Create wellbeing by performance in office buildings

Permanent wellbeing with infinite material flows

Stéphanie Bergen Henegouwen, 2020

The cover page, figure 1 (Raaij, 2017) shows the case study of this research, the headquarter of a bank in the Netherlands.

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Figure 2. Headquarter bank (Zuidas, 2018).

Abstract

This research concentrates on creating wellbeing by performance; behaviour and technical performance of materials and products in office buildings. This research is focused on the case study conducted at; the headquarter of a bank in the Netherlands, whereby the building users are criticizing the indoor comfort. Moreover, the building materials are end-of-life and the building is using a large amount of energy. The following research question is answered: 'How can the indoor comfort be improved in a circular way, by creating an optimal floorplan including the interior and technical aspects for, the case study, one the pilot floors of the headquarter of a bank in the Netherlands, while taking the energy consumption into account?'

Within this study different research methodologies are applied. The first research method is literature study and reference projects to gather knowledge about the indoor comfort with the following possible stressors; indoor air quality, thermal comfort, light and visual quality and acoustic comfort and circularity within the building environment. This information is derived from the Dutch regulations, certification rating systems, the case study and articles with the same theme. The literature study and reference projects are analysed to draw up criteria that the measurements and the design of the floorplan must meet. The second research method is material analyses to identify the materials and products which are used in the interior of the case study and how they can be improved to contribute to the indoor comfort, circularity and energy efficiency. The third research method is analysing the existing survey conducted in 2019 by the company Leesman. Analysing this survey can profile the building users and rate the satisfaction level of their workplace, activities, and facilities. The last research method is analysing the performed measurements. To study the current situation of the case study by testing the indoor comfort stressors on the criteria prepared with literature study and reference projects. These measurements are performed with 24 GreenMe cubes which records the indoor comfort values every ten minutes for three weeks, which resulted in 3024 measurement points within ten categories of the indoor comfort stressors. The research results are translated into a circular and indoor comfort framework and floorplan design including the interior and technical aspects.

The analyses results show that it is desired to renovate the headquarter of the bank in the Netherlands. This conclusion is based on the following results of this study, first of all most of the materials and products are not demountable. Therefore it cannot be cleaned well and it pollutes the air. Moreover, it is not fully circular when only the materials are obtained sustainable, but cannot be reused or remanufactured after its first lifecycle, when they are not demountable or additives are added.

Secondly, the building users are not satisfied with the indoor comfort within the headquarter of the bank. According to the satisfaction and importance level of the indoor comfort stressors. The indoor air was rated with 28,6% satisfaction and 71% importance, thermal comfort with 19,1% satisfaction and 80,7% importance and acoustic comfort with 13,9% satisfaction and 75,1% importance. These results show a low satisfaction level, while the building users rated these facilities as very important.

Furthermore, the measurements results show that the indoor comfort stressors exceed the permitted values during office hours. The carbon dioxide concentration is measured 1,7% above 800 ppm, total volatile organic compounds is measured 0% above 120 ppm. In addition, the temperature under 20°C and above 24°C is measured 10,5% and the relative humidity under 30% and above 70% is measured 14,6%. Moreover, the light level under 500 lux is measured 72,2% and flicker light under 0Hz and above 50Hz is measured 2,6%. Lastly, the average background sound level above 57dB is measured 2% and average installation sound level above 35dB is 0%. These values needs to be improved according the program of requirements of the case study.

The analyses emphasize the importance of the renovation of the case study. Measures are recommended to improve these values. The measures have been compiled on the basis of the circular and indoor comfort framework and the developed ‘Circular Indoor Comfort Step Strategy’. This strategy is as follows:

1) Improving the source
2) Improving situation without energy
3) Improving situation with renewable energy
4) Improving processes

The measures are categorized in interior aspects, improving the building users activities, and technical aspects, improving the indoor comfort stressors. Every measure contributes to the environment and supports the wellbeing of the building users. One of these measures is a green wall, which is mostly composed from raw materials from biological cycles and contributes to the mental state of the building users. Moreover, it improves the indoor air by filtering the air, thermal comfort by increasing the relative humidity, and the acoustic comfort by absorbing background sound. This product is sold as ‘product as a service’, whereas the producer keeps the responsibility and reuse every part after its first lifecycle to new products with the existing raw materials.

This research shows that a big difference can be made by performing small interventions to maintain the current situation and increase the existing value. Moreover, these interventions have a positive influence on the satisfaction level of the building users, meeting the Dutch and the bank’s regulations and rating certificates to renovate and create a healthy circular headquarter.

Illustrations are made by Stéphanie Bergen Henegouwen, otherwise the source is mentioned in the figure of the illustration or table. All units are Standard Information (SI-units) units.

Figure 3. Circularity (Flager, 2020).

Acknowledgements

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Terms and definitions

Circularity - “the development, use and reuse of buildings, area’s and infrastructure, without avoidable depletion of natural resources pollution of the environment or negatively impacting ecosystems. Construction which is economically responsible and contributes to well-being of humans and animals, now and in the future” (Kubbinga, Bamberger, Van Noort, Van den Reek, Blok, Roemers, Hoek & Faes, 2018).

Criteria - A principle or standard to be able to make a certain decision.

Demountable - Take it apart from each other, mostly as binder screws to remove the connections by performing multiple actions.

Detachable - Take it away from each other, mostly as binder glue or click system to remove the connection by performing one action.

Health - “State of complete physical, mental and social well-being..” (WHO, 1999).

Indoor comfort - Comfortable, happy and healthy feeling of the human body, caused by the environment.

Indoor discomfort - Uncomfortable, unhappy, worried or painful feeling in the body, caused by the environment (Bluyssen, 2013).

Recycle - Converting waste or used products into reusable raw materials, whereby the reusable raw material can be remanufactured to new reusable products.

Remanufacture - Producing products with reusable materials.

Requirements - Settings, limit values, quality or intensity which are compulsory to meet by the government or third party.

Sick building syndrome - An unhealthy and stressful situation and conditions affecting office workers.

Toxic gasses - Gases containing harmful substances for living organisms.

Upcycle - Converting waste or used products into reusable raw materials, whereby the reusable raw material can be remanufactured to new reusable products, whose value is higher than the original material or product.

Chapter 1. Introduction

1.1 Paris agreement

Climate changes are causing challenges for the indoor comfort in offices. Whereby, materials can create solutions for the challenges, paying attention to the materials which are scarce. Another way of thinking and creating solutions need to be developed to meet the rapidly changing world. Generally, the climate has changed drastically in the last few decades. This influences the way how the building environment is organized and the preferences and needs of the building users.

The rapid development of the environment caused a need to find a joint solution for challenges caused by the climate change. This resulted, among other things, in the Paris agreement (United Nations Climate Change, n.d). This agreement goes beyond country boundaries and is therefore intended for all countries who want to contribute to create solutions without boundaries. The Paris agreement originates from 12 December 2015, with as purpose to contribute to a sustainable and low carbon footprint future.

The agreement with the countries is to deal with the impact of the climate change by minimizing the rising global temperature. In addition, every 5 years, the teams who represent each individual country come together and assess the collective progress of each country. Furthermore, the countries develop new financial flows and technologies. The Paris agreement was signed on the 4th of November 2016 by 55 countries, which account for 55% of global emissions. Recently, in December 2019, 187 countries signed this Paris agreement (United Nations Climate Change, n.d.). The Paris agreement is adjusted to goals for the Netherlands and the case study of this research, a headquarter of a bank in the Netherlands.

Therefore, the Paris agreement is translated into national goals for the Netherlands, illustrated in figure 4. In 2050, energy needs to be generated in a sustainable way. The first goal is to minimize the energy use, because currently there is only 610 PJ (one petajoule is 10^{15} joules) sustainable energy for all buildings in the Netherlands. This means that an offices can only use 50 kWh per m^2 per year (DGBC, n.d.). The second goal, stated by the Dutch government, is to be 50% circular by 2030 and even fully circular by 2050. For example, by creating material passports and demountable buildings (Buijs, Van Heel & Wolf, 2019).

In addition, the installation sector is changing as well due to social and technical trends, such as user control within buildings, higher demand for comfort and safety and an increase in knowledge and innovation. This leads to changes in ownership including lease contracts and monitoring the performance of a building and the building users (Uneto-Vni, 2019).

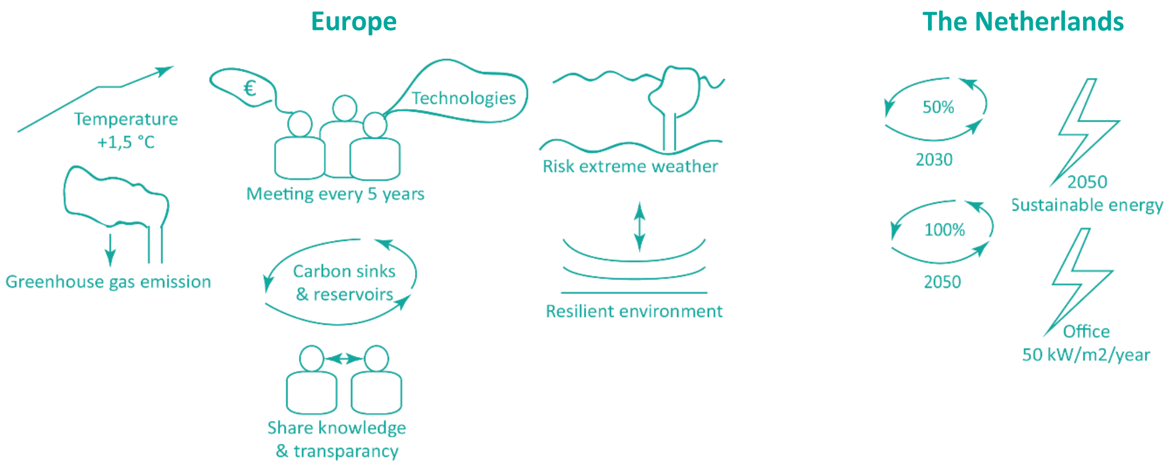


Figure 4. Paris Proof agreements.

1.2 Indoor comfort

People spend most of their time inside buildings, therefore the indoor comfort of buildings is important for the health of the human body. Some problems are experienced inside buildings, such as air pollution, rising temperature and more people who use the space than intended. Besides the indoor comfort, some materials are scarce and there is a need to reuse and recycle the materials to close the lifecycle of the materials (BCC, 2018B). In the Netherlands the construction sector uses half of all raw material, with include 40% CO_2 emission. The market is even growing, which means higher quantities of materials are going to be needed, while meeting the regulations of the government (Van Heel, 2019). In other words said by Levy (2004) "We do not seem to recognize that our real customer is the occupant, not the building." Concluding placing the building users at number one, followed by the environment and business models.

In the Netherlands, people spend a lot of time inside offices. There is minimal attention for the indoor comfort and how to improve this (Elsevier weekblad, 2017). This problem exist already for a long time, even in 1989 the indoor comfort within offices were not optimal. Some building users got health problems and a new term arose; The sick building syndrome (Elsevier, 1989). The indoor comfort of the case study, the headquarter of a bank in the Netherlands, is criticized by the building users. In addition, the current state and capacities of the indoor climate are not meeting the regulations.

Improving the indoor comfort of offices in a circular way includes different aspects and issues socially, ecologically and financially. A lower indoor comfort can cause challenges, due to disease, lower building quality and higher costs. The challenges of the bank are influenced by the changing buildings users and the buildings installations which are end-of-life. The changing amount of building users and their preferences and needs causes unsatisfied building users, mostly related to the stressors; indoor air quality, thermal comfort, visual & light quality and acoustic comfort. These stressors are mostly not suitable for the amount of building users and are not performing in a sustainable way, due to not fulfilling the modern requirements and the amount of energy use. Nowadays, most of the knowledge of the indoor comfort is obtained from older sources, where the fast changing environment is not taken into account.

1.3 Circularity

Circularity has been established since the 1970s and got more attention since a few years (Ecochain, 2019), due to the scarcity of materials, use of toxic materials, emission of carbon dioxide and the demolition waste including 23 million tons demolition waste in the building sector (UN environment program, 2019 & Van Heel, P., 2019). Innovations and feasible business models need to be developed to reduce the use of materials and energy including less CO_2 emissions and demolition waste, while the society accepts the changing building environment with transition toward a circular system instead of a linear system.

The bank's construction materials have ending lifecycles, without a circular approach to close the systems. In addition, the building uses more energy than needed and allowed by the Paris agreement. In conclusion, the circular building environment must be accelerated in the near future (ABN AMBRO, n.d).

1.4 Case study

The case study of this research is the headquarter of a bank in the Netherlands. The bank wants to meet the Paris agreement and achieve a higher indoor comfort satisfaction level of their employees. The bank has several focus areas related to energy, circularity and indoor comfort. The first focus area is improving the indoor climate due to large scale renovation of the installation, to make the system circular. The second focus area is renovating the headquarter of the bank, to become 'Paris Proof', with less than 50 kWh/m^2 energy use per year. The topics of the bank are improving indoor climate and meeting Paris Proof agreements, include energy efficiency and making the building future proof.

In 1999 the bank opened their new headquarter located in Amsterdam. This office was built for 3200 employees. Nowadays 7000 employees are working here. The building consists of different parts, with the highest part of 105 meter consisting 26 building floors. This building includes 30 elevators and installations that have been used for over 20 years. The bank has the aim to renovate the entire headquarter in a circular way and focusing on the installations floor by floor from 2020 till 2025, starting with three pilot floors. The bank did a satisfaction survey among employees, one of the largest concern was the indoor comfort, especially temperature regulation, air quality and sound level (ABN AMBRO, n.d).

The banks mission is to invest in sustainable and circular renovations, for their own real estate, as well to inspire their clients. Kees van Dijkhuizen (2019), former CEO of the bank said 'The real estate needs to contain on average energy label A by 2030 including circular business models'. In 2017 the bank built 'the Circl' in front of their headquarter. The building has a restaurant as main function to inspire people before, during or after their work and show how to build circular, demountable and reusable with low CO_2 emissions (ABN AMRO, 2018 & Zuidas.Magazine, 2017).

A large amount of the energy is used by the building sector. The amount of energy use, in 2018 was 125 exajoule (EJ). For the bank, this means an energy use of 120 kWh/m^2 per year, while the 'Paris Proof' regulation states 50 kWh/m^2 per year. This resulted in three problems which the case study contains; the building materials are end-of-life, the building users are criticizing the indoor comfort and the building uses a large amount of energy, see figure 5.

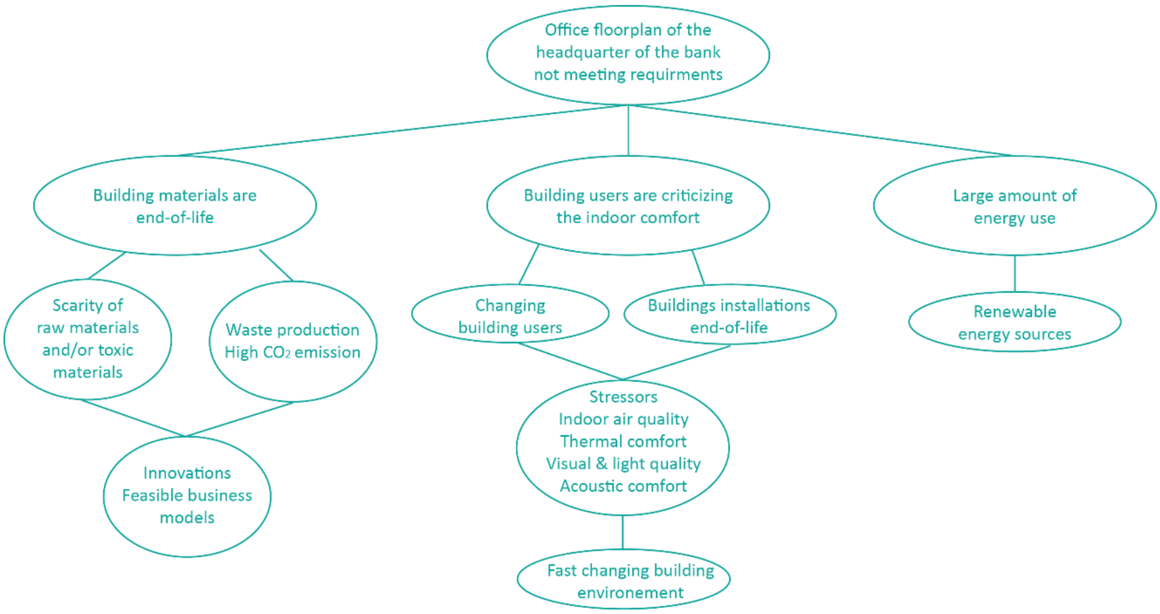


Figure 5. Problem statement.

Recent study (Rau & Oberhuber, 2016) shows a knowledge gap between indoor comfort and circularity. Moreover, according to Bluyssen (2019) indoor comfort is mostly defined according to laboratory studies instead of a combination of laboratory and field studies. This research connects indoor comfort with circularity and includes field studies.

1.5 Research structure

1.5.2 Objective

The general objective of this research is to create a circular indoor comfort framework and develop an office floorplan design, including the interior and technical aspects, to improve the indoor comfort of the case study in a circular way. This recommendation is written for the department Facility Management, including the Technology Refresh Program (TRP) and relocating building users team.

1.5.3 Main research question

To achieve the objective of this research the following research question will be answered: 'How can the indoor comfort be improved in a circular way, by creating an optimal floorplan including the interior and technical aspects for, the case study, one the pilot floors of the headquarter of a bank in the Netherlands, while taking the energy consumption into account?', see in figure 6.

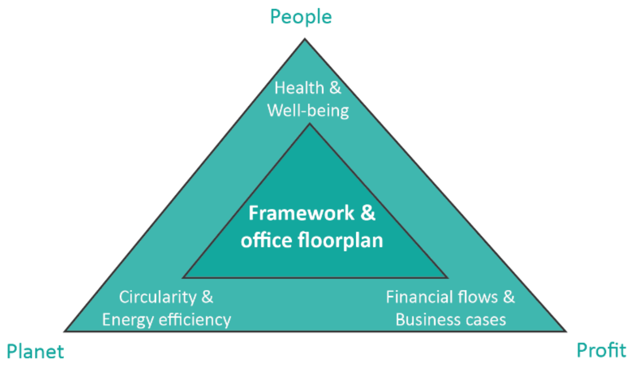


Figure 6. People, Planet and Profit model for research questions.

1.5.4 Sub-research questions

1. Indoor comfort	1.1 What influences the indoor comfort (in offices)?
	1.2 What are the governmental regulations for the indoor comfort in offices?
2. Circularity	2.1 How to apply circularity in the building environment?
	2.2 What are the preferred requirements of a circular office building?
3. Case study	3.1 What is the current state of the indoor comfort of the case study; the headquarter of a bank in the Netherlands?
4. Literature study	4.1 How can the literature study be translated into criteria for the research methodology?
5. Analyses	5.1 Which interior materials are applied in the case study and how do they effect the indoor comfort and circularity?
	5.2 What is the indoor comfort of the case study based on the questionnaires?
	5.3 What is the indoor comfort of the case study based on measurements?
6. Framework	6.1 What kind of framework can influence the indoor environment in a circular way?
7. Case study	7.1 How to improve the measured indoor comfort of the case study in a circular way, while taking the energy consumption into account?
	7.2 How does the floorplan, which improves the indoor comfort of the case study looks like?

1.5.5 Boundary conditions

Indoor comfort is limited to indoor air quality, thermal comfort, visual & light quality, acoustic comfort. The case study, the pilot floors of the headquarter of a bank in the Netherlands, focuses on one fit-out of the floorplans without looking at the structural support and the façade of the building.

Feasibility for the bank:

- Balance between healthy indoor air and energy use of the system, it needs to meet the requirements of 'Paris Proof' with a maximum energy use of 50 kWh/m^2 per year.
- The concept improving the indoor comfort needs to be affordable.
- The concept needs to meet Bouwbesluit 2012 requirements and Dutch regulations.

Connection between circularity and indoor comfort:

- Focus on materials which have positive effect on the indoor comfort and circularity in the way of demountable and reusable after end-of-life.

Circular economy of the bank:

- Design for the future, demountable and recyclable buildings materials and services;
- Use digital technology, store and monitor information;
- Collaborate value creation, performance, trust and transparency with social, ecological and social value (Van Heel, 2019).

1.5.6 Step-by-step lay-out of report

The research is divided into various chapters, namely introduction, literature study including indoor comfort, circularity and case study current state. This results in the literature conclusion. The literature conclusion formed the methodology. The methodology described the survey Leesman, measurements, the survey interior materials, the circular indoor comfort framework and the floorplan design. This design includes technical, social and financial aspects. These results are critical analysed in the discussion and conclusion, see figure 7. These topics will be explained more in depth in Chapter 5 Methodology.

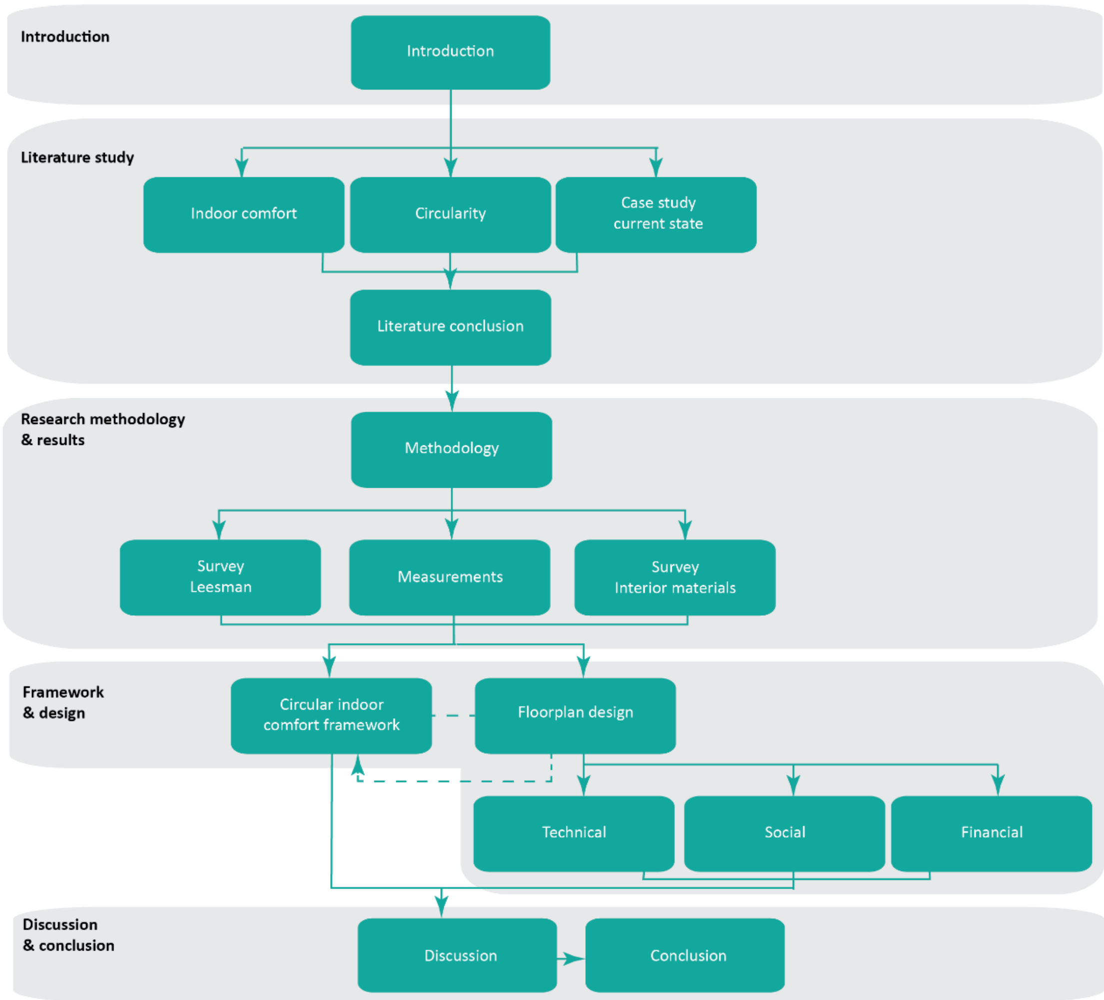


Figure 7. Step-by-step lay-out of report.

Chapter 2. Indoor comfort

2.1 Introduction

People spend most of their time, 80-90% inside enclosed spaces. Around 16 hours per day during the week and 17 hours per day in the weekend. Elderly and children spend even more time inside. The comfort of the enclosed space is influenced by potential stressors; indoor air quality, thermal comfort, visual and light quality and acoustical comfort. Other important factors are; aesthetic quality, spatial quality, ergonomically quality and plants. These stressors and factors will be sensed by the human body, like nose, respiratory tract, skin, eye and the ear and react to the nervous system, immune system and endocrine system, see appendix 2. These stressors and factors can cause mental and physical stresses, diseases and disorders. The stressors influence the higher sense, also called intellect; vision and audition and the lower sense, also called body; touch, taste and smell (Bluyssen, 2013).

