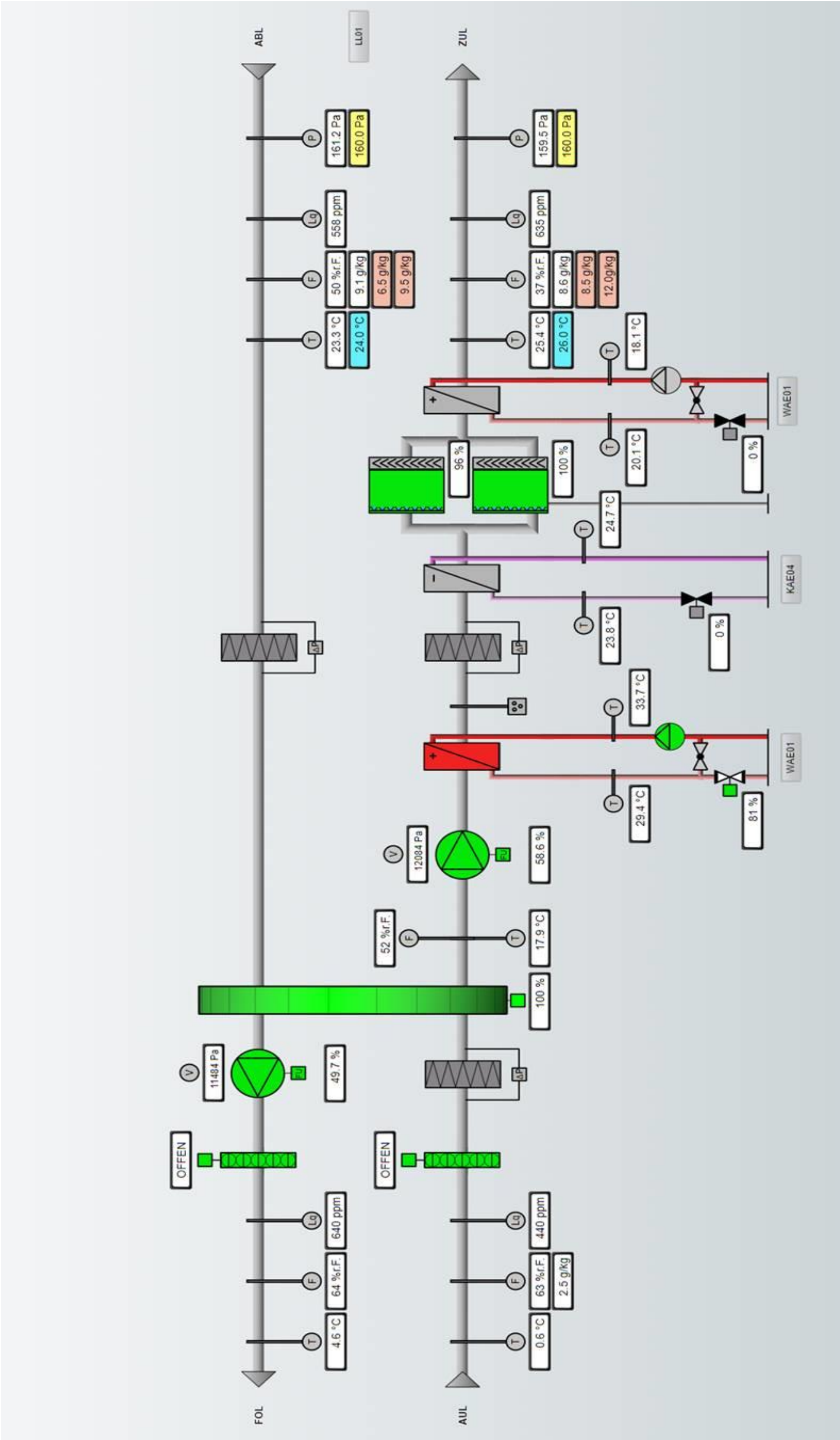


Figure H.8. Ventilation system office area



APPENDIX I. SUN CYCLES OVER NORTH OFFICE BUILDING IN SCHAAN [64]

Figure I.1. December's solstice over North Office Building location [64]

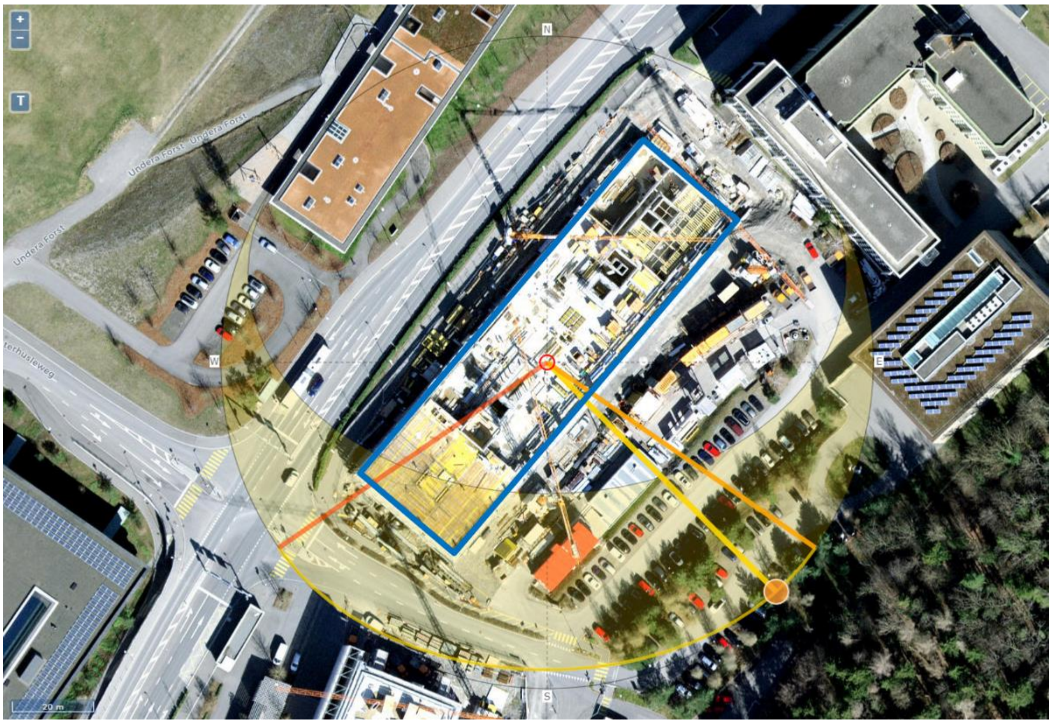


Figure I.2. June's solstice over North Office Building location [64]