People react different to the various stressors. Firstly, because of their physical, physiological and psychological state. Secondly, because of their history and lastly the influence from the context of their location. The building materials and furniture can affect the human health as well, whereby products may release biological, physical or chemical emissions. The effects of those emissions depend on exposure, dose and response over time. The human senses impact their feelings of healthy and comfortable space, consciously and unconsciously. This information goes from the sensory receptors via the nerves to the brain and sends messages to the human body. The human senses are; hearing (ears), sight (eyes), smell (nose), taste (mouth) and touch (skin). Other senses and systems regulate the body, like kinaesthetic motion sense (organs, reflex, movement), sense of balance (ears), receptors circulatory system (blood pressure and CO_2 concentration in blood) and receptors digestive tract (hunger and thirst).

Not only the buildings influences the health of humans, but also the surroundings (Geldermans, Tenpierik & Luscuere, 2019; Bluyssen, 2009; Kwon, Remoy & Dobbelsteen, 2018). Next to the biological aspects, health care costs a lot of money. Studies show, within the European Union including 375 million inhabitants in 2002, when the indoor comfort is improved and allergies and asthma is reduced, 3 till 6 billion euros can be saved. While reducing the sick building syndrome can save even 30 till 240 billion euros. This can save up to 50 till 290 billion euros per year including a higher productivity (Bluyssen, 2002).

A long time ago governments, pioneers and innovators developed building standards to improve the indoor comfort, only the building standards have difficulties to adjust fast to the changing world. The Sustainable Development Goal are developed by the United Nations Member States in 2015. This is establish to develop global partnership to improve education and health, reduce spur economy growth and inequality, while tackling climate change (Sustainable Development goals, n.d.). This chapter focusses on Sustainable Development Goals 3, good health and well-being, is developed to improve globally the environment (Geldermans, Tenpierik & Luscuere, 2019). This sustainable development goal is explained in appendix 3.

The aim of this indoor comfort literature research is firstly, gain background information about the changing indoor comfort. Secondly, to know how the stressors are working in general and specific for an office environment. Thirdly, how the indoor comfort is improved in other (field) studies and lastly, which requirements are stated by the Dutch government, the certifications and by the case study. Two research questions will be answered: 'What influences the indoor comfort (in offices)?' and 'What are the governmental regulations for the indoor comfort in offices?' This research begins with the background information about the changing indoor comfort preferences and need, regulations and importance.

2.2 Changing building environment

The indoor comfort challenges started a long time ago. Accordingly to the 'Ten books of architecture' from Vitruvius, written around 85 till 20 year before Christus, this topic especially the indoor air quality was mentioned already. From the 18th century, the architects, together with the specialists, were designing the buildings, where the architect was no longer entitled to perform the work alone, because the challenges became too complex. During the 1900 the challenges around the indoor comfort changed, because of the use of new materials. Some new materials included the toxic substance formaldehyde and new diseases arose such as legionnaires.

These changes were influenced by external drives, like regulations, economic, social and technical developments, the climate change and internal drivers such as; construction industry, regulations within the building environment, the society and the end-users (Bluyssen, 2009). From 1960 some challenges arose in office buildings, containing bad air and thermal conditions and poor light, which resulted into less productivity and higher sick leave rate. Around 1970 the personal computer and open floorplan set in, which made the human health only more difficult within office buildings (Bluyssen, et al., 2016).

The perception and regulations of the indoor comfort changed the last few centuries. From the 17th till the 19th century the indoor air quality was an important topic and there were a lot of diseases including micro-organisms and discomfort. Ventilation was discovered to prevent diseases from spreading. In the 19th century thermal comfort was introduced. During the Egyptians, Romans and ancient Greeks sunlight and daylight was important in their daily routine and in 1900 light therapies were developed, while in 1890 the artificial lighting came to make the day rhythm longer. In 1970 acoustic comfort changed a lot and improvements were studied (Bluyssen, 2009).

These changes arose mostly because the indoor comfort was not meeting the requirements of the building users. The indoor comfort is summarized by Bluyssen (2009) as personal factors and with the four potential stressors; indoor air comfort, thermal comfort, light and visual quality and acoustic comfort. In addition, these stressors could cause diseases and disorders. These stressors and diseases and disorders are defined in the next chapter, the indoor comfort factors.

2.3 Indoor comfort factors

The indoor environmental stressors consist of the personal factors, indoor air quality, thermal comfort, visual and lighting quality and acoustic comfort, figure 8. Additional factors influence the indoor comfort as well, like aesthetic quality, spatial quality, tactile quality, ergonomic quality and plants (Bluyssen, 2013). These stressors and factors can be described by indoor comfort indicators, like Mollier diagram, Fanger model and Adaptive temperature limits. This is described in appendix 4.

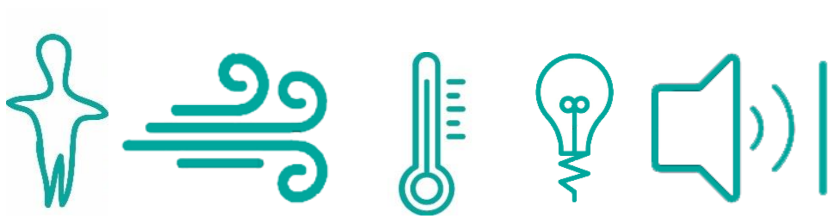


Figure 8. Left personal factors and stressors of the indoor comfort, left to right indoor air quality, thermal comfort, visual and lighting quality and acoustic comfort.

2.3.1 Personal factors

These indoor comfort stressors are influenced by personal factors as well. Firstly, demography; gender, age, social status, education and income. Secondly, states; personality at the moment and traits; personality over longer time. Thirdly, lifestyle and health status; food pattern and activities. Lastly, status of allergies or other diseases and genetics; the risk to certain diseases genetically determined.

Demography age can cause degradation of eyes, tears, immune system and hormone secretion, heart rate and increase of the blood pressure. Building users who are over 40 years old are in general more satisfied. Gender differences can determine how the environment is experienced, for example adult women are less sensitive to stress compared to men, only women experience more symptoms related to the indoor environment, whereby women are more annoyed by odours and men by light.

The social status influences the experience of indoor comfort by income. Lower social status can cause higher psychological stress, symptoms and mortality. The states and traits are the personal state of the building users. Consequently, negative mood, mostly stimulus-driven processing, can contribute to feeling negative symptoms in the building, while positive mood, mostly knowledge-driven processing, can increase the satisfaction of building users.

The personal traits are related to emotions and evolving by evolution and self-efficacy. Self-efficacy can only take place after meeting the needs of Maslow; self-actualization, esteem, love and belonging, safety and physiological needs. The lifestyle and health status influence how to cope with stress, diseases and/or disorders (Bluyssen, 2013).

2.3.2 Indoor air quality

The indoor air quality can be detected by the human senses of the nose and the respiratory tract.
The quality of the air can be improved by less odour and air pollution, while adding fresh air supply and increasing the air velocity. The concentration of the pollutants over time (µg/m^3) depends on the production of pollutants (µg/s per surface), the ventilation rate (m^3/h or l/s) and the concentration of pollutants (ppm or µg/m^3). The pollutants are divided into chemical and biological pollutants and come from outdoor sources, occupants-related activities and products, building materials and furniture and installation system components.

The polluted emissions can be released by the product interacting with the environment, using the product itself or the material absorbs the emissions and releases it later. The emissions can be transported by filters, ducts, humidifiers and rotating heat exchangers. In addition, odours are linked to moods, change attitudes and memories and can evoke emotions and affect task performance. Even if the smell is gone, the mood and behaviour can still be influenced. Furthermore, air pollution can cause pain and tears in the eyes, which can create an allergic reaction, redness or itching (Bluyssen, 2013). The air changes all the time, the quality is a dynamic situation. The ventilation efficiency is the concentration difference between supplied and exhausted air and the age of air is the residence time of the particles in an enclosed space (Bluyssen, 2009).

A lot of studies are done, only restrictions are difficult to define, because of the various pollutants and their chemical reactions. Airtightness is one of the new requirements which lowers the energy use, but the air exchanges as well, therefore the installation becomes more important to provide healthy air. Next to the ventilation system, source control, exposure concentration and time influence the indoor air as well (Geldermans, Tenpierik & Luscuere, 2019).

The air exchange, to refresh the particles in the air, can be done by natural ventilation, mechanical ventilation or hybrid system. Natural ventilation can be controlled by users, low cost and it cost no energy, only the system is not possible in noisy or polluted neighbourhood and ventilation grills need to be located on both sides of the building where the airflow can vary. The mechanical ventilation can reach deep spaces and is suitable for airtight buildings with continuous airflows, the system can make use of heat recovery, whereby less energy is used. Only the system is difficult to control by the users,

it needs maintenance and is high in cost, the system can make some noise or breaks down. The hybrid ventilation is combination with the benefits of both systems (Bluyssen, 2009).
The pollutants which are influencing the indoor air quality are explained, such as particulates, carbon dioxide, VOCs, CO and NO_2. The parameters which are influencing the indoor air quality are illustrated in figure 9.

Figure 9. Parameters indoor air quality.

Small particulates
The small particulates are floating in the indoor and outdoor air. The concentration of particulates in the air are influencing the indoor comfort. A certain concentration is unacceptable for the human health. PM_{10}, meaning the floating particulates are smaller than 10 micrometer in the air, which need to be lower than 40 µg/m^3 yearly and 50 µg/m^3 daily. Smaller particulates $PM_{2,5}$ concentration need to be lower than 25 µg/m^3 yearly. Smaller particulates entering the lungs easier, than a slightly bigger particulates and harming the human health even more. The concentration of the particulates are higher during the winter than during the summer. TNO (2019A) did research and discovered that around 50% of the particulates are produced inside and other 50% come from infiltration from the outside air via the ventilation system. When the concentration of particulates in the outside air is less, the indoor comfort will increase, this also applies if the indoor sources of the production of particulates will be eliminated. Next to the smallest particulates in the air, other contaminants can be detected in the air, like carbon dioxide.

Carbon dioxide
The concentration of carbon dioxide (CO_2) affects the indoor air quality, this contaminants concentration is produced by humans and processes of organic materials. The air consist of 87% nitrogen, 21% oxygen, 0,039% CO_2 and 1% water vapour. A higher concentration of CO_2 can be unhealthy for humans. The health commission in the Netherlands stated, in 1984, that the limit for indoor buildings a concentration of no higher than 1200 ppm. The CO_2 concentration of 10.000 ppm can cause drowsiness and concentration of 70.000 till 100.000 can even cause suffocation (Bluyssen, 2013). Therefore the CO_2 concentration is being influenced by the air exchange inside the building and effects the productivity. To be able to exchange the air pressure difference inside the buildings is needed (TNO, 2019A). Next to carbon dioxide, some other harmful contaminants can be found in the air, like volatile organic compounds, carbon monoxide and nitrogen dioxide.

Volatile organic compounds (formaldehyde and radon) / carbon monoxide and nitrogen dioxide
The concentration of substances inside the indoor air can cause some health problems. Generally, the substances are not mentioned in the Dutch laws, only formaldehyde is mentioned in Bouwbesluit 2012. This law stated that, Formaldehyde can contain a maximum concentration of 120 µg/m^3. Accordingly the World Health Organization (WHO, 2010) this concentration can contain only a maximum of 100 µg/m^3. Next to formaldehyde, radon and thoron can be measured as well and can increase the change of lung cancer. These are radioactive noble gasses, originally from the soil or building materials. The health counsel organisation (2000) stated a maximum value for volatile organic compounds (VOCs) of 200 µg/m^3.

In addition, another harmful gas, Carbon monoxide (CO) consist of a concentration that comes from defect in the heating or hot water system and a high concentration can even cause death.

The last mentioned harmful gas is nitrogen dioxide (NO_2). The maximum permitted concentration in the air is 40 µg/m^3, with a maximum of 200 µg/m^3 for 18 hours a year. According to TNO (2019A) this concentration comes from combustion, mostly from traffic and industry.

2.3.3 Thermal comfort

The thermal comfort can be detected by the human sense of the skin. Thermal comfort can be improved by the regulation of the temperature, relative humidity and air velocity (Bluyssen, 2009). Thermal comfort means the regulation of the body temperature and relates to the activities of the human body (Bluyssen, 2013). The parameters which are influencing the thermal comfort are illustrated in figure 10.

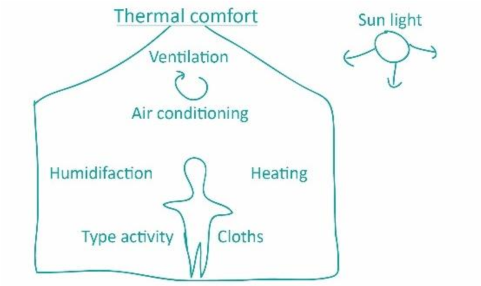


Figure 10. Parameters thermal comfort.

Temperature

Temperature is the motion of molecules and measured in degrees Celsius (°C). When temperature differences appear in one area, the air moves from a higher to a lower temperature until the temperature is the same in this area. This air movements goes via conduction, convention or radiation. Conduction is the heat transfer through the material, convection is the heat transfer from a solid medium to a flowing medium and radiation is the heat from a material. Furthermore, evaporation and condensation may also occur. The air can be filled with water or the water from the air condenses, because of temperature change (Bluyssen, 2009).

Relative humidity

The relative humidity differs from place to place inside the building. According to TNO (2019A) this is depending on cold bridges, insulation, ventilation and temperature. The humidity is the amount of water vapour in the air. Relative humidity is the water content in a parcel of air (%) and absolute humidity is the quantity of water in particular volume of air (g/m^3). The density of humid air at 0°C is 1,25 kg/m^3, while density of humid air at 30°C is 1 kg/m^3. The Mollier diagram, illustrated in appendix 4. indoor comfort indicators shows the water-air vapour mixture (Bluyssen, 2009).

2.3.4 Visual & lighting quality

The visual and lighting quality can be detected by the human sense of the eye. The quality of the visual and lighting comfort can be improved by view and appearance, illuminance and reflections. Light is a form of energy that always moves and transports information from the source to the light. The perception of light is managed by the amount of radiant energy, illuminance and the spectrum, frequencies and colours.

The quality of light is determined by the source, natural or artificial light, the distribution of light and the way how the users perceived the light. The quality of the light depends on equal light distribution, controllability, colour impression, day-night rhythm, less blinding, glare, task which needs to be performed, time of the day, weather and individual needs (Bluyssen, 2009; Bluyssen, 2013. The parameters which are influencing the visual and lighting quality are illustrated in figure 11.

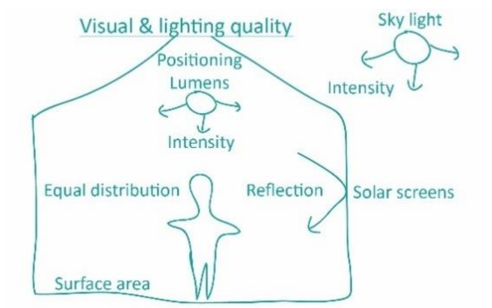


Figure 11. Parameters visual & lighting quality.

Light level

The quality of the source of the light depends on the light flux (Φ); the rate of emission expressed in lumen, the intensity (I), illuminance (lux) and the frequency of light determined by the colour temperature and colour index. The source of light can be daylight, direct sunlight, atmospheric light or artificial light (Bluyssen, 2009).

The distribution of light is controlled by the lighting level (E); the amount of light in a certain area, called the illuminance in lumen/m^2 or lux. 20 lux is the lowest scale a person can recognize and 200 lux is needed to recognize a person in an enclosed space. Recommended is to provide 500 lux in working spaces, like an office. The amount of lux in a certain area depends on the task, which needs to be performed. In addition, the reflectance (R) plays an important role in comfort and means how much the surface can reflect in %. White surface can reflect 100%, while black surface can only reflect 2%. Lastly, the luminance (L) which is distributed, this amount depends on homogeneous light or light with an angle (Bluyssen, 2009).

Discomfort, like too high luminance, can cause blinding and too high luminance differences tiredness, while too low luminance can cause non stimulation environment. In addition, light above 1000 lux can provide discomfort, detailed information described in NEN 17037. Radiation and UV light can cause damage to the skin and eyes. UV light is also needed and produce vitamin D for the skin (Bluyssen, 2009; Bluyssen, 2013). The perception of light is formed by the light colour and the daylight openings in the façade.

Light flickering

The quality of light can be improve by non or high frequent light flickering Low frequency of light fluctuation; 15-50 Hz can cause headage (Bluyssen, 2009).

2.3.5 Acoustic comfort

The acoustic comfort can be detected by the human sense of the ear. This comfort can be improved by limiting the noise and vibration. Sounds are wavelengths moving the air, whereby the velocity of the particles in the air (v) and the movement of the air, the speed (c) is important. If the velocity and the speed are moving in the same direction, the wave is longitudinal and moving perpendicular from each other, the wave is transversal. Each sound wave exist of wavelength (λ), amplitude (y) and frequency (f). The human ear can handle a wavelength between the 20 and 20000 Hz, figure 12 (Bluyssen, 2009).

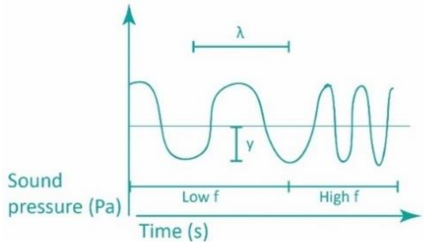


Figure 12. Sound pressure and time (Adapted from Bluyssen, 2009).

The quality of the sound is determine by the source noise or sound, the distribution of sound and the way sound is perceived and interpreted. The loudness of the sound; average power transmission in a sound wave per area and the sound pressure level (Lp); is caused by sound wave in the air, unit Decibel (dB). The minimum hearing level is 0 dB and maximum, pain level is 140 dB, 200 Pa (Bluyssen, 2009). Long exposure to noise can lead to DNA and hearing damage (Bluyssen, 2013). The parameters which are influencing the acoustic comfort are illustrated in figure 13.

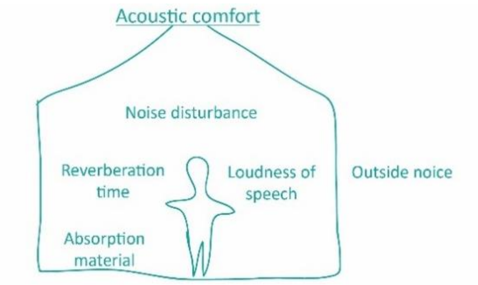


Figure 13. Parameters acoustic comfort.

Sound level
The source of sound is related to the spectrum of sound, the type of sound and the location. The sound pressure level can be presented as point (person) or line (road) source, where doubling the distance causes reduction of sound for a point source 6 dB and a line source 3 dB (Bluyssen, 2009).

The quality of the distribution of sound is influenced by the reverberation time and the sound insulation. The reverberation time is the time the sound level decrease after it was released by the source. The sound insulation is the sound that is being transferred between spaces, this depends on the mass and absorption of the materials, the connections and the occupancy which can absorb sound with their clothes within the enclosed space (Bluyssen, 2009).

The perception of the sound is influenced by the predictability and controllability of the sound, the motivation, attitude, individual sensitivity of the building users and the content of the information. Sound can be absorbed, reflected or going through the space or material (Bluyssen, 2009). Noise can harm the human body when the sound level is too loud, the effects on the human body are illustrated in the figure 14.

The sound can be measured as average sound level or maximum sound level. Next to the possibilities to measure the background sound and installations sound are the most valuable parameters to measure. The background sound level is difficult to measure, because it depends on various factors (Bluyssen, 2013).

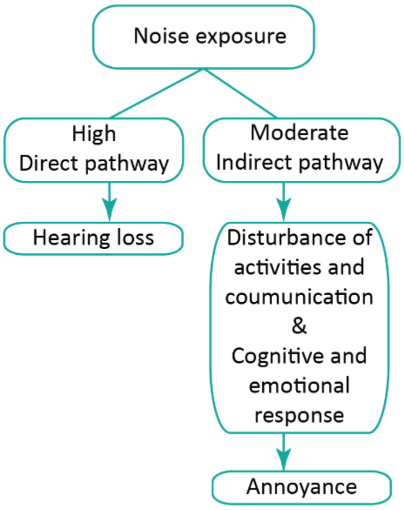


Figure 14. Noise effects on the human body (Adapted from Bluyssen, 2009).

2.3.6 Plants

The leaves and the roots of the plants, microorganisms in the soil and the growing media have the ability to remove VOCs and convert CO_2 to O_2 from the air (Cruz, et al., 2014). The ability to purify the air was already proven by the NASA around 1980, even formaldehyde can be reduced by 29-50% when living plants are placed in an area. Plants are low cost, environmental friendly and improving the indoor air quality. The VOC degradation depends on the efficiency of the plant species and their air purifying abilities, the chemical property of volatiles and internal and external factors of the location of the plants (Kim, et al., 2017).

Generally, plants can increase the workers quality of life, higher satisfaction about their workplace and improving the well-being of the human and the financial health of an organization (University of Exeter, 2014). Plants can make building users happier, 15% more productive and higher level of concentration, lower physiological stress and increase the attention span during working hours (Smith, Fsadni & Holt, 2017). Experiments have already been carried out, whereby measure devices measured the relative humidity, temperature and the concentration of VOCs. Next to the experiments, questionnaires are performed to analyse the perception of plants. In conclusion, living plants did not achieve a positive effect on the relative humidity and related temperature and background noise level, only minimal improvement were measured. The positive effects of the living plants are on the working environment aesthetics and their perception, the reduction of emissions and the amount of energy use (Smith, et all., 2017).

Every plants species have their own ability to purify the air, for example 300 gram chlorophytum comosum could detoxify 100 m^2 room in 6 hours. Dracaena sanderiana can remove benzene from the air, Sansevieria trifasciata toluene, chlorophytum comosum ethylbenzene and hydroculture plants CO_2. Besides purifying the air, plants provide oxygen (Smith, et all., 2017).
In the table 1 below the VOC removal rate is described and which factors influence this rate.

VOCs	Effect on the human body	Plant removal rate
Benzene	Drowsiness, headaches, unconsciousness, irritation on the skin, decrease red blood cells and high levels cancer and deaths.	43,8-205,6 $mg/m^2/day$
Formaldehyde	Irritation eye, throat, skin and noise and high level cancer.	20,4- 25,3 $mg/m^2/day$
Factors that influence the removal rate		
Plant	Plant species and growing media	
Environment	Temperature and light intensity	
Chemical	VOC concentration, identification and mixture	

Table 1. VOC plant removal rate (adjusted from Cruz, et all., 2014 & CDC, 2018).

2.3.7 Diseases and disorders

The stressors and additional factors can cause disease and disorders. These diseases and disorders are interpreted in the brain by incoming signals. These signals are associated with previous experiences. This can affect the human senses, the nervous, immune and endocrine systems, the concentration level and psychological state. In addition, it can cause irritation, hyper-reactive and allergic effects, infections and toxic chronic diseases. These potential diseases and disorders can increase when the age increases. The environmental, stressors and additional factors including effects are illustrated in figure 15 (Bluyssen, 2009).

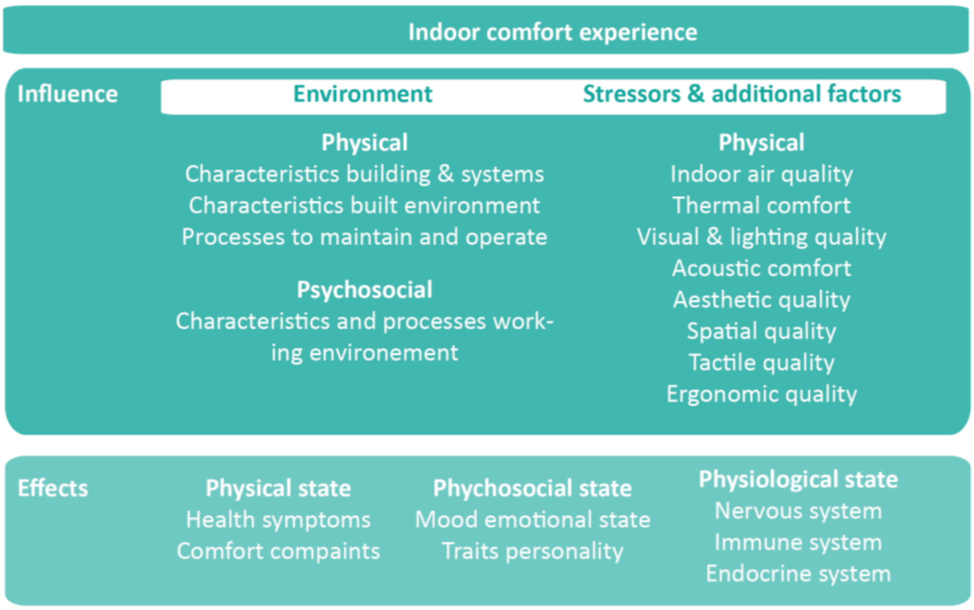


Figure 15. Indoor comfort experience (Adjusted from Bluyssen, 2013).

2.4 Indoor comfort in offices

The indoor comfort influences the satisfaction of the buildings users who are working in offices. Various studies (Bluyssen, Aries & Van Dommelen, 2010) show relations between the indoor health and comfort, influenced by the building conditions and environmental control, and productivity in office in enclosed spaces. Some relations are already proven. Firstly, maintaining and cleaning the installation systems. Secondly, improving the ventilation capacity and possible odour. Thirdly, the type of view. Fourthly, the light quality and lastly, the occupancy density in enclosed space (Bluyssen, Aries & Van Dommelen, 2010). Other factors which influence the indoor comfort in office are, according to Kwon, Remoy and Dobbelsteen (2019), building location, organisation management, employees way of working; workspace, work equipment, social interaction, work pattern, feeling at home, privacy and flexibility and office lay-out; ceiling height and openness. The requirements for offices are changing the last few years, because of the building users' needs and activities and the advanced ICT.

The highest pollution sources in offices are the HVAC system and the building users. Next to the sources and already mentioned stressors and factors, other factors plays a role like; the office location and lay-out. There are three types of floorplans; open floorplan, cellular floorplan and a mix between the floorplans. According to Bluyssen (2013) working in open floorplan reduce the privacy and job satisfaction. In addition, it is more likely to perceive thermal discomfort, noise and poor air quality. Besides the open floorplan, the cellular floorplan is easier and faster to control the indoor environment, where building users are mostly more satisfied.

An office renovation process contains various focus areas, like thermal comfort and visual and light quality. 19 articles about the indoor comfort inside offices are studied and ranked by studied by Kwon, Remoy & Dobbelsteen (2018), figure 16. In this model, the building is perceived healthy if 80% of the buildings users are satisfied, this can be monitored with a questionnaire. The influence factors in offices are illustrated in figure 16 and described in appendix 5. To create this indoor comfort, materials and energy is needed. This needs to calculated win the company budget.

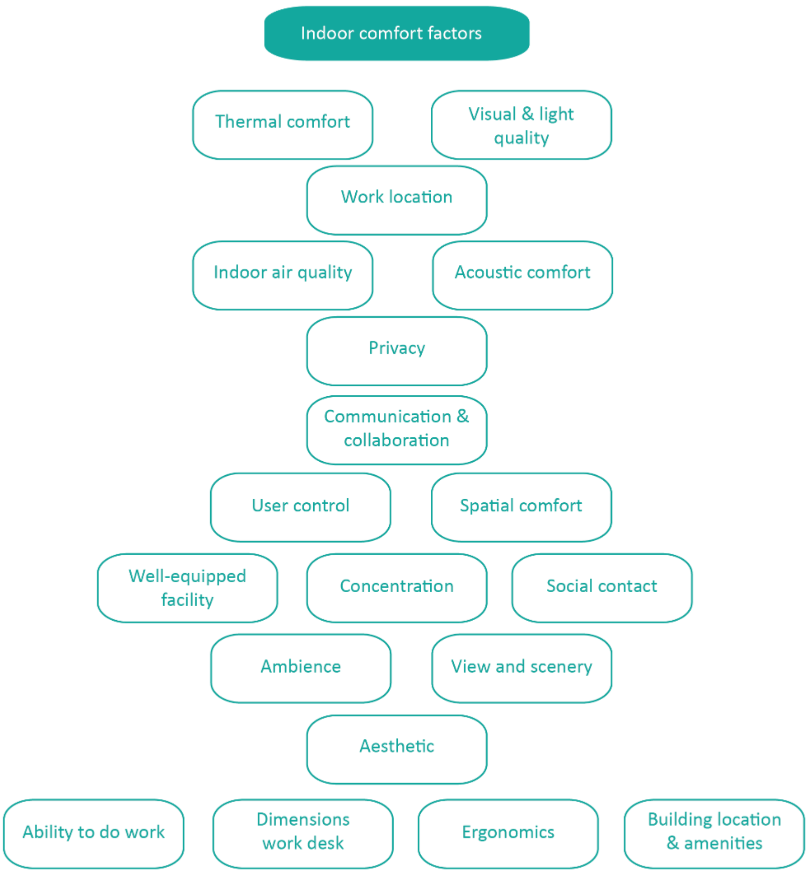


Figure 16. Ranking influence factors user satisfaction (Adjusted from Kwon, Remoy & Dobbelsteen, 2018).

The indoor comfort potential stressors are different perceived by the building users in offices. The stressors are described in the table 2 below.

Stressor	Challenge	Source(s)	Impact	Potential solution
Indoor air quality	Bad air quality or odour	Rate of occupants, pollutants, contaminants and ventilation system	Less concentration and lower productivity	High ventilation rate of minimal 45m^3/h/p.p. and relative humidity between 30%-70%
Thermal comfort	Too warm or too cold	Sun or heating and cooling installation system	Less concentration and lower productivity	Temperature optimum performance; Summer 23,9°C – 25,4°C Winter 19,7°C - 21,9°C
Visual & light quality	Less sun exposure	Windows	Depressions and dissatisfied	Natural light otherwise artificial light. Window dimensions 1,8m x 2,4m wide, lateral view
	Too much sun exposure	Windows	Glare	Windows <40% transparency
Acoustic comfort	Distraction and disturbance at work	Too loud noise and in open office colleagues conversations and telephone ringing	Less concentration and privacy and lower productivity	Sound absorbing materials Background noise level European standard; Open office 35dB - 45dB Cellular office 30dB - 40dB

Table 2. Stressors influence perceived comfort in offices (Kwon, Remoy & Dobbelsteen, 2018).

2.4.1 Productivity

The productivity of the building users can be influenced by the indoor comfort stressors. Firstly, the indoor air quality, where building users are 3% more productive when the ventilation is 10 l/s higher than normally ventilated. Since 2000, the ventilation norm in offices is 50 m^3/h per person, this is 13,9 l/s per person (TNO, 2019A). According to TNO (2019A), the productivity can be influenced by higher CO_2 concentrations as well, especially concentrations above 1000 ppm. In addition, the 'Programma van Eisen gezonde kantoren' (2018) assumes a maximum difference of 400 ppm CO_2 concentration inside and outside the office. Moreover cleaning the ventilation filters and providing the 50 m^3/h per person ventilation capacity, can increase the productivity by 10% including less complaints. Secondly, the temperature influence the productivity when the temperature is too hot or too cold. Resulting in the highest performance around the 21,6°C (TNO, 2019A). Lastly, the productivity influenced by the acoustic comfort. Noise disturbing by conversations, ringing phones and installations, can cause remembering fewer things, more tired and less motivated (TNO, 2019A).

The disturbance caused by stressors depend always on the tasks the building users are performing. All factors are illustrated in figure 17 (Bluyssen, 2013). The OFFICAIR research by Bluyssen (2015) shows 29% of the office employees expect a productivity decrease caused by the indoor comfort of 17%.

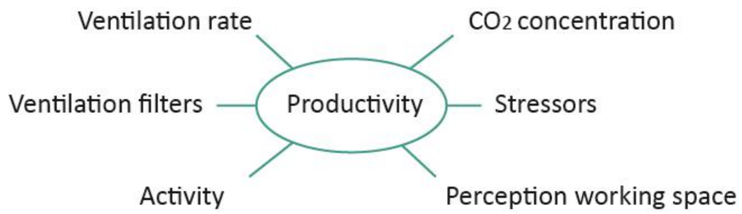


Figure 17. Factors influencing the productivity in offices (adjusted from TNO, 2019A & Bluyssen, 2013).

2.4.2 Complaints in offices

Offices can cause health problems, defined as 'sick building syndrome'. These problems vary from location, building and the state of the end-users. The most common health problems are described below.

Sick leave

According to Milton (2000), there is higher risk of 1,53% for sick leave when lower ventilation (43 m^3/h) is applied compared with higher ventilation (86 m^3/h) (TNO, 2019A) and the self-reported sickness absence is related to the number of occupants in offices (Bluyssen, 2013). 43% of sick leave is caused by stress (TNO, 2019C).

Stress

Building users in offices can experience stress, which has great social and financial consequences. In 2017, stress costed 8,7 milliard euros in the Netherlands. Stress level is rising the last decades, because of the need for working efficiently and working faster. This causes burn-outs, less productivity and more sick leave. In addition, this can cause problems in their private life, which will influence the working environment as well. During acute stress, the person cannot function and think anymore. Recovering from stress takes time, if this time is not taken, acute stress can turn into a chronic disease (TNO, 2019C).

Stressors

The stressors can influence the human health as well, like described in the OFFICCAIR study by Bluyssen (2013) performed in Europe. Out of the 7441 workers in 167 offices and 8 countries, 23% rated the comfort less than 4. This was mostly because of, noise, too dry air or the temperature was too variable. In addition, 1/3 of the people felt more symptoms during the winter and in the afternoon. 68% of the 7441 workers concluded that the symptoms came from their working environment. As it has been noticed, the materials, which were used in the offices, where 40% carpets, 33% smooth floors and 32% of the wall were painted. Furthermore, the office furniture was made mostly out of particleboards or fibreboards (MDF). Positively, 84% of the offices took care of plants.

This study shows also that other factors can influence the indoor comfort, such as the location of the printers and copy machines, controllable installation systems, number of occupants, smoking areas and the view. Building users were more satisfied when the office was cleaned in the morning before arrival than later during the day and the ventilation was turned on before the users entering the building (Bluyssen et al., 2016).

The study Hope by Bluyssen, Aries & Van Dommelen (2010), was performed in 9 countries with 164 buildings. 69 offices and 5732 building users were questioned. This study shows results of how the indoor comfort is perceived by the building users. Gender related outcomes are concluded, where women were less satisfied than men. Also, the managers have a positive influence on the indoor comfort and the building users are more satisfied with a view, controllability, direct sunlight and good orientation of the façade in the summer.

In the Audit project, 56 office buildings were investigated from 1993 till 1994, relatively older research, but includes valuable results. 6537 buildings users who were questioned, 47% males and 53% females with an average age of 39 years old. 32% of the building users experienced the indoor air quality as not acceptable and the air was stuffy, the temperature was slightly cool or slightly warm. Building related symptoms were 32% dry skin, 31% blocked and stuffy nose, 31% tiredness, 27% eczema, 10% asthma and 25% hay fever. The pollutions came mainly from the building materials and activities, like ventilation systems, occupants behaviour and smoking. The pollutions sources can be divided into six categories; outdoor sources, tobacco smoke, office equipment, building materials, furniture and customer products (Bluyssen, et al., 1996).

The factors which are influencing the indoor comfort, analysed from the studies OFFICCAIR, Hope and The Audit project 56 office buildings are summarized in figure 18.

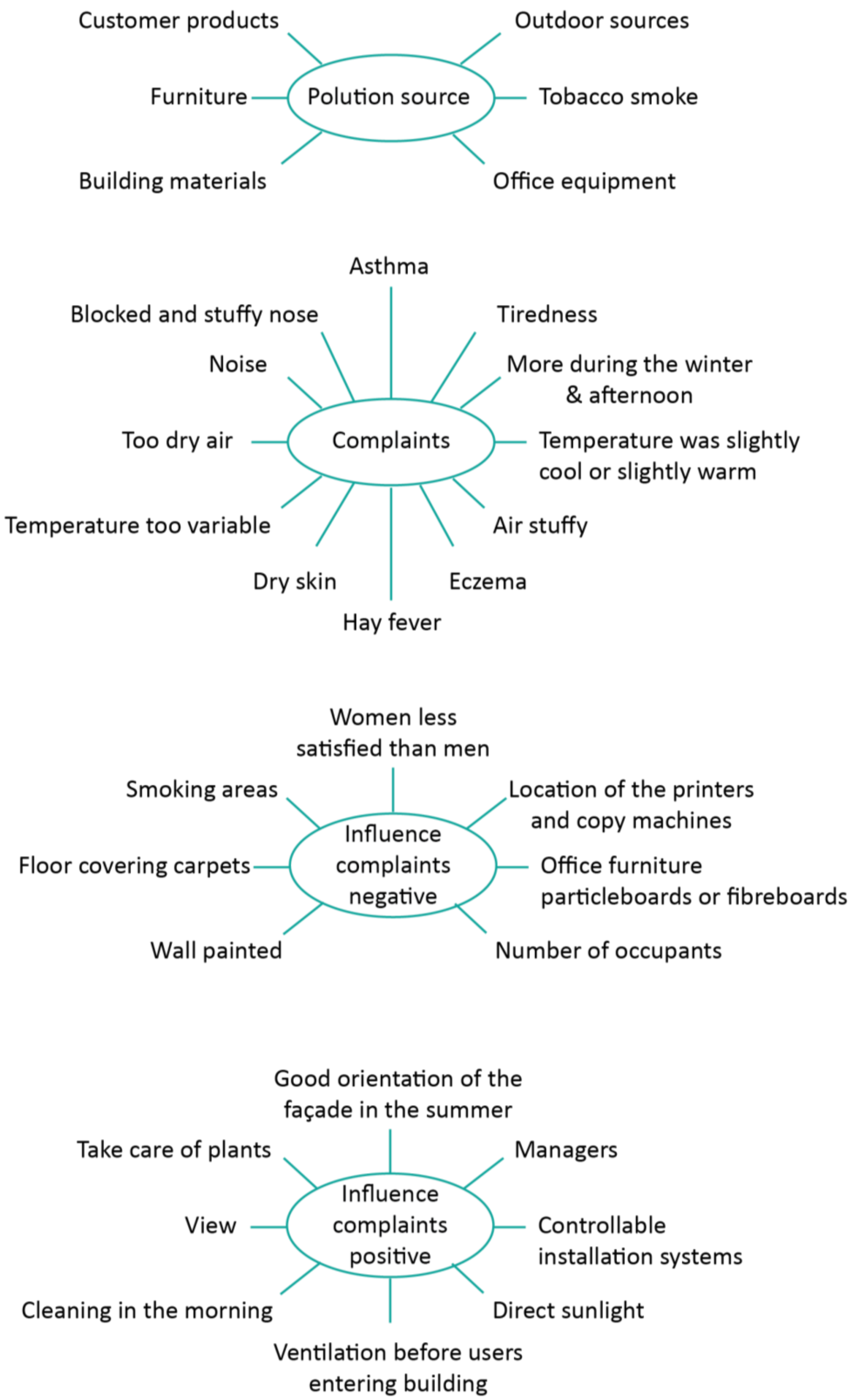


Figure 18. The indoor comfort, analysed from the studies OFFICCAIR, Hope and The Audit project 56 office buildings (Adjusted from Bluyssen et al., 2016; Bluyssen, et al., 2010 & Bluyssen, et al., 1996).

2.5 Reference renovation indoor comfort office

Reference projects contain many lessons learnt, which can contribute to this research and the approach on which criteria are important and which and how the measures can be implemented. This reference project is about the government office at Rijnstraat 8 in the Hague, the Netherlands which is renovated to improve the indoor comfort, figure 19. The aim was to renovate the building and providing higher efficiency, flexibility, innovation, sustainability and aesthetic. This included standard ambitions as well, such as employees satisfaction, safety and healthy working space. This research is done to analyse how the indoor comfort changed after the renovation by questioning 4152 employees, 59,3% responds, interviews, measurements and analyse of the floorplans. In conclusion, the building users are dissatisfied with their working environment compared with the database national average of occupancy in offices with a flexible workplace concept (SUM), mostly because of the concentration, productivity and privacy level, the atmosphere and appearance of the building and the quantity of building users, illustrated in table 3. In addition, diversity of working spaces and building users are more tired. The concentration level is disturbed by employees walking by and the conversations between colleagues. The indoor comfort factors play a role as well, such as too loud noise level, cold climate close to the façade, stuffy climate in the meeting rooms, odours from the catering and dark coloured walls and floors (Beijer, Colenberg, Den Hollander, Pullen & Smid, 2018).

	SUM benchmark	Rijnstraat 8
Average occupation by building users	36,5%	44%
Temporary empty spaces	20,5%	23%
Peak occupancy	76,4%	93%

Table 3. SUM Benchmark (Beijer, et all., 2018).

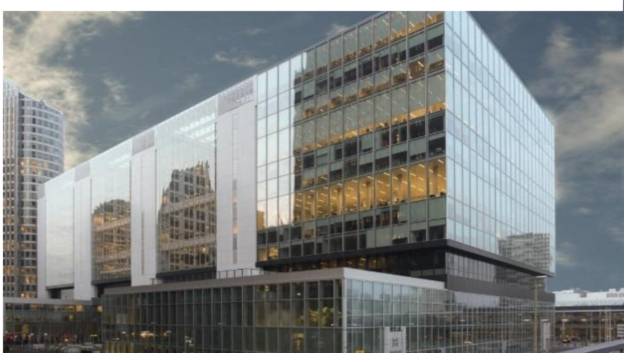
Some building users were more positive, probably because of their activities, organisation culture and spaces within the building. Positive aspects are the ICT facilities and the communication between colleagues in the open office space (Beijer, et all., 2018). The lessons learned from this renovation process are sorted per category; facility management, organisation, behaviour and communication and building.

Facility management:
- Cleaning frequency.
- Waste separation in the coffee corners.
- Procedure for employees to submit complaints.

Organisation, behaviour and communication:
- Occupancy and type of activities per space.
- Spaces to come together for social activities.
- Pay attention for absence and complaints as a result of the working environment.

Building:
- Call station, one per 20 open office workplaces.
- Sound absorption in open work spaces, acoustic screens.
- Limit visual nuisance and lack of privacy due to the walking routes.
- Concentration zones.
- Consulting rooms for confidential conversations.
- Variation possibilities in lay-out of meeting rooms.
- Placing plants in the open work spaces and in the larger enclosed spaces.
- Minimal 500 lux for office workplaces.

Figure 19. Rijnstraat 8 (Duurzaam gebouwd, 2018).



2.6 Requirements of indoor comfort offices

Restrictions are difficult to define, especially related to the human heath, because of the various existing pollutions (Geldermans, Tenpierik & Luscuere, 2019). The Dutch government sets certain requirements, described in Bouwbesluit 2012. Various companies have set up rating systems to indicate among other things the indoor comfort, such as BREEAM, LEED, WELL, The Living building challenge, ASHRAE and WHO. All rating systems have their own categories (Kwok & Grandzik, 2018). Some studies showed that the certifications not always support comfort and satisfaction (Kwon, Remoy & Dobbelsteen, 2019). The requirements are summarized in the conclusion and detailed information about the rating systems and organisation are described in appendix 6. Background information on the requirements are described in appendix 7.

2.7 Conclusion indoor comfort in offices

The indoor comfort inside buildings is very important for the health and wellbeing of the human, because people spend around 80% till 90% of their time inside buildings. The indoor comfort is influenced by indoor air quality, thermal comfort, light & visual quality and acoustic comfort. Furthermore, by the building users, materials & products and the location of the building. The last three influence factors are described more in detail. Firstly, the building users are formed by their physical, physiological and psychological state and their history, demography, states, traits, lifestyle and health status. Secondly, the materials and products are effected by the organic or inorganic materials, the existing furniture and installation systems and aesthetic, spatial, ergonomics and tactile factors. Lastly, the location is influenced by their surroundings, people, nature, real estate, weather and traffic. In conclusion, this results in a satisfaction level of the indoor comfort. These influence factors are illustrated in figure 20.

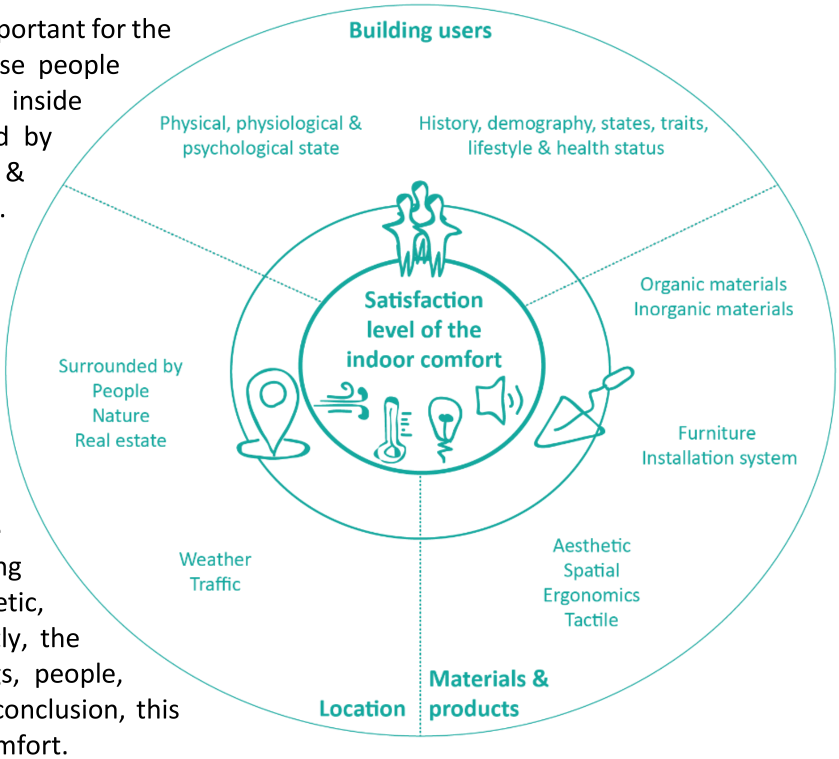


Figure 20. Influence factors indoor comfort.

The stressors can affect the body senses; human nose, respiratory tract, skin, eye and ear and systems; nervous system, immune system and endocrine system. This can cause stress, diseases and disorders, which influence the working atmosphere and financial situation in an office, figure 21.

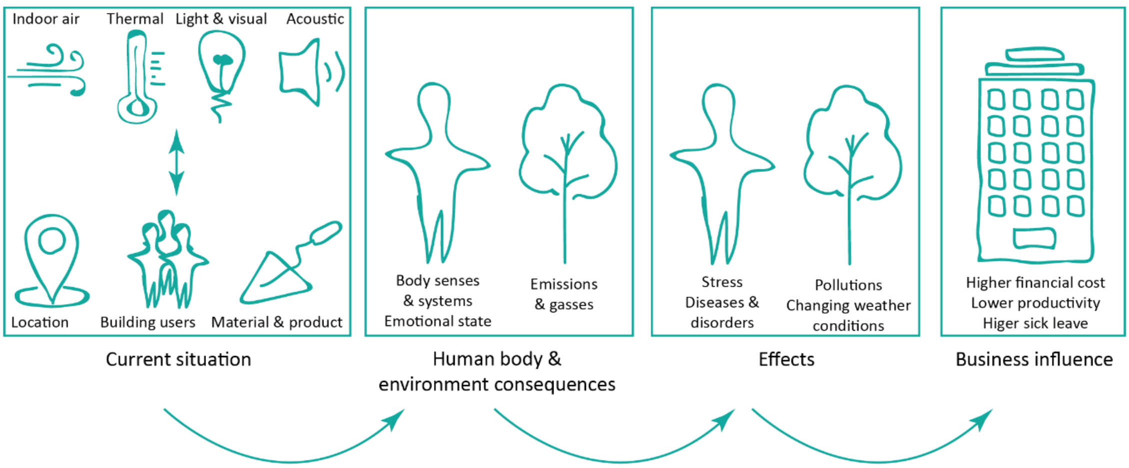


Figure 21. Wellbeing of humans in offices.

Improving the first phase of the wellbeing of humans in offices consist of the current situation to prevent negative business influence. The fast changing world, including the changing building users preferences and needs, innovation and new materials influence the regulations. These regulations consist of Bouwbesluit 2012 reviewed in 2020 and rating systems, illustrated in figure 22. It is important to make a profile of the building users to indicate their mood, physical state and body health.

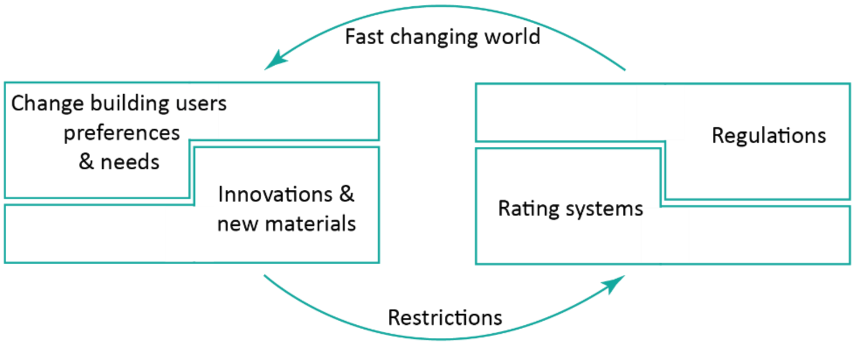


Figure 22. Fast changing world.

The influences of the stressors are mentioned in the table 4 below.

	Indoor air	Thermal	Light & visual	Acoustic
Source	Outdoor air Furniture Customer products Tobacco smoke Office equipment Building materials	Air & vapour Human body Local climate	Façade Sunlight Artificial light Local weather	Sounds people & traffic Installation Materials Location
Influence factors without energy	Fresh air supply (natural) Materials Filters Plants	Cool/warm air supply (natural) Openable windows Shading system	Openable floor, façade or roof	Absorption materials Mass construction Connections
Influence factors with energy	Fresh air supply (mechanical)	Heating/cooling system (de) Humidification system Cool/warm air supply (mechanical)	Light bulbs	
Influences human body	Nose & respiratory tract	Skin	Eye	Ear
Influences environment	Pollutants; VOCs, CO_2, CO and NO_2	Air movement with various temperature & vapour	Disturbing day & night rhythm living organisms	Sounds living organisms
Influences financially	Materials & energy	Materials & energy	Materials & energy	Materials

Table 4. Stressors and their influences.

The indoor air quality is analysed in detail during this research. Firstly, analysed how it is influenced by the sources where the air enters or leaves the building. Secondly, which materials are not using energy to perform their filtering function and lastly, which installation systems are using renewable energy. According to the literature study, measures without energy which can influence the indoor air quality are plants. The advantages and disadvantages of plants are described in table 5.

Plants	
Advantages	Disadvantages
Remove VOCs	Maintenance
Carbon dioxide convert into oxygen	Low positive influence relative humidity, temperature and background noise level
Low cost	
Environmental friendly	Plants need water and nutrients
Influence physical state building users	Some plants cannot purify the VOCs from the air
Nature aesthetics	

Table 5. Advantages and disadvantages of plants.

The indoor comfort in offices contains different focus areas to improve the stress, productivity and sick leave, whereby the building users can control their own indoor comfort. The factors that can influence the stressors in a positive way are illustrated in figure 23.

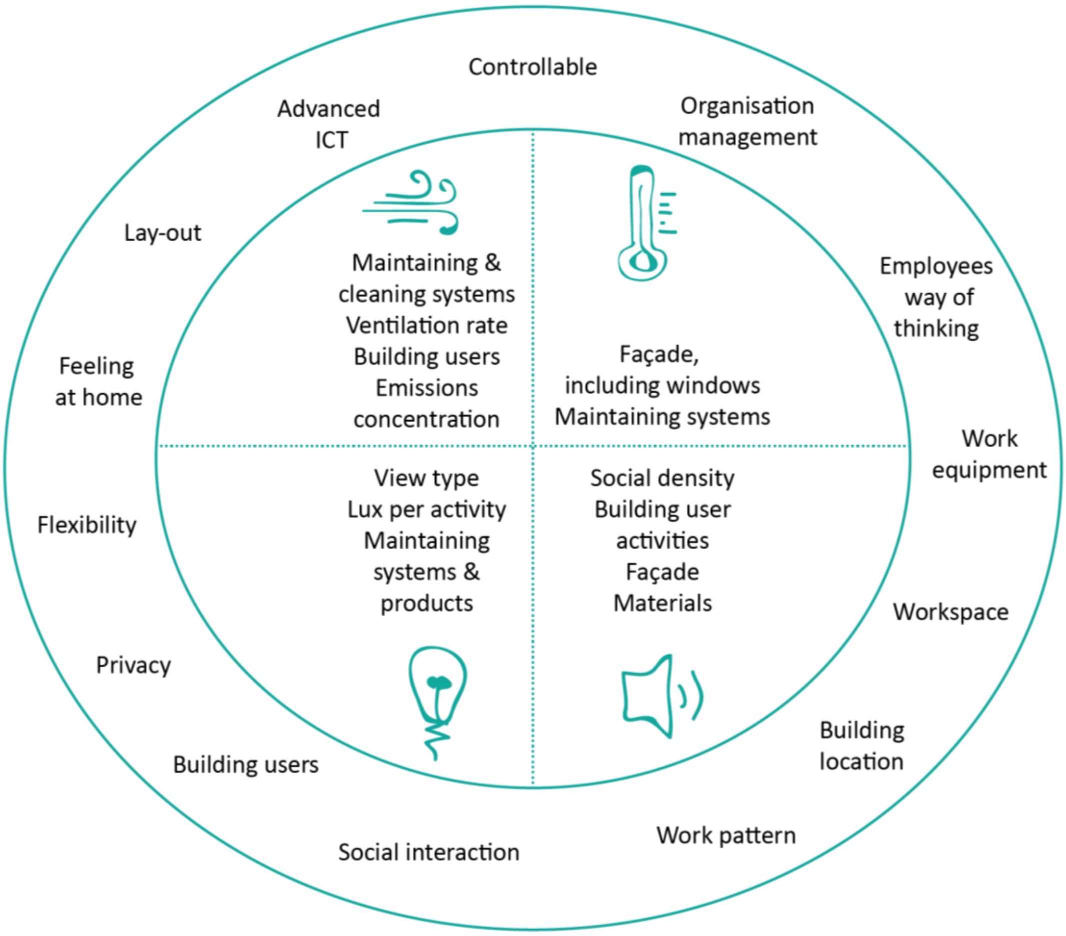


Figure 23. Factors improving the indoor comfort in an office.

The requirements of indoor comfort in offices are described in Bouwbesluit 2012, advised by ratings systems, like BREEAM and WELL certificate and indications of TNO. The illustration below figure 24 shows the main requirements for the indoor comfort in offices. The background information on the requirements are given in appendix 7. In conclusion, these requirements are compared and merged with the requirements in chapter 3 circularity and chapter 4 case study current state. These requirements are used to create the criteria for this research, described in chapter 5 literature study results.

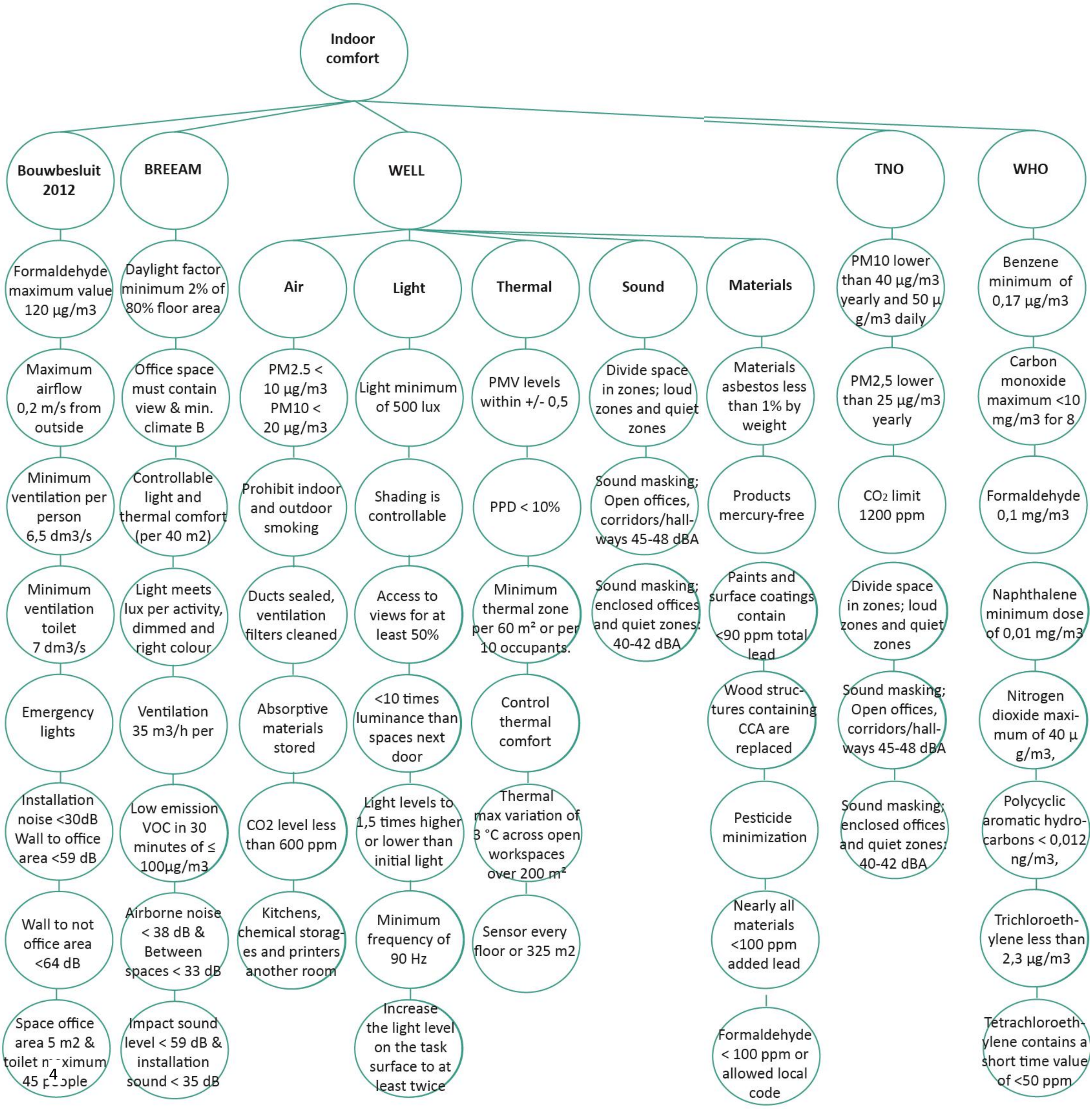


Figure 24. Illustration of most requirements of the indoor comfort (NEN 1824, 2010; Bouwbesluit, 2012; BREEAM, 2019; WELL, 2019 & TNO, 2019A).

Chapter 3. Circularity in the built environment

3.1 Introduction

Products of today become materials of tomorrow. This circularity approach is part of a sustainable environment. Sustainability is defined by the World Commission on Environment and Development (WCED). The definition is written by the commission of Brundtland in the paper 'Our Common Future' published in October 1987 and is "Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruton, 1987). The definition of a circular building environment is still in development and research is done by universities and companies. This research defines circularity as materials originated from infinite resources, which are demountable, reusable, contribute to the indoor comfort and connect flows with each other.

Nowadays, resources are limited, where material consumption is accelerating every year since 2000. The expectations are that resources will rise up to 190 billion tons by 2060. In 2017, this was 92,1 billion tons. The natural material footprint per person has enormously enlarged. In 1990, this was 8,1 tons per person, while in 2015, this has grown up to 12 tons per person. The resource efficiency needs to improve. In addition, a reduce of waste and a sustainable approach is necessary in every sector (Sustainable Development Goals, 2019).

Due to the current health crises, COVID-19, the carbon dioxide will fall with 4%-8% in 2020, around the between 2 and 3 billion tonnes of CO_2 (BBC, 2020). This is not a real-time number, because the crises is still going on and the numbers are updated every time. This is caused by less traffic both air and roads, less electricity demand and less industrial activity. The buildings use around the same amount of CO_2. In conclusion, the biggest reduction in CO_2 is caused by road transport (CarbonBrief, 2020).

Furthermore, the needs and requirements of the end-users changes over time, therefore the sustainable approach needs to be flexible. Next to flexibility, according to Geldermans, Tenpierik & Luscuere (2019B), stakeholders need to be integrated in every step of the process. Various sustainable development goals are connected to circularity, such as goal 12 'Responsible consumption and production' and goal 13 'Climate action'. These goals are explained more in detail in appendix 8.

The aim of this literature research is firstly, to gain background information about circularity in the built environment. Secondly, the circular existing approaches to formulate a plan of approach how to create a circular building environment. Thirdly, how a circular approach is used in other (field) studies and lastly, which requirements are stated by the Dutch government, the certifications and by the case study. Two research questions will be answered: '*How to apply circularity in the building environment?*' and '*What are the preferred requirements of a circular office building?*'. This literature study begins with the background information about the changing building environment.

3.2 Changing building environment

There is a need to change the way the built environment is organized, because of the climate change, which causes rising temperature, depletion of resources and high carbon dioxide emissions and higher concentration of other gasses (Rakhorst, 2007). The building construction uses 40% of the primary energy and 26% material resources. 35% of all waste is generated in the building sector, usually caused by earthwork. 95% of the recycled building materials are used for the infrastructure to build asphalt roads. The building sector hardly uses secondary materials, 3-4% of the materials are reused to build new buildings (EdX; Course Circular Economy, 2019 & Rijkswaterstaat, 2019). This process is described as a linear building environment, whereby materials and products are produced and used only one lifecycle. Also stated as the take, make & waste environment.

The building environment is slowly shifting from a linear building environment to a circular building environment. This circular building environment contains new ways of thinking, transparency in knowledge, closing loops, minimize resource input, eliminating waste, avoid disposal and losses of economic, technical and ecological value, building as material banks and new business model including leasing and products become a service (Geldermans, Tenpierik & Luscuere, 2019A; Rijkswaterstaat, 2015 & Kubbinga, et al., 2018).

The building processes are divided into 4 phases: development, construction, use and end-of-life. After end-of-life the process starts again with the development phase. The building environment is divided into various systematic layers: materials, products, buildings, cities and regions. All levels have to deal with technology, design, flows & resources, society & stakeholders, the economy and management & government regulations. These factors are interconnected with each other.

Designing a product, which can be reuse, repair, remanufacture or recycle is called 'Design for Disassembly'. This can be a challenging, because most of the materials have their own life-span, therefore looking at each material can contribute to a higher value in the circular system. Equally important factors which need to take into account are firstly, design robust for longer lifecycle, without hidden components. Secondly, avoid wet building methods. Thirdly, design and engineer building installations visible to access, update and maintain. Lastly, create interactions with stakeholders to optimize the workflows (EdX; Course Circular Economy, 2019 & Geldermans, Tenpierik & Luscuere, 2019B).

This circular economy is a way to reach a sustainable environment including new technologies, employment, processes, waste flows and business models by smarter materials, product use and manufacture optimization, extend lifespan, use after end-of-life and reducing dependencies.

In addition, assessment tools are changing as well from Life Cycle Assessment (LCA) to Multi-Cycle Assessment (MCA). This tool takes not only the materials into account from 'cradle to grave', but also the whole life-cycles of the materials, the 'Cradle to Cradle' principle. This assessment tools are changing to be able to calculate the value of the material or product after its first lifecycle for the following lifecycles (Geldermans, Tenpierik & Luscuere, 2019A & Kubbinga, Bamberger, Van Noort, Van den Reek, Blok, Roemers, Hoek & Faes, 2018).

Health & well-being is in synergy with circularity and can benefit from each other. The market moves faster than the science. Some companies are sceptical about circularity, because of their supply chain and footprint they already built up, difficulty to identify circular products and some decisions which are already made for tens of years. This changing process will take time, before the consumers, companies and the governmental systems are contributing and accepting the new, circular way of building (Geldermans, Tenpierik & Luscuere, 2019B).

3.3 Circularity indicators

Circularity can be seen from various perspectives. The perspectives that are taken into account in this research are divided into the overview of the circular economy and the circular building environment. The circular economy is explained in a 'Butterfly' diagram and the circular building environment in 'New Stepped Strategy', 'Cradle to Cradle', 'People, Planet and Profit' with various views and 'Materials Matters'. These perspectives will contribute to the general framework.

3.3.1 Butterfly diagram

The circular economy contains more topics than only the built environment, to get a broader view of the circular economy which is shown in the 'Butterfly' diagram. This diagram provides a connection to the built environment and the economical society and is illustrated in figure 25. The butterfly diagram includes the following aspects: social, natural, manufactural and financial. This diagram shows a division into technical and biological flows, where the material flows are continuous. The technical flows consist of materials, components and products. These flows can be reused, recycled, remanufactured or repaired. The biological flows consist of food and biologically-based materials. This can return back into the system in an organic way, like composting (Ellen Macarthur foundation, n.d.).

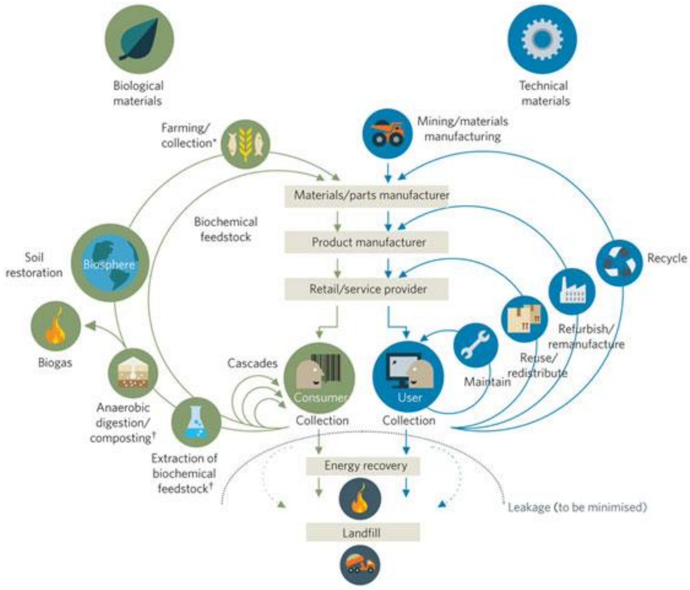


Figure 25. Butterfly diagram
(EdX; Course Circular Economy, 2019).

3.3.2 New Stepped Strategy

In the 1980s the methodology 'Trias Energetica' was developed. This methodology incorporated three steps; step 1) reduce energy, step 2) use sustainable energy and step 3) if fossil energy is needed, use the energy efficient. The 'New Stepped Strategy', figure 26 developed by Van den Dobbelsteen (2008) is a substitute of the 'Trias Energetica' with an added step between reduce energy and use sustainable energy. This step contains waste stream strategy, inspired by the 'Cradle to Cradle' principle focused on materials and products (Van den Dobbelsteen, 2008 & Van den Dobbelsteen & Tillie, 2011). The 'New Stepped Strategy' is as follows:
Step 0) Use location
Step 1) Reduce the demand
Step 2) Reuse waste streams
Step 3) Use renewable energy sources and ensure that waste can be used as food

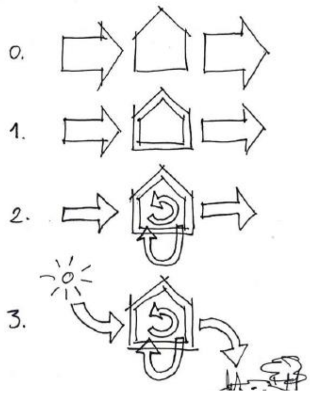


Figure 26. 'New Stepped Strategy'
(Van den Dobbelsteen, 2008).

The 'New Stepped Strategy' adjusted by Geldermans (2016) can be applied to support a circular building environment, the three steps are as follows:
Step 0) Use location
Step 1) Reduce resources
Step 2) Reuse resources
Step 3) Apply regenerative-circular- solutions with regard to the remaining resource demand
Firstly, step 1) can be done by smart dimensions and materials with similar lifespans. Secondly, step 2) is to reuse materials, which are used before by making the design demountable, 'Design for Disassembly'. Lastly, after reduce and reuse step 3) can be applied by closing the biological and technical systems.

3.3.3 Cradle to Cradle

Cradle to Cradle is explained in the books of chemist Michael Braungart and architect William McDonough, started with their ideas from 1991. They developed the concept 'waste is food' from the moment the raw material comes out of the ground till it is used in another product. Raw materials are never ending and can be used over and over again. Cradle to Cradle uses three principles for the materials and products, is it biodegradable, reusable or the product can be burned for energy without any toxic gasses (Rakhorst, 2007 & Cradle to Cradle, 2010).

Certificates

Cradle to Cradle develops certificates to proof safer and sustainable materials, components or products with a positive impact on people and the environment The Cradle to Cradle Certified Program started in October 2005. The certificate is divided into biological metabolism and technical metabolism, figure 27 focused on environmental and social performance including five subtopics; material health, material reuse, renewable energy & carbon management, water stewardship and social fairness.

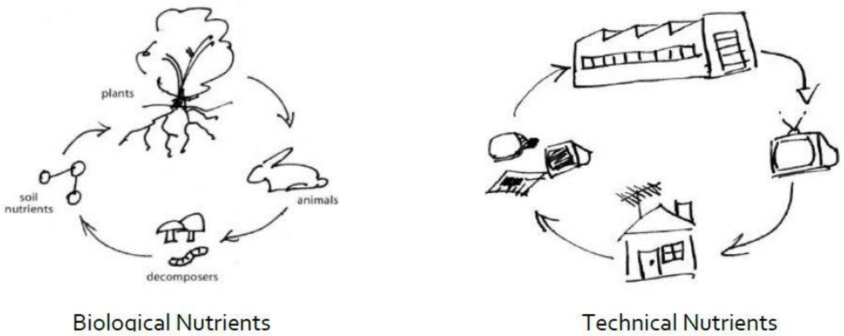


Figure 27. Technical & biological nutrients (Cradle to Cradle, 2019).

Firstly, material health uses materials that are optimized and not containing any toxic characteristics. Equally important is the production process of the product, especially which materials are used. Secondly, material reutilization, separating the biological and technical cycles and how the material can be reused after its first lifecycle, like compostability or recyclability. Thirdly, renewable energy and carbon management provides a positive impact to the community, ecosystem and energy supply and keeps carbon dioxide in the soil. This contains the energy which is needed during the manufactory as well. Fourthly, the water stewardship is analysing the water consumption and minimize the use. Lastly, social fairness is about stakeholders that are contributing to the process. Furthermore, a sustainable business plan is made, which measures the impact on the people and communities. The certificate of the product is ranked as basic, bronze, silver, gold or platinum (Cradle to Cradle, n.d. & Cradle to Cradle, 2016). This topics can be used later in the requirements for circularity.

Cradle to Cradle principles

The Cradle to Cradle principle is described to define requirements how to improve the indoor comfort in a circular way. The principle is categorized in: eliminate waste, use renewable energy and celebrate diversity.

Eliminate waste

- Nutrients back in the cycles, division between technical and biological cycles.
- Materials and products can be used in other systems, incorporated in design.
- Materials and products are safe.
- Effective management of scarce materials, collect and recover value.
- Manage water streams, healthy ecosystems and use efficiently.
- Carbon dioxide back in the soil and not in the oceans or atmosphere.

Use renewable energy

- Make the design effective with renewable energy resources.
- Renewable sources; wind, solar, biomass, hydrogen fuel cells and hydropower.

Celebrate diversity

- Social fairness for companies and stakeholders.
- Let participate more people in the design process.
- Explore various technical options.
- Support local ecosystem; cultural, social and ecological footprint.

Material flows are 'products of consumption'. These flows consist of biological nutrient materials, these materials are defined by living organisms. The materials can return into the soil, air or water. Materials after use 'products of service', these products are mostly not owned by the users and falling into the technical cycle. These materials can be constructed and deconstructed; reuse, physical transformation or chemical transformation (Cradle to Cradle, 2016).

The goal of McDonough and Braungart: "Our goal is a delightfully diverse, safe, healthy and just world, with clean air, water, soil and power - economically, equitably, ecologically and elegantly enjoyed." (Cradle to Cradle, 2016).

3.3.4 People, Planet & Profit

The principle People, Planet and Profit originates from the term 'Triple Bottom Lines', developed in 1981 by Freer Spreckey. This term was published in 'Social audit - A management tool for co-operative working', to measure the business on the social, ecological and economic performance. Later in 1995, Joh Elkington used the 'Triple Bottom Line' in short as People, Planet and Profit to create sustainable development. The company Shell used this term for the first time in 1997 (Van Mierlo, 2011 & Ojo Arowoshegtbe, Gina & Emmanuel, 2018). This is about finding balance and interdependence between environmental aspects and provide inside in social, environmental and economic decisions, actions or goals, illustrated in figure 28.

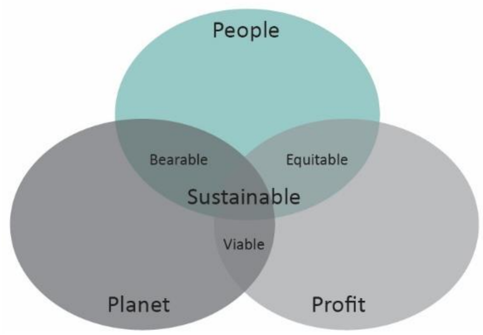


Figure 28. People, Planet & Profit circles.

Copper 8, a circular consultancy firm, stands for creating and adding value to the existing systems, they created the model illustrated in figure 29.

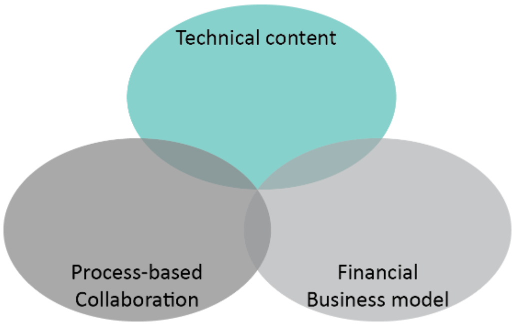


Figure 29. Copper8 circular model (Adjusted from Copper8, 2020).

3.3.5 Material matters

The economy which is applied at the moment contains a the take, make and waste strategy, where the need for raw materials grows exponentially, while the earth has only finite resources in a closed ecosystem. Small changes in this ecosystem can have major consequences, the effects are connected with the whole system and must remain in balance. The responsibility of these raw materials lies with the consumer instead of the producer, who knows everything about the raw materials within the product. This economy creates a lot of waste, because of the anonymity and ownership of the raw materials. Next to the anonymity and ownership challenges, there are no laws for materials, whereby materials cannot be protected. Materials cannot disappear, only change shape and size (Rau & Oberhuber, 2016).

A circular building environment uses the raw materials instead of consuming it, whereby the materials stay in their original state, oppositely of disappearing in gasses. True-cost accounting calculated the cost of the product, not only to manufacture it, but also the potential damages to the environment. This new strategy creates performance instead of ownership, a product as a service, illustrated in figure 30. A product becomes a deposit of raw materials to meet the temporary needs of human beings. Three business models need to change. Firstly, design to fail becomes design to perform, the product will not break after a programmed period, but continues till one of the materials are end-of-life and can be replaced, to perform again. Secondly, design to be outdated turns into design to be updated, a product can adjust to the certain needs and innovations. Lastly, design to be out-fashioned shifts towards a design for passion, where the consumer does not always need new products, illustrated in figure 31 (Rau & Oberhuber, 2016).

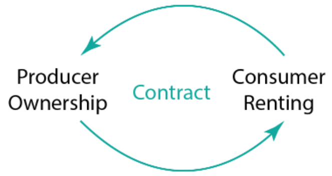


Figure 30. Product as a service
(Adjusted from Rau & Oberhuber, 2016).

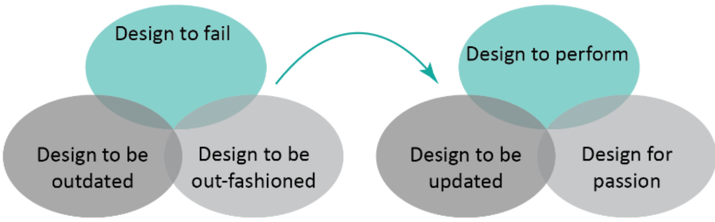


Figure 31. Changing business models
(Adjusted from Rau & Oberhuber, 2016).

To be able to identify raw materials within products, it is necessary to mark the various raw materials. This can be done with a material passport. These passports are stored in Madaster to make it accessible for everyone. The location of the materials can be located in a Building Information Modeling (BIM) model. Information that is described in a materials passport; original location of each raw material, the raw material itself, how it is adapted during the manufacture process, where it is located in the building and in the future the location and adjustment to the raw material will be documented as well. When renovating a building, some materials and products can be end-of-life, while looking at the individual raw materials, they can still be reused or recycled. Applying this strategy, an existing building acts as a material mine and a new building as a material depot. Raw materials can contain a value including the value of its existing cycle and the next lifecycles.

3.4 References circular office

The headquarter of Alliander, surface of 24000 m^2, houses 1550 employees. The renovation and adding an additional building was focused on interconnectivity and circularity, where 83% of the existing construction remains and optimized by adding a new building between the six existing buildings to connect all buildings with a large atrium. The link between the buildings and landscape was made to provide inspiring and healthy working space (ArchDaily, 2015 & Hutton, Adams, Hobbs, Cari, Bricout, Ollerenshaw, Steinhausen, Oberhuber & Sukhdev, 2016), illustrated in figure 32.

Circularity

Most of the existing buildings are reused and the additional construction is reusable in the future. The wood which was removed from the façades is reused in the interior, while reusing the existing ceiling plates and toilets. In addition, the doors were reused for the interior furniture. The construction of the roof was made in cooperation with a roller coaster construction company to minimalize the weight and standardize the construction components, which resulted in reducing material and the possibility for disassembly in the future. Next to the opportunity, to disassembly the construction, a material passport was made to identify each raw material. Next to the circular design of the building components, the building generates more energy than is needed and can be used in the neighbourhood via a smart grid (ArchDaily, 2015).

Stakeholders

The stakeholders who worked on the project are defined below (Hutton et al., 2016).

- Client: Alliander
- Architect: RAU
- Developer and general contractor: Volker Wessels
- Circular expert: Turntoo
- Interior design: Fokkema & Partners
- Technical installations advisor: Innax
- Landscape design: Kuiper Compagnons
- Structural engineer: Van Rossum R.I.
- Building contractor: Boele & van Eesteren
- Technical installations contractor: Homij

Figure 32. Headquarter Alliander (ArchDaily, 2015).

3.5 Requirements to achieve circularity

The building requirements of the European and Dutch government are difficult to adjust to the fast changing world. Besides the changes, reliable circular measurements tools are still in development. The European parliament is driving to a circular economy transition and resource efficiency.
To be able to meet the aim of the European parliament the following needs to happen; a chain approach including all stakeholders, developing financial models and simplification of methods and indications (Rijkswaterstaat, 2015).

The Dutch government can support the changing environment to remove regulatory impediments in association with social cooperation. The government will start together with businesses living labs to experiment and share knowledge. Building on greenfield is still cheaper than renovate a vacant building. The government develops systems to change this by creating collective money to create affordable recycling processes for vacant buildings. Besides this system, less tax can be asked for low CO_2 emission buildings or using secondary resources. These systems will be more attractive when they are applied in Europe or even better globally. The system to measure circularity must be uniform, accessible and reliable. There are no building requirements to build circular yet, therefore only soft requirements are mentioned in the sub-chapter 'Requirements of circularity' (Rijkswaterstaat, 2015).

3.6 Conclusion circularity in the built environment

Sustainability is meeting the needs of the present without compromising the ability of future generation needs. Sustainability stands for, among other things; firstly, circularity including material rights and energy efficiency and secondly, social fairness including human rights and wellbeing.

Circularity is a subcategory of sustainability, to be able to serve the fast changing world in a flexible way, closing systems, identifies materials, responsible consumption and production of materials, reduce climate change and integrate stakeholders in every step. At this moment, most of the materials and products are managed with a linear system; take, make and waste, illustrated in figure 33. Only this system cost a lot of energy and raw materials and causes waste, whereby the most materials are not recycled and reused in the construction industry, figure 35. The circular technical and biological cycle is illustrated next to the linear system, figure 34. Figure 36 described the components of a circular system.

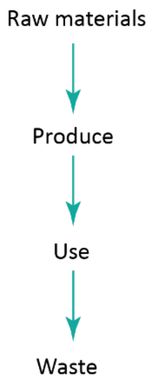


Figure 33. Linear system.

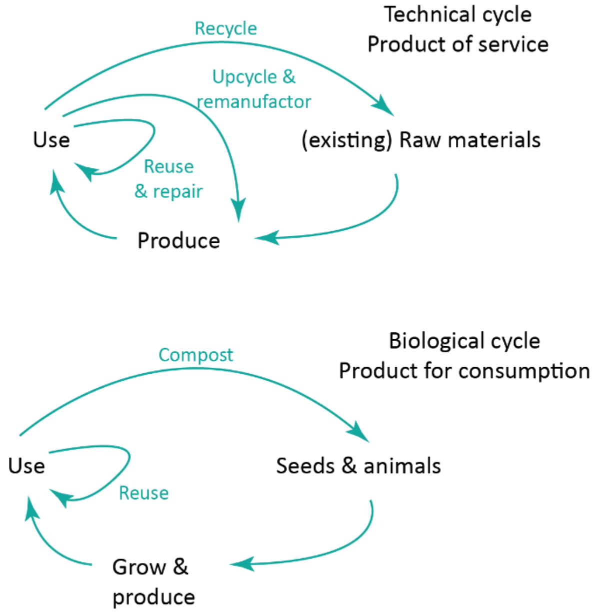


Figure 34. Circular system.

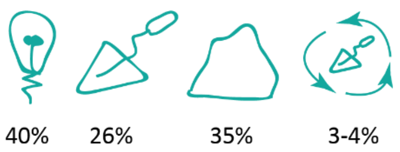


Figure 35. Component of a linear system.

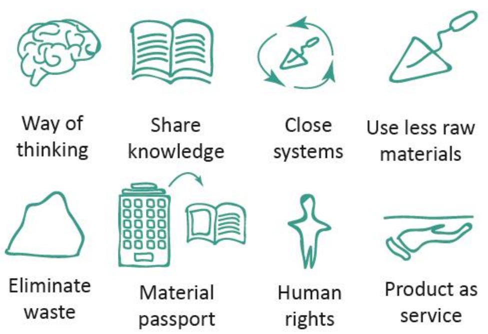


Figure 36. Components of a circular system.

The improvements will be advice with an adjusted New Stepped Strategy base on circularity.

1) Sources
2) Interventions without energy
3) Interventions with renewable energy

Step 2 and 3 will be advised in a Cradle to Cradle way, to have a positive impact on the people and the environment, divided into technical and biological circular cycles with subcategories; material health, material reuse, renewable energy & carbon management, water stewardship and social fairness. The overall advice includes a balance between people, planet and profit.

The requirements to achieve circularity with as main focus to improve the indoor comfort are described below and defined from Cradle to Cradle Material Health certificate, from the reference project and additional requirements from articles figure 37. The description of each requirement can be found in Appendix 9. In conclusion, These requirements are compared and merged with the requirements in chapter 2 indoor comfort and chapter 4 case study current state. These requirements are used to create the criteria for this research, described in chapter 5 literature study results.

Figure 37. Requirements to achieve circularity (Cradle to Cradle, 2016; Hutton et al., 2016 & Geldermans, 2016).

Chapter 4. Case study current state

4.1 Introduction

The bank acts as a living lab, improving every construction phase both socially, technically and financially. The aim of this case study research is to give background information about the case study and related projects and the regulations which are stated by the bank. The sub-research question that will be answered is: *'What is the current state of the indoor comfort of the case study; the headquarter of a bank in the Netherlands?'*

4.1.1 Headquarter of the bank

The case study is the headquarter of a bank in the Netherlands and is located between the city centre of Amsterdam and Schiphol, figure 38. The main building contains different parts with a gross floor area of 125.000 m^2 including the highest tower of 105 meters consisting of 26 floors. The building is built around 1990 and was opened on 13 October 1999. After the opening, the building stayed mostly the same without any major sustainable renovation. The installations are over 20 years old. The building is built to house 3200 employees, nowadays the building is used by 7000 employees, while the space and the technical installations stayed the same as the original design. The headquarter received the certificate BREEAM Excellent. However, this is not valid anymore and needs to be renewed. In 2016 the headquarter received the certificate BREEAM Excellent (ABN AMRO, n.d.).

Figure 38. Location of the bank (Google maps, 2019).

4.1.2 Renovation plans

The technical installations of the headquarter of a bank in the Netherlands will be renovated, the structure and building envelop stay the same. The renovation starts in 2020 with three pilot floors, two pilot floors, the case study, are located in the main building and one pilot floor is located in another office of the bank. The pilot floors will be evaluated and the design will improve every phase of the project. The pilot floors in the headquarter contain gross floor area of 1280 m^2 and only 99 working spaces can be created per floor area, figure 39. The bank wants to achieve a BREEEAM certificate again, because this certificate expires every 3 years (ABN AMRO, n.d.).

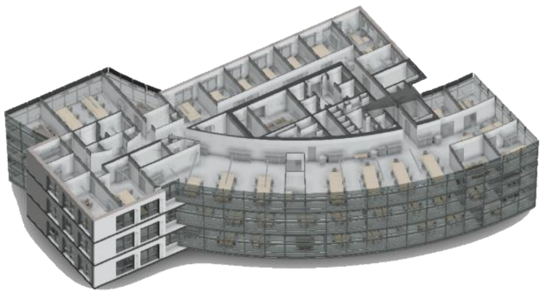


Figure 39. Floorplan of the bank (People Power, 2020).

4.1.3 Building installations

Air handling system

In a conversation with the Senior sustainability advisor (G. Limmen, personal communication, June 12, 2020) the air handling system of the current situation in the A tower of the case study works as follows explained in table 6 and figure 40.

Air handling system existing situation	
Type ventilation	Balanced ventilation, mechanical supply and exhaust
Distribution systems	Separate supply and exhaust cabinets
Primary distribution network	Constant flow with a fixed speed, heat recovery via twin coil system with an approximately heat efficiency of 50%
Batteries system	Heating battery 80°C - 55°C Cooling battery 7°C - 14°C
Humidification system	The installed adiabatic humidification system is used in tower A
Air supply	Line grilles with a fix flow
Air exhaust	Climate façade and installation shafts with a fix flow

Table 6. Air handling system existing situation case study (Limmen, 2020).

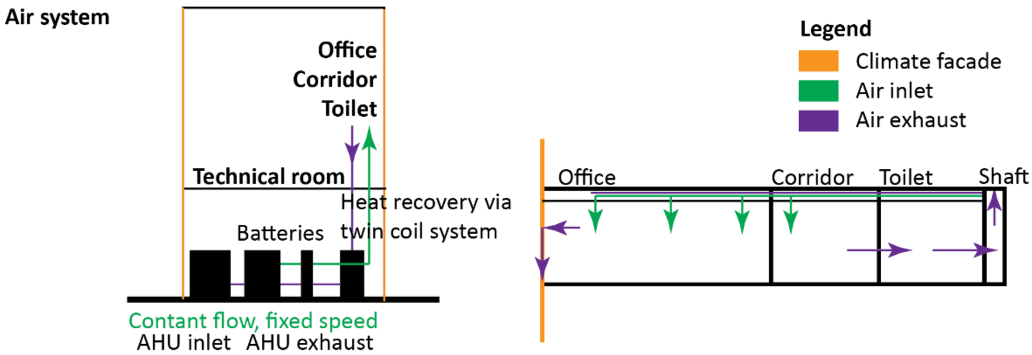


Figure 40. Air handling system existing situation case study.

Cooling system

The cooling system of the current situation in the A tower of the case study is explained in table 7 and figure 41. This information is gained from a conversation with the Senior sustainability advisor (G. Limmen, personal communication, June 12, 2020).

Cooling system existing situation	
Generation	District cooling, compression cooling machine, cooling towers and heat and cold storage only this system is out of business. The heat of the heat and cold storage is is discharged through the cooling towers
Distribution control systems	Volume controlled via two-way valves and variable speed pumps, statically adjusted
Primary distribution network	Main net: Summer 6°C - 18°C Winter 12°C - 18°C
Distribution network air handling units	Sub net: Summer low-rise building 6°C – 14°C Summer high-rise building 8°C – 14°C Winter 12°C – 14°C
Climate ceiling distribution network, return air handling units used for supply ceiling	16°C – 18°C
Delivery of cold on office floors	Climate ceilings, 16°C – 18°C and with air handling unit minimal of 16°C
Delivery of cold in server rooms	Fan coil units, 16°C – 18°C
Delivery of cold in MER rooms	Fan coil units, 16°C – 22°C

Table 7. Cooling system existing situation case study (Limmen, 2020).

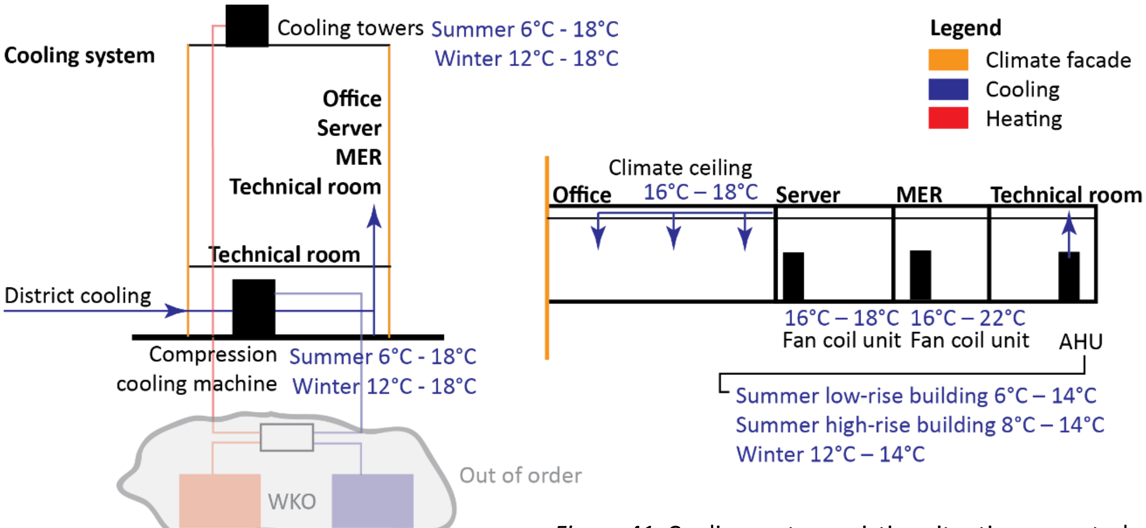


Figure 41. Cooling system existing situation case study.

Heating system

In a conversation with the Senior sustainability advisor (G. Limmen, personal communication, June 12, 2020) the heating system of the current situation in the A tower of the case study works as follows explained in table 8 and figure 42.

Heating system existing situation	
Generation	District heating, gas central heating boilers
Distribution control systems	Volume controlled via two-way valves and variable speed pumps, statically adjusted
Primary distribution network	Main net: high temperature heating of 80°C - 50°C
Distribution network air handling units, radiators and reheaters	Main net: high temperature heating of 80°C – 55°C
Climate ceiling distribution network, return air handling units used for supply ceiling	Sub net: low temperature heating of 45°C - 35°C
Delivery of heat on office floors	Climate ceilings, low temperature heating of 45°C - 35°C
Delivery of heat in corridors, stairs and other spaces	Radiators and reheaters, high temperature heating of 80°C - 55°C and small number of underfloor heating, low temperature heating of 45°C - 35°C

Table 8. Heating system existing situation case study (Limmen, 2020).

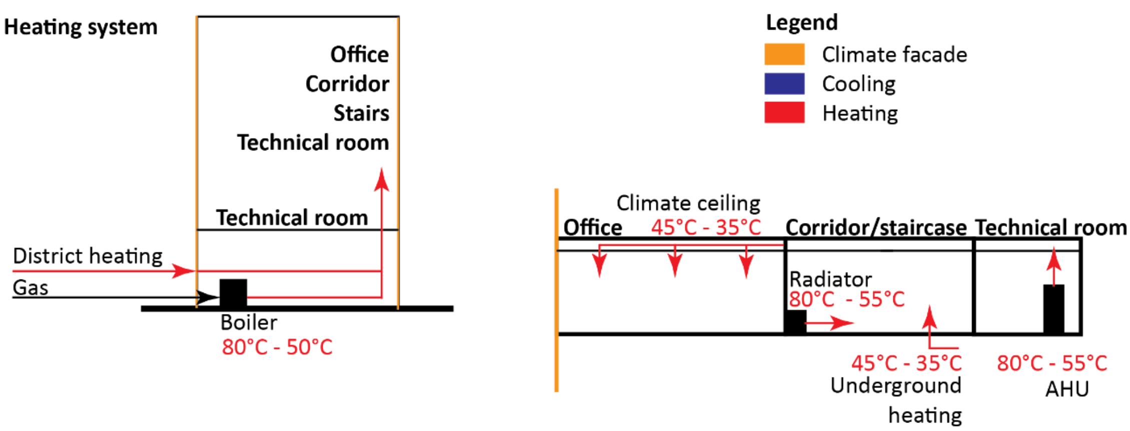


Figure 42. Heating system existing situation case study.

4.1.4 Circl

The bank pursues sustainability ambitions within the built environment. Their aim is to inspire employees and customers to build their real estate portfolio sustainable, which includes a circular approach, to make the society future-proof and facilitate circular business models. The banks' sustainability approach is reducing the energy consumption and their circularity approach is reducing the use of raw materials. This means there is an ambition to be 50% circular in 2030, including reusing raw materials and by 2050 100% circular. This ambition is formulated by the Dutch government as well.

The bank has built a living lab, the Circl, illustrated in figure 44. This building is located in front of their headquarter in Amsterdam. The materials come from natural cycles, can be directly reused or high-value recycled. In addition, the materials give a positive impact on the environment by closing the systems, while improving the health and productivity of the users. Furthermore, this concept is lowering the energy consumption of the building. The building acts like a raw material bank where their performances can be tracked. The main aim was to close the loops and provide new business models within the built environment to stimulate the circular environment.

The Circl emerges as sustainable, only a large amount of energy is needed to provide a comfortable indoor climate. This project is a good circular example, only some improvements in the Circl must be made, will be building be energy efficient and provides wellbeing for the building users.

Their circular approach is about; waste-free and resilient economy, where products last longer and materials are never ending. To achieve this goal five new business models are created; circular inputs, product-service systems, lifetime extension, sharing platforms and value recovery. The circular business model is illustrated in figure 43. Factors to make this possible are designing for the future, including innovative and digital technology and collaboration with every partner (Van Heel, 2019)

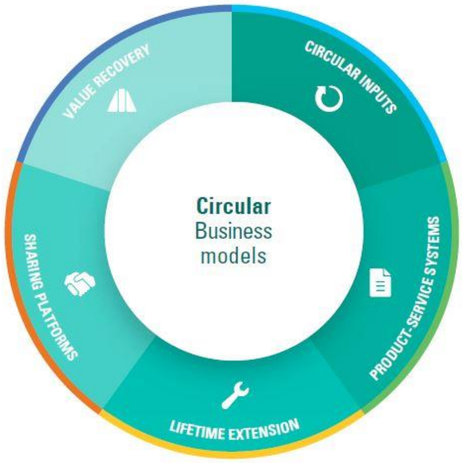


Figure 43. Circular Business models of the bank (Van Heel, 2019).

Figure 44. Building Circl (Circl, n.d.).

4.2 Requirements of the bank

The general objects of the renovation are; business continuity, safety for building users, high comfort, lowering energy use and technical documentation. Summarized in four main topics; business continuity, safety, indoor climate and sustainability. First three pilot floors will be renovated, continued with the other floors from 2020 till 2026 (ABN AMRO, n.d.).

Business continuity

The business continuity can take place, while all systems remain their function. The systems need to be replaced or renovated to monitor and support the business continuity for the next 20 years with 29% energy savings, with the help of smart technology. The renovation consists of a phasing strategy to minimize business disturbance and maximize the workflow (ABN AMRO, n.d.).

Safety

The safety for the building users is one of the main topics, focusing on fire safety. The fire safety installation changed a lot over time and needs to be replaced to meet the requirements of the Dutch government for the next 20 years (ABN AMRO, n.d.).

Indoor climate

The user satisfaction is investigated with a questionnaire in 2019, performed by the company Leesman. The results show a lower indoor comfort satisfaction, than the bank is aiming for. This needs to be increased to improve the engagement and productivity of the buildings users (ABN AMRO, n.d.).

Sustainability

The headquarter needs to be renovated to meet the 'Paris Proof' requirements by 2026. These requirements includes 23% energy savings, including demand driven installations. The current energy usage is 120 kWh/m^2 per year, this need to decrease to 50 kWh/m^2 per year to meet the 'Paris Proof' requirements. Energy savings can be achieved by; changing lighting system, demand driven ventilation, sustainable heating and cooling system, less warm tap water, solar panels and smart building management system which can monitor the indoor comfort installations (ABN AMRO, n.d.).

Circularity will be guaranteed meeting certain circular criteria of the bank, designed by the bank and consultancy companies, like Copper8 and Ellen McCarty Foundation, these companies are pioneers in the circular built environment.

Requirements

The requirements of the bank are divided into various categories, based on their objects; general topics, business continuity, safety, indoor climate and sustainability and are described in figure 41. The requirements are explained in detail in appendix 10. Requirements of the bank.

4.3 Conclusion Case study

The case study; the headquarter of a bank in the Netherlands opened in 1999. Twenty years later, the building users' needs and preferences changed and the occupancy rate is doubled. Next to that, the installation system is end-of-life and not functioning according the building regulations. The pilot floor, A11 of the headquarter with 1280 m^2 and 99 working spaces will perform as a living lab, how to renovate all the office floors within the headquarter.

The renovation focuses on firstly, replacing the building installations. The facility services contain lifetime of around 7-15 years. Secondly, the doubling of building users, the floorplan supports the building users' needs and preferences 3-30 years and interior elements supports the building users' needs and preferences 0-3 years.

The bank built the Circl in a circular way, to be an example by creating sustainable buildings. The aim was to create a future-proof society, circular business models, less energy consumption, reduce the use of raw materials and improving the health and productivity of their employees, by closing systems of the used materials, materials are reusable or high value recyclable and creating a raw material bank. From this living lab experiment, 5 new business models where developed; circular input, product-service system, lifetime extension, sharing platforms and value recovery. During this project less attention was paid to the energy efficiency. This can be improved in next projects.
With the results of the Circle and the building regulations, the bank has formulated requirements for their headquarter. The requirements of the bank are visualized in figure 45. In conclusion, These requirements are compared and merged with the requirements in chapter 2 indoor comfort and chapter 4 case study current state. These requirements are used to create the criteria for this research, described in chapter 5 literature study results.

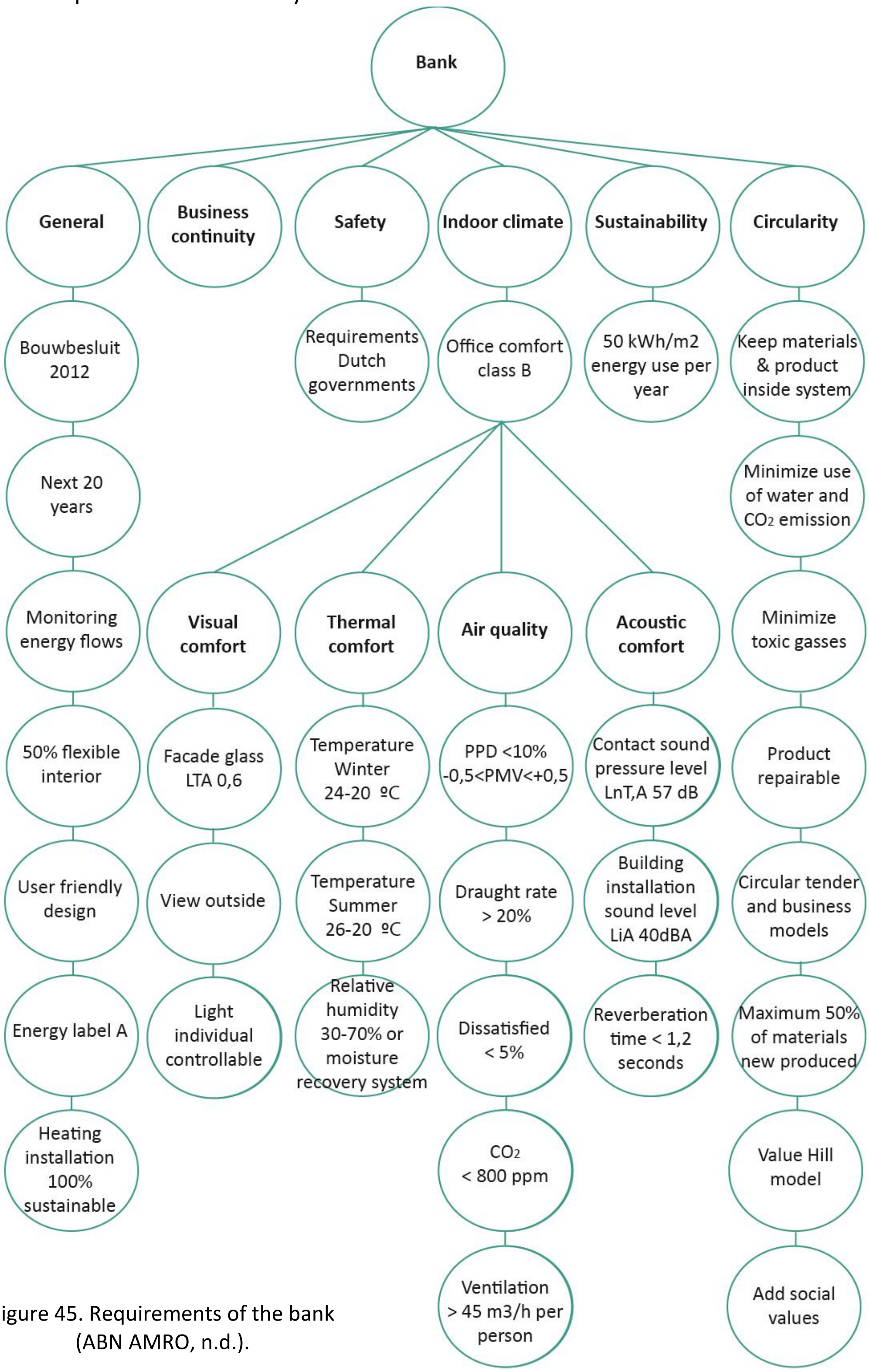


Figure 45. Requirements of the bank (ABN AMRO, n.d.).

Chapter 5 Literature study
The literature study integrates the literature and case study results into criteria for the development of the analyses and design.

5.1 Results
Multiple research terms were used to find the literature, such as circular (in the built environment), indoor comfort (in office), indoor air quality (in office), office renovation, innovation, comfort, wellbeing, green building, circular (office) and circular frameworks. The databases which are uses are Google Scholar, ScienceDirect and TU Delft Library. To limit the information unrelated to this field, boundaries are applied. The terms which will not be used are: school, hospital, house, city, infrastructure and software, these will not be taken into account. The literature comes from books, articles, websites and information from the company.

Database Google Scholar can find for ‘Circularity built environment’ 53.600 articles and since 2016 13.500 articles, this means most of the articles are written before 2016. The term ‘Indoor comfort offices’ obtains 115.000 articles, since 2016 22.600 articles. To sum up, more literature is written about the indoor comfort in offices. Only a few papers describe the gap between circularity and improving the indoor comfort, the focus of this research.

The building users are the focus area of this research. To make the feasibility study complete the environmental and financial aspects will be taken into account as well. The literature study investigated various criteria, which contain a prioritization. The measurable criteria will be linked to the survey and measurements, to analyse if the case study meets the criteria. These criteria are composed of the indoor comfort, circularity and the banks’ requirements. The subjective criteria are connected to the materials and survey, to describe the current state of the case study. These criteria are composed of articles described in the chapters 2 and 3.

The literature study is concluded for this research into five main categories; social fairness, indoor comfort, circularity, energy efficiency and the floorplan. This five topics are the most important to combine indoor comfort with circularity and the case study. Firstly, social fairness is to develop a workspace for specific the buildings users. Secondly, the indoor comfort to measure every related stressor. Thirdly, circularity to identify the existing materials and products. Fourthly, energy efficiency to use as less as possible energy to meet the Paris Proof agreements. Lastly, the floorplan A11, which will be the next renovated floorplan within the case study. This results in a general framework and specific floorplan design for the A11 floorplan of the case study, see figure 46.

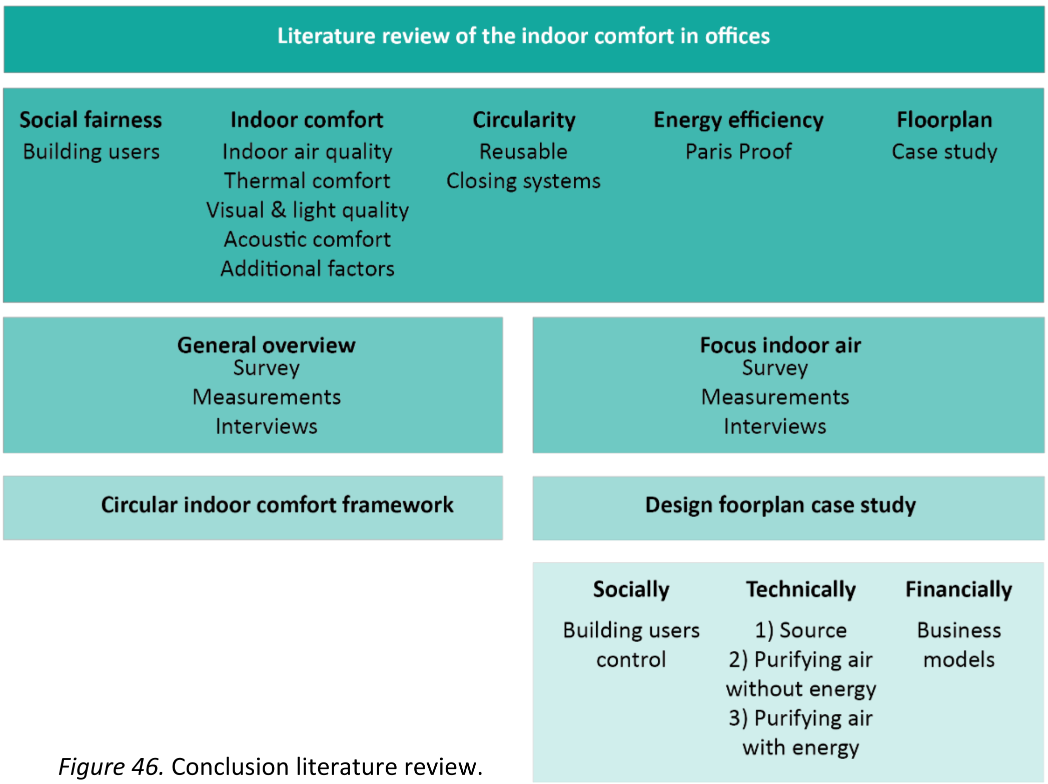


Figure 46. Conclusion literature review.

5.2 Criteria

The requirements written in chapter 2 Indoor comfort, chapter 3 Circularity in the built environment and chapter 4 Case study current state are translated and summarized. This resulted in measurable and subjective criteria, making a distinction between criteria which will be analysed for the current situation and the future situation. Both criteria are categorized by social fairness, indoor comfort, circularity, energy efficiency and floorplan.

The project meets the minimum requirements of the Dutch government; Bouwbesluit 2012 and shows additional higher ambition criteria. Some requirements of the Dutch government and requirements of the rating systems and requirements of the bank overlap or are interwoven with each other. All the requirements of Bouwbesluit 2012 and the bank are visualised in figure 47. In addition, the following requirements are used from the rating systems: controllable façade, systems and spaces. Moreover, The circularity material properties, the VOC concentrations, the minimum thermal zones and temperature level differences between adjacent rooms. Furthermore, spatial criteria with kitchen, chemical storages and printers need to be located in another room than the open office. Lastly, light requirements with 50% view from desk, sound level in open offices and cellular offices and plant properties that they have to convert CO_2 and purify VOCs. These criteria are written down in the measurable criteria, figure 47. This figure is the result of the literature study and appendix 11.

Measurable criteria

Social fairness	Indoor comfort	Circularity	Energy efficiency	Floorplan
Building users: Space for break	**Properties:** Controllable; facade, systems & spaces	**Material properties:** Material asbestos <1% Re-utilize 35-65% Mercury-free Paints and surface coatings contain <90 ppm lead Nearly all materials <100 ppm added lead	**Renewable energy:** 100% **Energy use per year:** <50 kWh/m²	**Interior:** Floorplan A11 113 building users with 800,1m² 90 desks and 82 meeting spaces 50% flexible
Indoor air: Airflow <0,2 m/s CO_2 <800 ppm Minimum ventilation 45 m3/h per person VOC <0,01 mg/m3 or <1 µg/m3	**Thermal:** Temperature winter 20-24 °C Temperature summer 20-26° C Humidity 30-70% Minimum thermal zone per 60 m² or per 10 occupants Variation <3 °C across open work-spaces over 200 m²	**Spatial:** Office workplace 4 m² p.p. Office meeting room 2 m² p.p. Kitchens, chemical storages & printers another room		
Visual & light: Emergency lights Light lux per activity minimum 500 lux 50% view from desk Flicker light <0Hz or >50 Hz	**Acoustic:** Contact sound level <57dB Building installation level <40dB Sound level Open office 35-45dB Cellular office 30-40dB Loud zones & quiet zones	**Plants:** Convert CO_2 into O_2 VOC purifying capacity minimum 20,4mg/m2/day		

Legend
Criteria current situation
Criteria future situation

Figure 47. Final criteria for the case study.

The subjective criteria will be investigated via the survey and are written down below, figure 48. These criteria come from articles described in chapter 2 indoor comfort, chapter 3 circularity and chapter 4 case study current state.

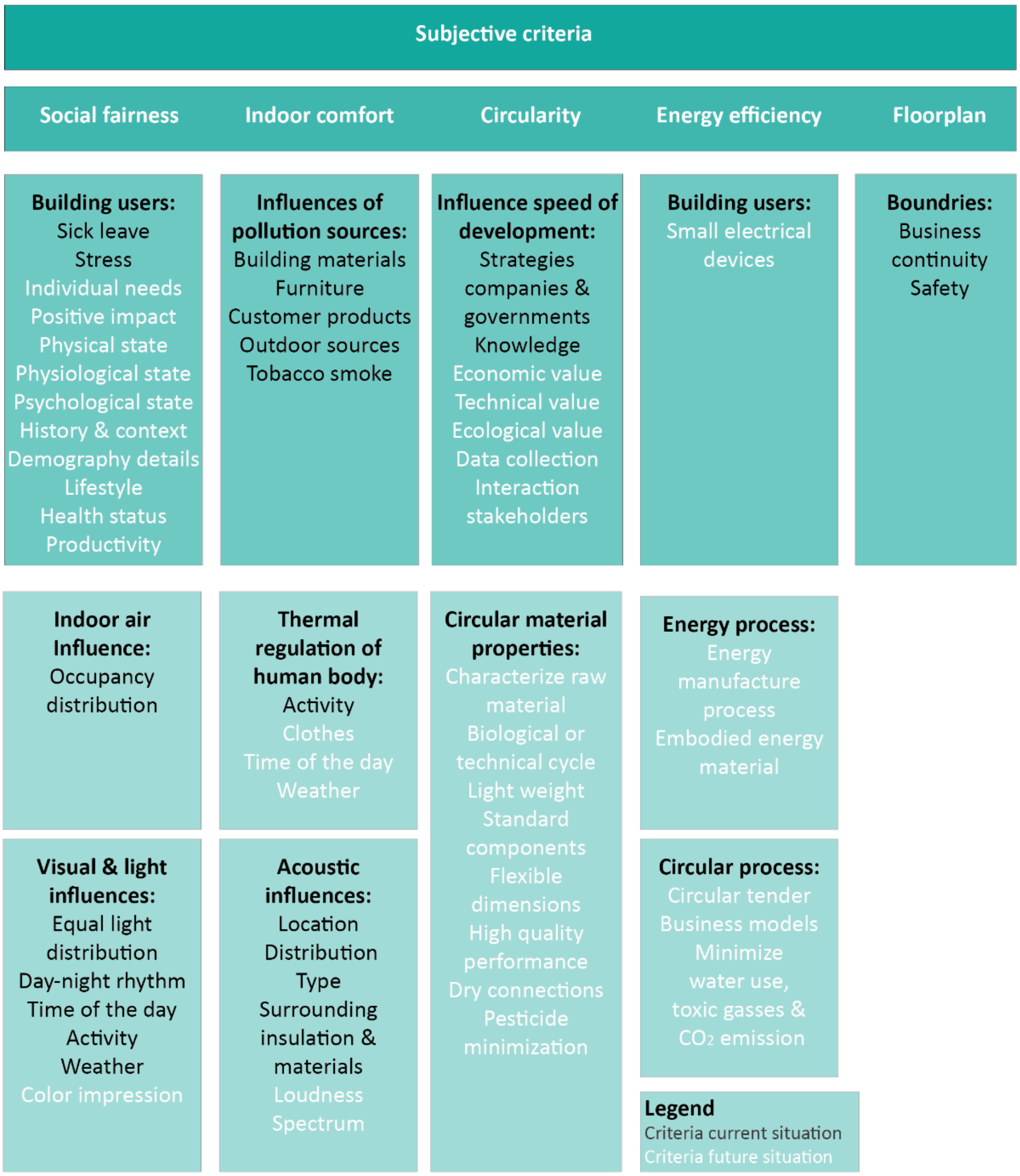


Figure 48. Subjective criteria.

Chapter 6. Methodology

6.1 Introduction

Analysing the current situation of the case study; the headquarter of a bank in the Netherlands provides information about the building users and the building itself. Analysing the materials and interior elements which are used, can provide insight in the raw material usage. Evaluating the survey, which is performed in 2019 by the company Leesman, profiles the building users to understand their working location, needs, preferences and comfort level. These studies can provide a broad understanding of the current situation of the case study. The material, survey and measurements results are based on the measurable and subjective criteria, to provide detailed information about the indoor comfort stressors. A division is made between the measurable and subjective criteria. The subjective criteria come from articles and findings from the literature study and the measurable criteria come from building legislations, certification organizations and the requirements of the bank.

These criteria will be used to analyse the current state of the case study. These results are the first steps towards the design to know the current indoor environment situation and if the current situation meets the criteria. The focus of this research is the indoor air quality.

6.2 Materials & products

The building materials and interior elements are analysed with information provided by the case study company and the producers of the materials and products. In addition, the information from the producers will be verified with information from other producers who are developing and producing the same products and research about those raw materials and connection systems from universities. The raw materials and the products itself will be analysed on the following subject circularity containing: raw materials & lifespan, demountable or detachable, remanufacture and recycle or upcycle. Moreover, on the flowing subject indoor comfort including influence on health of the building users, if the materials containing toxic gasses and how the product can be cleaned. The connection between indoor comfort and circularity is important.

6.3 Survey

The survey is developed and executed in September 2019 by the company Leesman. The results of the survey will be critically analysed to see if all the components are represented in the questionnaire. The execution of the questionnaire was via the computer via an online program. The questionnaire contains the impact of the working environment, the performed activities, the physical working environment and the facilities provided by the building. The respondents selection came from three locations of the bank including a population of 6183 employees, where 1311 employees responded 21%. The satisfaction level of each survey topic is compared with the Benelux Benchmark. The Benelux Benchmark is an average of respondents within the Benelux in office buildings. This average can provide a comparison with the satisfaction level of the bank and the Benelux.

6.3.1 Subjective criteria

The survey results will be compared with the average and peak measurement results of the case study. The survey will be analysed on factors that influence the indoor comfort and circularity with the following topics working place and facilities.

In addition, the building analysis investigates other factors that influence the indoor comfort, which cannot be measured. These factors are the amount of emergency lighting, the clothes of the buildings users and the view of the offices. Next to the possible indoor stressor related factors, general factors will be analysed as well. These topics are occupancy distribution and activity of the building users.

6.4 Measurements

The goal is to measure the indoor comfort (indoor air quality, thermal comfort, visual & lighting quality and acoustic comfort) of two floors of the headquarter of the bank. These measurements will be performed before the renovation starts. Unfortunately, the small particulates cannot be measured yet, because non validated measurement devices are existing at the moment or the non-precise measurement devices are too expensive (Bluyssen, 2013). The measurable and subjective criteria which will be measured are described below in table 9 and 10. These criteria are written down in figure 47 and 48.

6.4.1 Criteria

Measurable criteria					
Category	**Subcategory**	**Reference**	**Requirement**	**Equipment**	**Accuracy**
General	Spatial	NEN 1824	Per person office space >4 m^2	Floorplan	-
Visual & lighting control	Emergency lighting	Bouwbesluit 2012	Emergency light <75 occupants	Floorplan	-
Acoustic comfort	Contact sound level	Bouwbesluit 2012	<59 dB	GreenMe cubes	± 3 dBA
		Bank	<57 dB	GreenMe cubes	± 3 dBA
	Contact sound level Building installation sound level	Bouwbesluit 2012/bank	<40 dB	GreenMe cubes	± 3 dBA
	Building installation sound level	Well and BREEAM certification/bank	<35 dB	GreenMe cubes	± 3 dBA
General	Plants	Articles (Kim, et all., 2017; Smith, et all., 2017 & University of Exeter, 2014)	Reduce VOC	GreenMe cubes	> 0,155 ppm
	Spatial	WELL certificate	Kitchens, chemical storages & printers in another room	Floorplan	-
Visual & lighting control	Illumination	WELL certification/bank	Minimum 500 lux	GreenMe cubes	± 2%
	View	WELL certification	50% view from desk	View plan	-
Thermal comfort	Temperature	Bank	Winter 20-24 °C Summer 20-26 °C	GreenMe cubes	± 0,2 °C
		WELL certification	Variation of at least 3 °C across open space over 200 m^2	GreenMe cubes	± 0,2 °C

	Relative humidity	Bank	30-70 % or ventilating heat exchange wheel	GreenMe cubes (2)	± 2%
	Thermal zone	WELL certification	Maximum thermal zone per 60m^2 or 10 occupants	Floorplan	-
Indoor air quality	VOC	BREEAM	<100 µg/m^3 per 30 min.	GreenMe cubes	> 0,155 ppm
	Carbon dioxide concentration	Bank	<800 ppm	GreenMe cubes	± 30 ppm
		WELL certification	<600 ppm	GreenMe cubes	± 30 ppm
	Air exchange	Bank	45 m^3/h/p.p.	Floorplan (1)	-

Table 9. Detailed measurable criteria (1) Ventilation air exchange= total ventilation capacity/occupancy rate and (2) Water vapour pressure (p) = Relative humidity (rh) * psat (NEN 15729) (NEN 1824, 2010; NEN 15729, 2010; Bouwbesluit, 2012; BREEAM, 2019; WELL, 2019& ABN AMRO, n.d.).

Subjective criteria		
Category	**Subcategory**	**Owner**
General	Occupancy distribution	Book (Bluyssen, 2009), article (Beijer, et all., 2018)
	Activity of the building users	Article (Kwon, et all., 2018; (Beijer, et all., 2018)
Visual & lighting control	Which view	Article (Kwon, et all., 2018), thesis (Hellinga, 2013)
Thermal comfort	Clothes	Book (Bluyssen, 2009)

Table 10. Detailed subjective criteria.

6.4.2 Measurement conditions

Location

The indoor comfort will be measured at two different floorplans; a cellular floorplan including closed spaces and an open floorplan including open spaces. To analyse the differences between room size and occupancy. The measurements will be done on exactly the same dates, from Tuesday 18th February till Monday 9th March 2020, to prevent influences from outside the building. 24 measurement devices will be placed over two floorplans. The location of the measurement devices is illustrated in figures 49 and 50. 12 measuring devices are placed in an open floorplan, 3 measurement devices are placed in a space with plants, the experiment zone. The other spaces function as a control zone, to be able to measure the influence of plants. The other 12 measurement devices are placed in a cellular floorplan. Including the same principle for the plants, 3 measurement devices are placed in a space with plants, the experiment zone. The other spaces function as a control zone, to be able to measure the influence of plants. The zones and measuring devices are illustrated on engineering drawings in appendix 12.

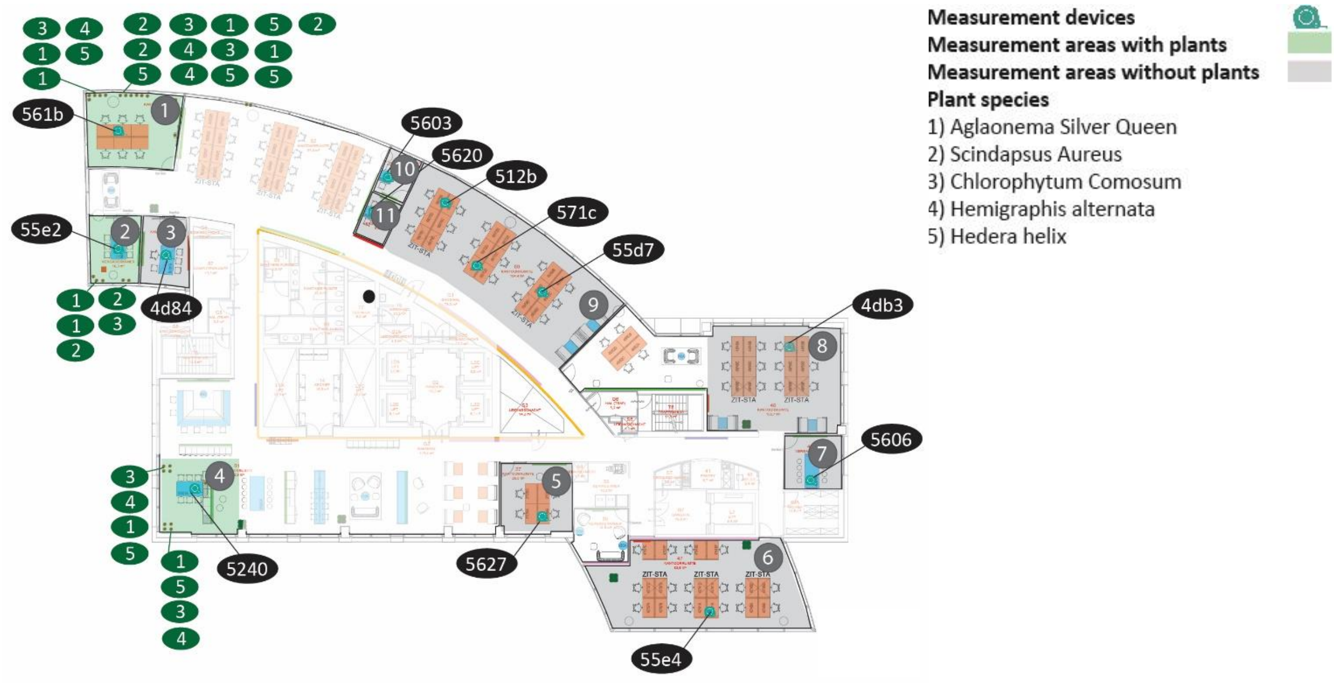


Figure 49. Pilot floor A11 measurement devices.

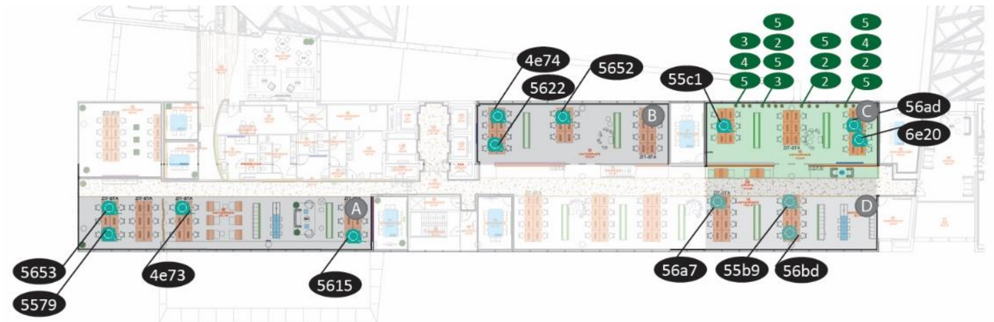


Figure 50. Pilot floor E03 measurement devices.

Equipment

The measurements are performed with the GreenMe cubes including CO_2 (GreenMe, 2019). These cubes are measuring the following elements; visual & lighting control (illumination and flicker light), thermal comfort (temperature and relative humidity), air quality (carbon dioxide concentration and total volatile organic compounds), acoustic comfort (average noise level and peak noise level) and the influence of plants for all factors, see figure 51. The measurements will be performed for 3 weeks, every 10 minutes over 24 hours per day. Total 21 days producing 3024 measurements per equipment.

Figure 51. GreenMe cubes measuring devices (Greenme.fr, n.d.).

The units of the GreenMe cubes

- Lighting quality: illumination (Lux) and flicker light: flicker (Hz) on height of 1,1 meter.
- Thermal comfort: temperature (°C) and humidity (%) on height of 1,1 meter.
- Air quality: carbon dioxide concentration (ppm) and total volatile organic compounds (ppb) on height of 1,1 meter
- Acoustic comfort: average noise level (dBA), peak noise level (dBA) on height of 1,1 meter.

Accuracy of the GreenMe cubes

- Lighting quality: illumination +/- 2%, flicker light +/- 2%,
- Thermal comfort: temperature +/- 0,2 °C, relative humidity +/- 2%
- Air quality: carbon dioxide concentration 400-5000 ppm ± 30 ppm + 3% of reading with temperature influence of 5 ppm per °C or 0.5% of the reading per °C (which is greater) and volatile organic compounds ± 30 ppb
- Acoustic comfort: +/- 3 dBA

6.4.3 Plants

Living plants will be ordered and placed in the specific areas described on the floorplans. These plants have a highly effective ability to purify the air (Aihong, 2019). The plants which will be used and their air purifying ability are described in the table 11 below.

Plant species	Plant species	Air purifying ability	Amount of plants
	Silver Queen	Eliminate nicotine and formaldehyde	8
	Scindapsus Aureus	Eliminate harmful substances; methanal, benzene, trichloro ethylene	8
	Chlorophytum Comosum	Absorb harmful gases	8
	Hemigraphis alternata	Eliminate benzene, toluene, octane, trichloroethylene and terpene	8
	Aglaonema	Absorb ammonia and formaldehyde	8
	Sansevieria trifasciata	Elininate benzene, toluene, Xylene	8
	Spathiphyllum hybride	Eliminate VOCs	8
	Dracaena deremensis	Eliminate benzene, toluene, Xylene	10
	Hedera helix	Eliminate benzene, toluene, octane, trichloroethylene, terpene and formaldehyde	16

Table 11. Air purifying plants for measurements (Aihong, 2019).

Chapter 7. Case study results

7.1 Introduction

The case study, the headquarter of a bank in the Netherlands, is being renovated till the end of 2025. Every building part with the corresponding floorplans are divided into phases. The first phase consists of the pilot floors. One of the pilot floor, more closed floorplan with smaller size areas; A11, and the floor of Facility Management, more open floorplan with bigger open office areas; E03, are chosen to analyse. These floorplans represent the case study; the headquarter of a bank in the Netherlands.

The case study is analysed on three different aspects, the materials which are used, the needs and preferences of the building users and the measurements of the indoor comfort. The analyses and results are focussed on the two floorplans, the closed floorplan A11 and the open floorplan E03.

The aim of this case study research is to firstly, identify the materials which are used on the A11 and E03 floorplan, figure 52 and their effect on the indoor comfort and circularity. Secondly, the mapping of the complaints, satisfaction and importance level of the building users of the case study. Lastly, comparing the criteria prepared in chapter 5 'Literature review' with the measurements results performed on the A11 and E03 floorplans of the case study, figure 53. The results described in this chapter are based on the case study.

Figure 52. Existing office case study.

Figure 53. Measurement devices indoor comfort.

7.2 Materials & products

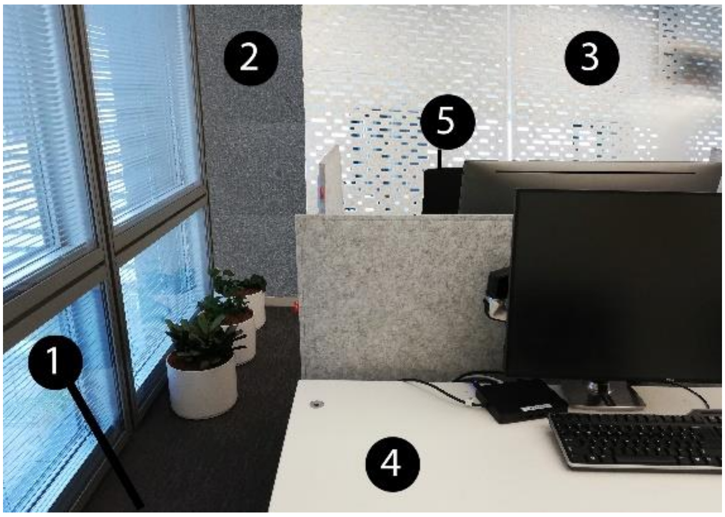
The materials and products used in the case study, can influence the human health. Especially the composition of raw materials of products and the connection between the materials. In addition, the origin of the materials, how and where they are produced and used and the possibility to repair, remanufacture, recycled or even upcycle. This effects the circular way of building the products.

At this moment, less information is available about the materials and products, which are used in the case study and how they contribute to the human health. Next to that, the way of using and disassemble the products is important to decide the circularity level of the existing situation.

The aim is to provide an answer on the following sub-question: *Which interior materials are applied in the case study and how do they effect the indoor comfort and circularity?* This sub-question will be answered by analysing the existing products used on the pilot floors of the case study. The analysis contains the following subjects: raw materials, demountable or detachable, remanufacture, recycle or upcycle, influence factor on human health, toxic gasses and cleaning. Background information about the material analyse can be found in attachment 13.1.

7.2.1 Materials & products case study

The interior of the case study consists of various materials and products. The façade and the structure stay the same, the limitations of this research, and are therefore not taken into account. The finishing products are: ceiling, walls, space dividers and floors. The workplace facilities within the interior consists of desks, chairs, cabinets and lights. The coffee corner, relaxation and toilet areas are minimally present, so these are disregarded during this analysis. The finishing product ceiling will be disassembled and cleaned and the workplace facilities cabinets and lights will be replaced. These products will not be analysed due to replacement. These current products play no role in the influence on the circularity and health of the interior. Therefore the following most common and reused products will be analyses: firstly, floor finish carpet Wave-B754; producer Desso. Secondly, wall finish felt wall 1001 Natural White; producer Viltex. Thirdly, space divider panels In-Felt Wave; producer In Zee. Fourthly, workplace desk TMNL Dual workstation; producer Gispen. Lastly, workplace chair Futu NPR; producer HAG. These products in the interior context are illustrated in figure 54.



❶ Floor finish-carpet
❷ Wall finish-felt wall
❸ Space divider -panels
❹ Workplace-desk
❺ Workplace-chair

Figure 54. Interior materials case study.

The materials of the top five products of the case study have been assessed on their circularity and health aspects. The analysis is illustrated in table 12.

Category	Circular				Indoor comfort	
	Raw materials & lifespan	Demountable or detachable	Remanu-facture	Recycle or upcycle	Influence factor health	Toxic gasses & cleaning
❶ Floor finish carpet Wave-B754 (Desso)	Dyestuff; PA6,6 yarn; Primary backing; Precoat and stabilizer; Polyolefin; Glass scrim; Fleece – < 10 years	No information available	Second backing layer remanufactured into new products	Second backing layer fully recyclable	Less glare and impact sound insulation	Production process can contain substance of acid, alkalis or bisphenol A (BPA) – hard clean layers
❷ Wall finish felt wall 1001 Natural White (Viltex)	Sheep wool-reusable multiple times	No information available	Product can be reused in the manufacture process	Biodegradable	Absorb sounds	Non-toxic substances – easy clean, one material
❸ Space divider panels In-Felt Wave (In Zee)	Polyester fibers (60% recycled PET bottles) - >200 years to decompose	Demountable, the rails is connected with screws	No information available	No information available	Higher acoustic comfort & privacy	The panels are coloured – easy clean, one material

4 Workplace desk TMNL Dual workstation (Gispen)	Every desk consists of various materials, depends on the recycle chain	Demountable 100%	Return to producent, the producer used it again in the manufacture process	The product is 76% circular, 24% is waste	Personal height adjustments, acoustic partition screen	Information not available, depends per desk if the parts demountable or easy to clean
5 Workplace chair Futu NPR (HAG)	Weight optimization, durable materials; aluminium >100 years, textile and plastic > 100 years	A small number of components, the way how to demount these component is not described	Long service life	Recycling options	Material with holes, air movement between back and chair, 'In balance' small movements, adjusted to height	Information not available, depends per desk-parts demountable easy to clean

Table 12. Existing interior material analysis.
(Adjusted from Arc edition, n.d; Cradle to Cradle, 2019; Desso, n.d.; Gispen, n.d.; Health2work, n.d.; In Zee, n.d.; Przybylek, n.d. & Vilton, n.d.)

This analysis shows the indoor comfort and the effects on the human health. Moreover, it illustrates the circularity of the raw materials and connections to make the interior products. Generally, the human health is supported by the interior. Nevertheless, mostly one or two indoor comfort stressors are taken into account. By improving multiple indoor comfort stressors, the products can support more indoor comfort factors. For example, the floor finish prevents the building users from glare and reduce the impact sounds level. Although, it can improve the indoor air quality by absorbing VOCs and the thermal comfort by installing a heating or cooling system under or connected to the floor finish. The level of toxicity is difficult to investigated, because of the limited amount of information. Some products or production processes can contain toxic substances.

The circularity level is analysed by characters of the raw materials, biological or technical cycle, demountable or reusable, the remanufacture and recycle or even upcycle possibilities. In conclusion, according to the table 10 above, more recycled or organic raw materials can be used. However, some of the materials, like the felt wall is fully organic. Equally important, the possibilities to reuse the raw materials are limited, mostly the way how to demountable the products is not visible and only parts of the materials can be reused or recycled. On the other hand, other financial models are used, like long service life and return the products after the lifecycle back to the producent.

7.2.2 Conclusion

The aim of this research is to identify the interior products, the circularity level and the effects on the human health. The analysed products are: Desso carpet, Viltex felt wall, In Felt panels, Gispen desk and HAG chair. These products contribute to the human health and contains a certain level of circularity. All products, except the wall finish felt wall need improvements to meet the circularity and indoor comfort criteria described in chapter 5.

7.3 Survey

The building users preferences and needs are mapped out, through analyses of Leesman survey, Planon complaint system and system that have insight into the occupation rate. The survey is executed by the company Leesman in 2019, from 11th September 2019 till 27th September 2019. The survey investigated 6184 employees, whereby 1311 employees responds, this represent a responds rate of 21% including an accuracy rate of 3,2%. Unfortunately, not all questions were answered, those answers are eliminated from this research. Detailed data about the survey can be found in appendix 15. The Planon system is used and analysed only the complaints from 1st January 2019 till 31st December 2019 and the occupancy system is used as well from 1st January 2019 till 31st December 2019. These analyses provide field research about the indoor comfort in offices.

The goal of this survey analysis is to profile the building users, the workspace, activities and facilities of the case study; the headquarter of the bank in the Netherlands. The sub-research question which will be addressed is: *Which potential indoor comfort problems encounter the building users of the case study; the headquarter of a bank in the Netherlands?* This research considers a few important topics which have been questioned to the building users. In addressing these questions, the study examines the indoor comfort experiences. The most important figures and illustrations are shown, others are displayed in appendix 14. The following questions are asked:

General information building users

Which gender and what age do the respondents have?
What kind of working space do the respondents need?
Do the respondents need to travel between working locations?
In which department are the respondents working?
How are the respondents employed?
How long are the respondents working?

Workspaces building users

Which workspaces can be improved related to the Benelux Benchmark?
Which workspaces need improvements?

Activities building users

Which activities are performed by the building users and supported by the building facilities?
How does the importance and the support level of the activities relate to the Benelux Benchmark?
How does the importance and the support level of each activity relate to each other?
In which rooms are the activities carried out?
What is the average occupancy rate of the building during office hours?
What is the occupancy during the most busy and less busy hours?
How are the activities rated by the departments Branding & Communication and Facility Management?

Workplace facilities building users

How does the importance and the support of the facilities relate to the Benelux Benchmark?
How does the importance and the support rate relate to each facility?
How is the lay-out related to the workplace facilities?
Which complaints are received from the respondents?
How is the indoor comfort related to the workplace facilities and complaints?
How is the indoor comfort rated by the departments Branding & Communication and Facility Management?

7.3.1 General information building users

General information about the building users is analysed to be able to profile the building users and relate this to the person factors. This information is categorized in the following subcategories; gender, age, primary working space, office mobility, departments, employment model and employment since. The profile of the building user is illustrated in the figures below.

Most of the respondents were men, 59%, while 37% were women and 4% did not fill in the gender. The subcategory age contains a wider range, compared to the subcategory gender. Less than 1% falls within the category >65 years and <25 years, while most of the respondents have are aged between 45 and 54 years. The other percentages are close to each other, which concludes in every category the respondents age is spread between 25 and 64 years, except the subcategory age >65 years and <25 years, figure 55.

The largest amount of respondents work in a shared space, 59% plus 20% plus 5%, total of 84%. Some respondents defined their shared space, whereby 20% are located in an open office and 5% with a team table. 11% are located in a cellular office. A small amount of the respondents work mostly in a meeting room, private room, informal workspace or technical space, figure 56.

What age are the respondents?

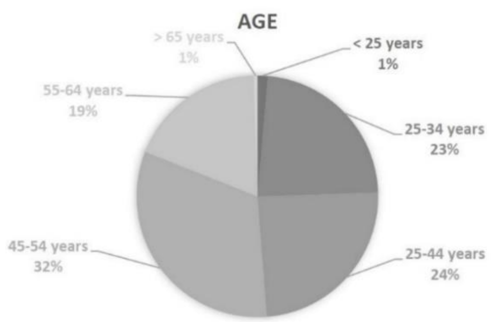


Figure 55. General information, age (Leesman, 2019).

What kind of working space do the respondents need?

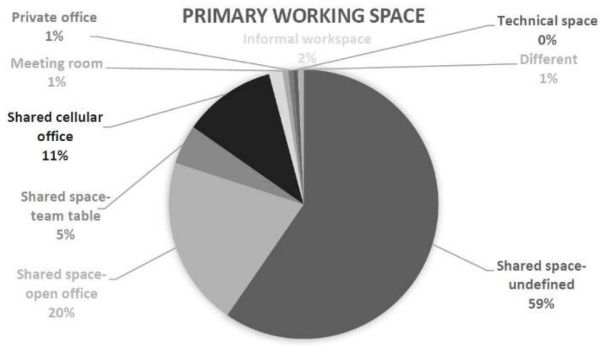


Figure 56. General information, primary working space (Leesman, 2019).

Do the respondents need to travel between working locations?

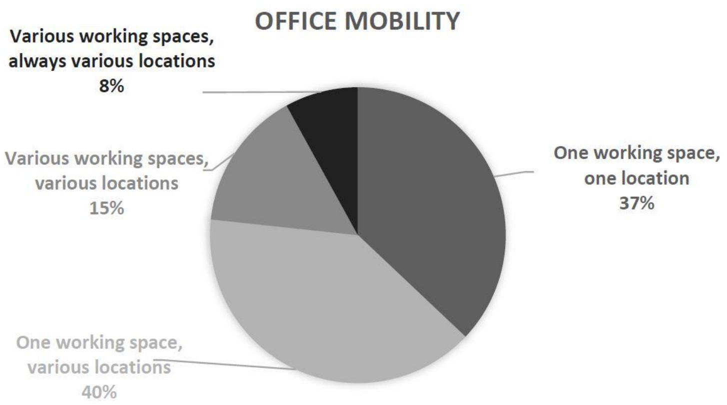


Figure 57. General information, office mobility (Leesman, 2019).

Generally, the respondents are located at one location, including 40% at various working spaces and 37% at one working space. Only 15% is working at various location in various working spaces. This means they can adapt to different working spaces. Even 8% has always a various location and working space, those 8% are flexible when it comes to workplace, figure 57.

The departments which were represented by the respondents are various, although the department Innovation & technology is the most represented. Secondly, Risk management represent themselves with 19%, followed by Commercial banking, Finance, Private banking, HR and transformation & communication.

How are the respondents employed?

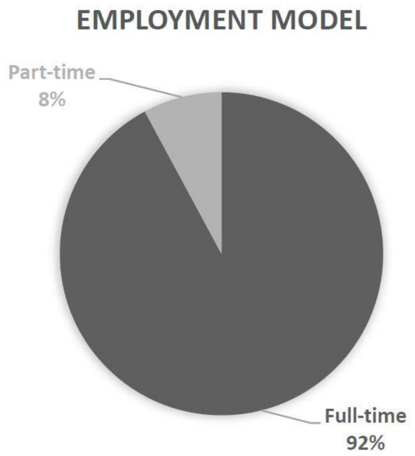


Figure 58. General information, employment model (Leesman, 2019).

How long are the respondents working?

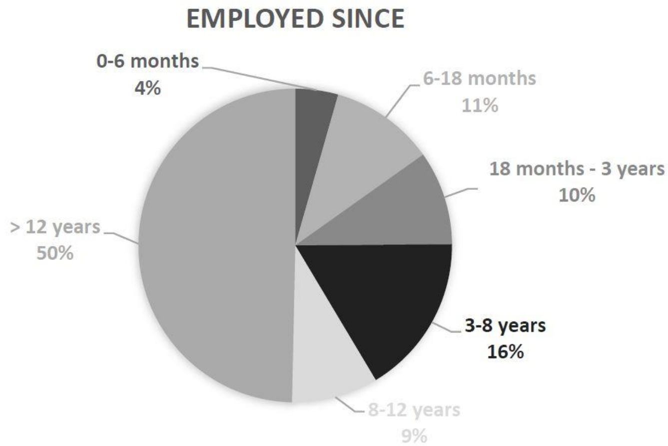


Figure 59. General information, employed since (Leesman, 2019).

Generally, the respondents work full-time, see figure 58. Furthermore, it is noticed that most of the respondents have been working a long period for their employer, 50% more than 12 years, see figure 59. This means a low staff turnover.

Conclusion building users

Most of the respondents are men, 59% and have an equal divided age between 25 and 64 years. Therefore the building users contain a wide profile. The primary working space is a shared space both open or cellular. This means that both floorplans contain a various design approach and the type of space need to be taken into account.

Generally, the respondents work at various locations, but at every location they have their own department, which can suit their indoor comfort needs. In conclusion, every department can be design the same in the various locations to make it recognizable for the building users. The respondents are usually full-time employed and working for a prolonged period at their working place. This concludes it is important to adjust the workspace to the needs of the building users, they use mostly the same working spaces and work there, for over 50%, longer than 12 years.

7.3.2 Workspaces building users

The workspace survey is divided into various subcategories; satisfaction level workspace related to the Benelux Benchmark and workspaces related to the building users of the case study. The satisfaction level of each workspace is illustrated in the figures below.

Comparing the results of the bank with the Benelux Benchmark, the respondents are less satisfied with the categories than the average respondents measured in the Benelux. Although, the respondents are more satisfied about the sustainable way of working. This can still be improved, because only 49,4% is satisfied how the company deals with sustainability. The biggest difference is a 'productive workings' space, whereby the bank respondents are not as satisfied compared to the respondents in the Benelux.

Which workspaces need improvements?

Generally, the respondents are not satisfied with their working space, when it comes to the importance of a working space. The working spaces support sharing ideas and knowledge and the company image is represented above the 50%. Some improvements can be made within the following subjects; space to be able to be productive with a team or individual, space to be proud of when visitors are received, the visibility of the organization culture, sense of togetherness, experience of sustainability and the atmosphere at work, figure 60. These elements can be incorporated and adjusted in the new floorplans.

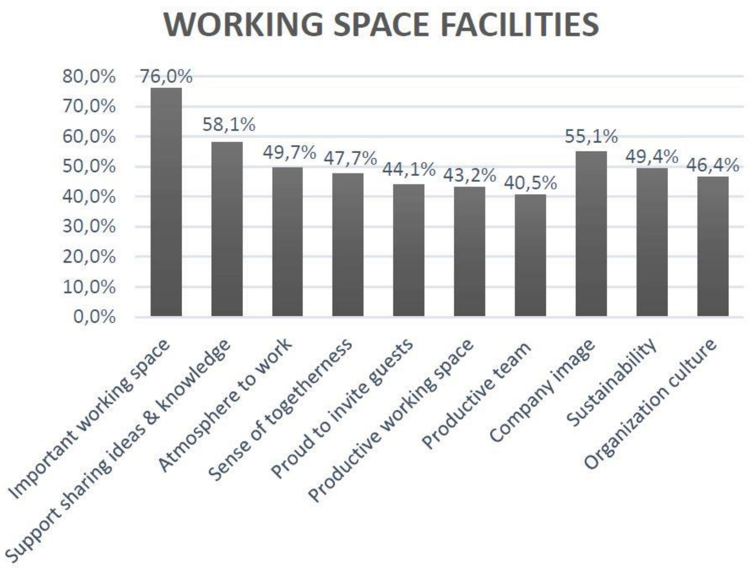


figure 60. Workspace, working space facilities (Leesman, 2019).

Conclusion workspaces

The workspace of the bank is ranked with an average of 51%, which means the respondents are not satisfied about how the company provides or deals with the working space (facilities). Improvements can be made in providing a productive working space, this contains the greatest difference compared with the Benelux Benchmark as well. To achieve an overall satisfaction level of 80% all categories need to be improved and to be taken into account during the design of the existing floorplans.

7.3.3 Activities building users

The activities influence the perception of the indoor comfort. Besides the perception, it determines the limits of the stressors, which have impact on the satisfaction level of the building users. The activities are ranked by the support of the building facility and by importance levels rated by the respondents. The results are compared with the Benelux Benchmark. The following elements are described below; activities performed and supported in the case study, these activities related to the Benelux Benchmark and these activities compared with importance and support level. Furthermore, in which rooms the activities are carried out and the average and over time the occupancy rate. In addition, the activities are rated by the departments Branding & Communication and Facility Management, where the measurements are performed on the floors of these departments. The data is illustrated in the figures.

Which activities are performed by the building users and supported by the building facilities?

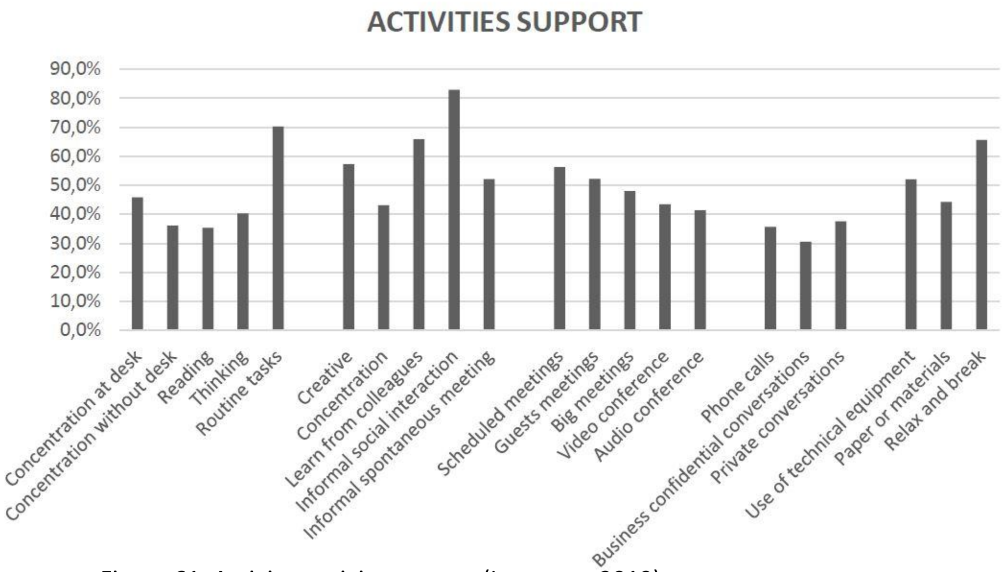


Figure 61. Activity, activity support (Leesman, 2019).

The activities performed within the bank are categorized in the following subcategories; individual, collaboration, formal meetings, communication and different activities. Most of the activities, which are supported by the building facilities are; informal social interactions, routine tasks and relax and break possibilities. Nevertheless, the vast majority; 49,4% is not supported by the building facilities. The following activities are rated below 40%: business confidential conversations, reading activities, concentration activities without a desk, having private conversations and being able to make a phone call. Activities between the 40% and 50% are; space to be able to think, performing audio conference, concentration work and video conference, concentration at a desk and finally areas where big meetings can be held, figure 61.

The activities analysed with the importance and support rate is compared with the Benelux Benchmark. The building facilities for the bank as well as the Benelux Benchmark support approximately the same activities. In addition, the importance rate is similar as well.

How does the importance and the support level of each activity relate to each other?

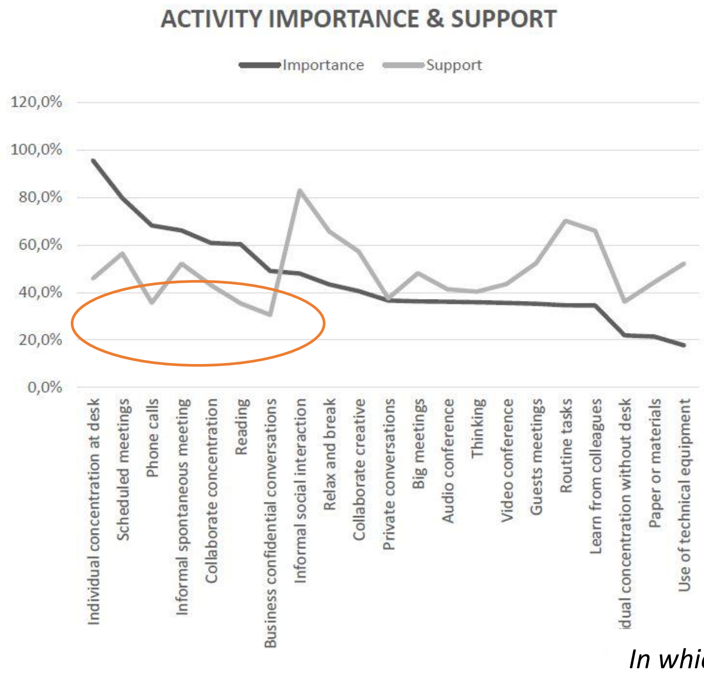


Figure 62. Activity, importance & support rate (Leesman, 2019).

The importance rate and the support by the building facilities give inside in which activities perform under their importance rate. Especially activities with a high importance rate and low support need to be addressed. These activities are; being able to make a phone call, business confidential conversations and possibility to read. As well as individual concentration work at a desk, possibility to schedule meetings, collaboration in a concentrated way and informal spontaneous meetings, see figure 62.

In which rooms are the activities carried out?

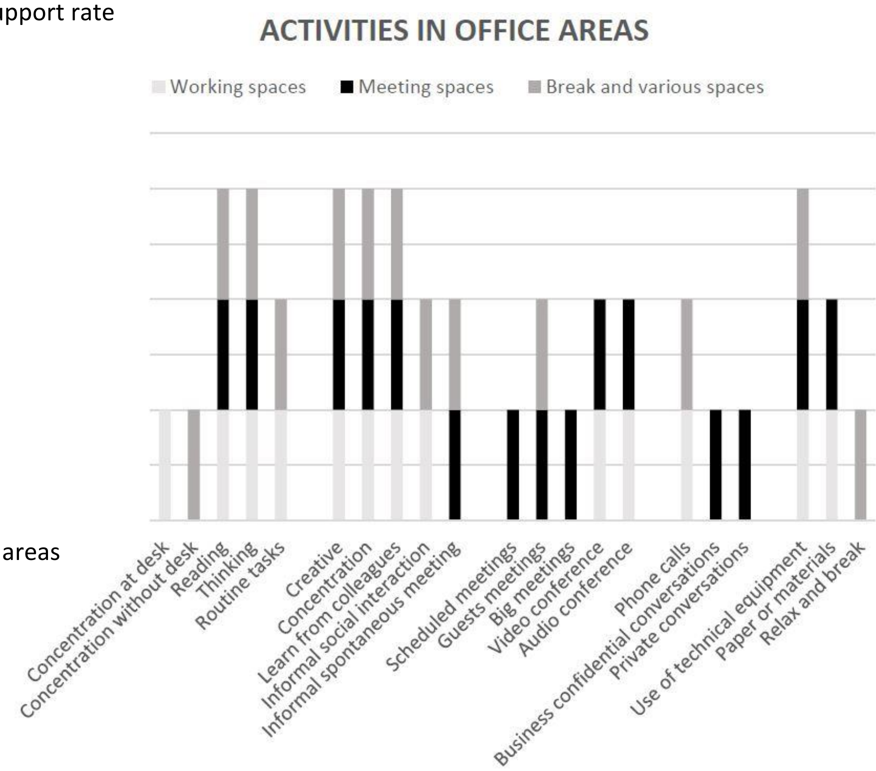


Figure 63. Activity, in various office areas (Leesman, 2019).

A meeting culture applies within the case study, this is visible in the results, figure 63. Most of the activities can be performed in a meeting area, 15 out of the 21 activities. Other 13 activities are equally important, these activities can be performed in a working space or break and various space. This means, that all three different spaces contribute to performing the activities. Only a few activities can be performed in only one space. These activities are; meetings, private or business conversation, concentration work or having a break. The amount of time, which is spend by performing the activities need to be taken into account, when developing a new floorplan including various spaces.

What is the average occupancy rate of the building during office hours?

The occupancy of the building users during the week is equally spread between 10:00 and 16:00. There are two peak moments, at 11:00 and 14:00, figure 64. Around these hours the indoor climate is more difficult to control. This will be verified with the measurements during these hours. In addition, there is a small decline in building users during the break.

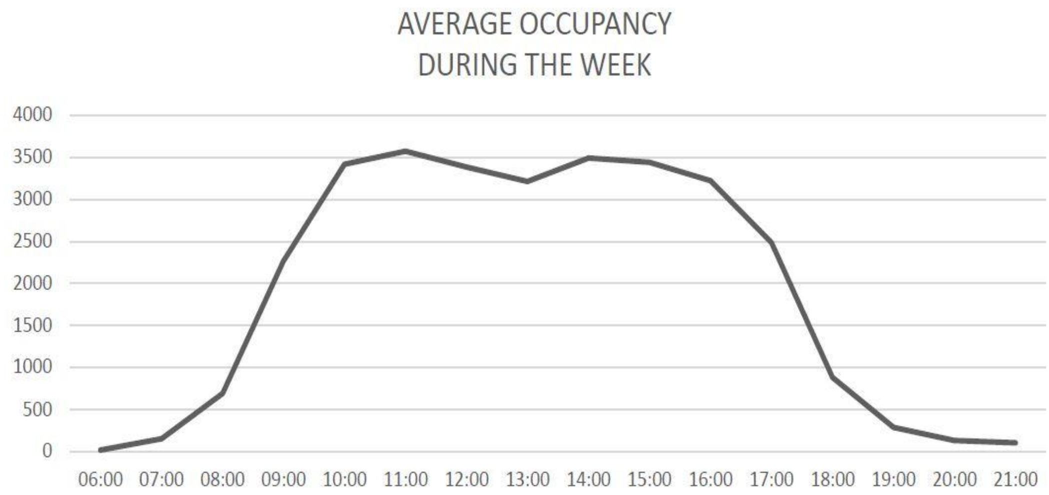


Figure 64. Activity, average occupancy in the building (Pandbezetting, 2019).

Comparing the occupancy in the building on Mondays, Fridays and the average during the week gives an overview about the spreading of the building users during the week. Around double of the building users work in the office on Monday instead of Friday. The average is much higher than the occupancy on Friday, which means, during the whole week the building is occupied except on Fridays. The average amount of building users during office hours on Monday are 3618,3, the maximum 4367,5 and minimum 1040,0 while on Friday the average is 1823,0 the maximum 2344,5 and the minimum 419,5. The occupancy will influence the indoor comfort and the energy use of the installation, this need to be designed flexible.

The total responds rate was 1311. Within the department Branding & Communication the respond rate was 28 employees, 2,1% of the total responds rate, while the department Facility Management includes 47 employees, this counts for 3,6% of the total responds rate. The floorplans which are measured are used by the following departments; Communication and Facility Management. Both departments are compared with each other. Results show that both departments rated the support of the activities by the building similar.

Conclusion activities

The following activities will be mainly taken into consideration during the design phase of this research: business confidential conversations, reading activities, concentration activities without a desk, having private conversations and being able to make a phone call. All these activities are rated below the 40%. Therefore this requires more support by the building facilities. Activities between the 40% and 50% are; space to be able to think, performing audio conference, concentration work and video conference, concentration at a desk and finally areas where big meetings can be held.

Most activities are performed in a meeting area, although the working space and break & various space support most of the activities as well. This means an equal distribution in various spaces is advised. In addition, the occupancy distribution within the building is the highest around 11:00 and

14:00 and between 10:00-16:00 there are more than 3000 people in the building. On Fridays there are less people in the building comparing with the other days of the week. This means that the building systems need to be adjusted to the occupancy rate which is different by day and hours. Recommended is to adjust the indoor environment to the amount of building users, to achieve the highest possible indoor comfort and environmental savings.

7.3.4 Workplace facilities building users

The workplace facilities are analysed, to be able to find the facilities which are not fully supported by the building yet. This information is categorized in the following subcategories; workplace facilities related to the Benelux Benchmark and the workspace facilities compared with the importance and support rate. Moreover, how the lay-out relates to the workplace facilities, the complaints from the respondents and how the indoor comfort relates to the workplace facilities and complaints. Lastly, the indoor comfort is rated by the departments Branding & Communication and Facility Management. The data is illustrated in figures below. The results compared with the Benelux Benchmark are relatively similar to each other, whereby the indoor comfort is assessed with the lowest rate as well as by the bank respondents as by the Benelux respondents.

How does the importance and the support rate relate to each facility?

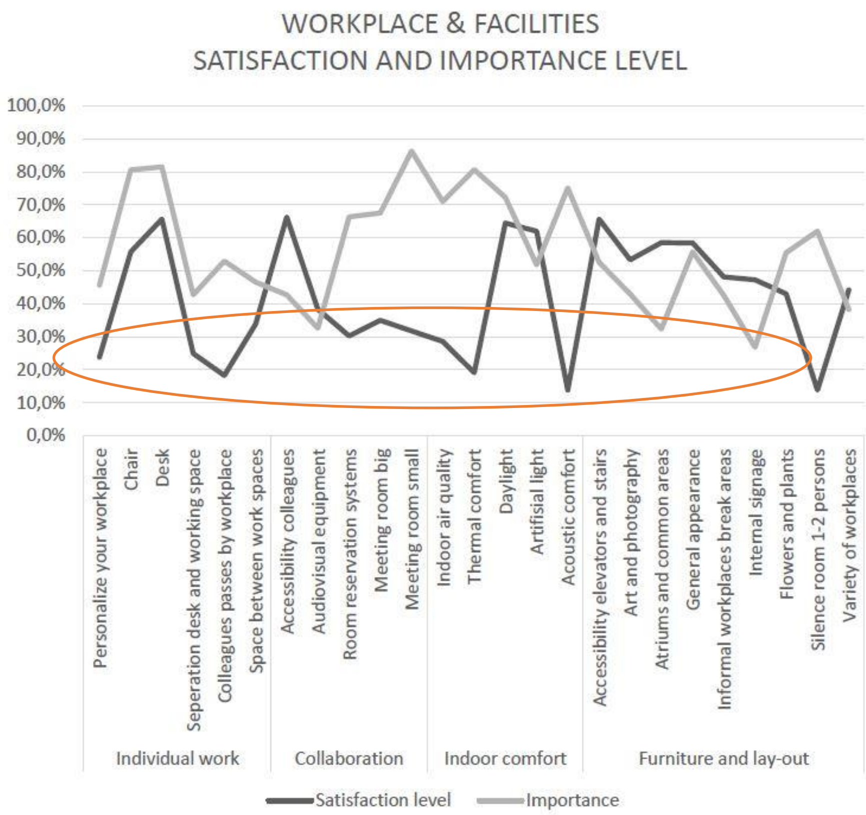


Figure 65. Facilities, importance & support rate. common areas (Leesman, 2019).

The workplace facilities are divided into individual and collaboration work, indoor comfort, furniture and lay-out. Most of the workplace facilities are performing under the support rate compared with the importance. The biggest difference between the satisfaction level and importance is the thermal comfort, acoustic, meeting room small, silence room 1-2 persons and indoor air quality including a minimal difference of 40%. Building users are most satisfied, compared with the support rate, about the atriums, see figure 65.

Which complaints are received from the respondents?

The complaints in 2019, mentioned by the building users, are described in table 13 below. The quantity of complaints is described behind the explanation of the complaint. Most of the complaints about the indoor air are about the ventilation system, mentioned as the ventilation system as not functioning. This includes the system provides more, less or no air, less fresh air and too cold or too warm air. Next to the ventilation system, the building users would like to have more plants and less smells, such as smells from the canteen or sewer system. Furthermore, the filters need to be cleaned more regularly. The thermal challenges are about a too high or too low temperature or great differences in adjacent rooms, whereby the sensors and shading system are not performing well. In addition, the light is sometimes defect or dirty, provides various light intensities and cannot be dimmed. Another topic is acoustic, whereby the systems or other factors make noise. Lastly, the materials are not always cleaned well.

Complaints about the indoor comfort in 2019				
Indoor air	**Thermal**	**Light**	**Acoustic**	**Materials**
Cold air stream (1).	Temperature is too low (36).	Light remote control is defect or lost (41).	Noise from the ceiling (23).	Product and materials are not cleaned well (3).
Smell from the canteen, a fire or sewer system (31).	Temperature is too high (145).	On top of the light lies dust (3).	Loud buzzing noise in the space (7).	
Being able or not being able to open a window (1).	Temperature is higher than thermostat (1).	The fittings are defect (106).	Ground and desks are vibrating (1).	Carpet keeps dirty after cleaning (10).
Ventilation system provides too much air (2).	Sensors falling down or are not working (2).	Automatic light control is not working (1).	Continuous beeping sound (3).	
Ventilation system is defect, provides warm air or no fresh air (24).	Sun shading system is not working (6).	The light makes a sounds, if the lights is searching for connection (1).	Ventilation system makes noise and vibrations (11).	
Too less plants close by the working spaces (1).	Relocating the sensors, because of relocating furniture (2).	Activating the light multiple times, because it turns on (1).	Follow conversations in another room (2).	
Ventilation grill is closed (1).	Temperature difference with adjacent rooms (3).	The ability to dim the light or adjust height (4).		
The filters are not cleaning the air enough (4).		Light can fall from the ceiling (2).		
The rotation or angle of the ventilation grills provide cold air stream (1).		Some of the fittings provide less light than others (1).		
Dry air, eye irritation or headache (8).		Sun shading system is broken (15).		
		Power failure, emergency lighting (10).		

Table 13. Facilities, importance & support rate comparison Bank and Benelux Benchmark (Planon, 2019).

How is the indoor comfort related to the workplace facilities and complaints?
The complaints from the building users are illustrated in an explanation model figure 66 below.

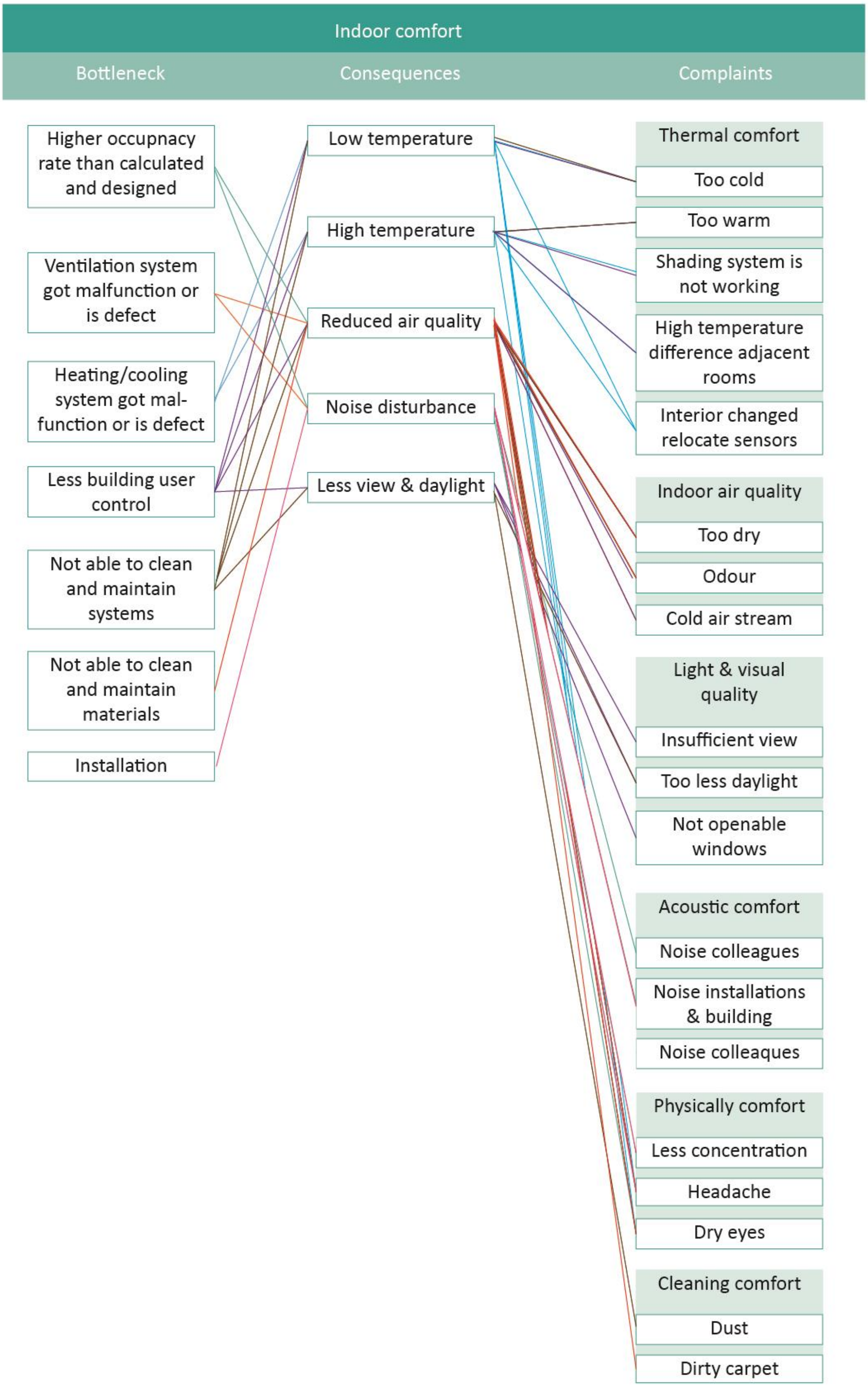


Figure 66. Indoor comfort explanation model
(Planon, 2019).

How is the lay-out related to the workplace facilities?
The activities and facilities related to the lay-out of a floorplan are illustrated in an explanation model, figure 67 below.

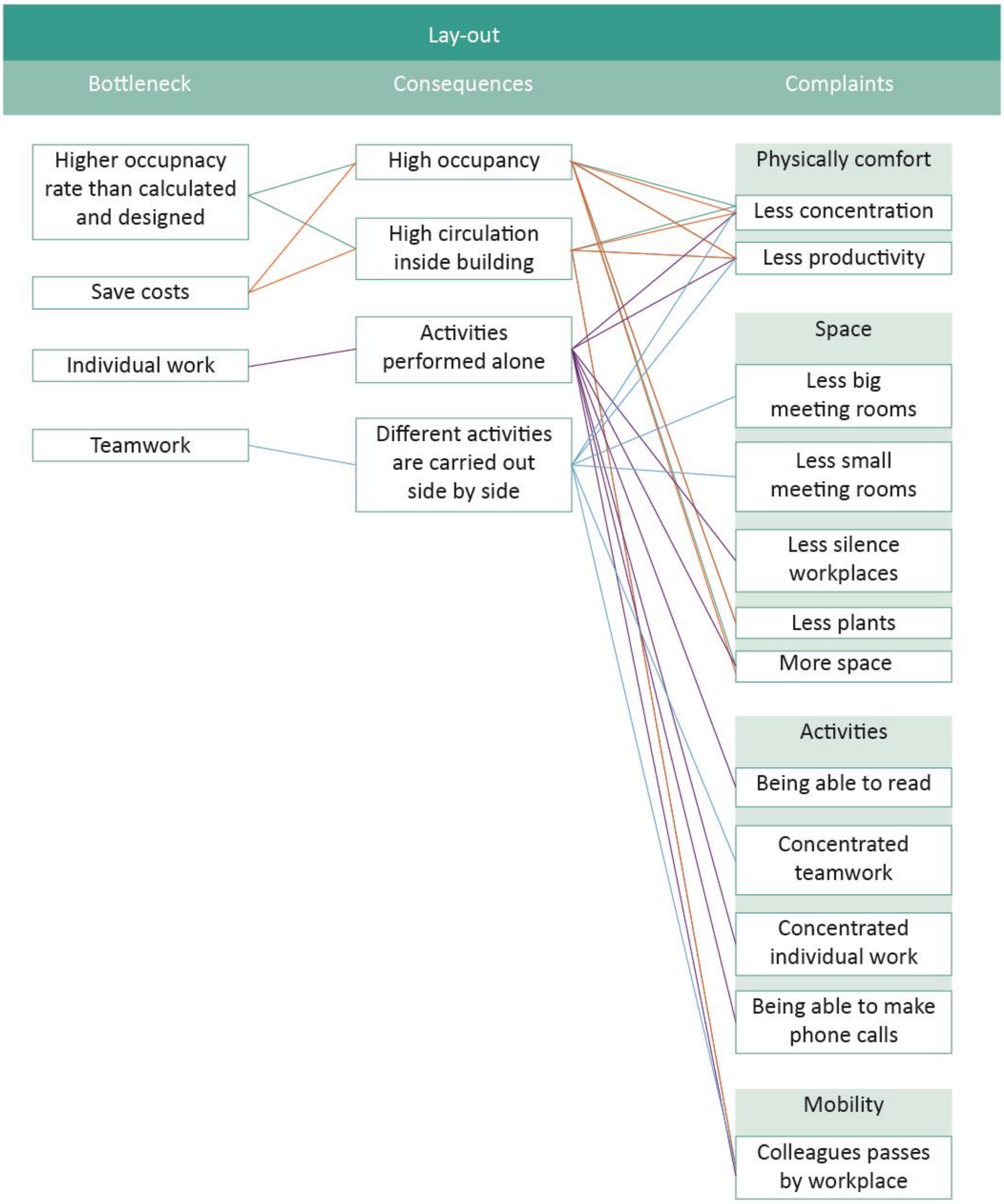


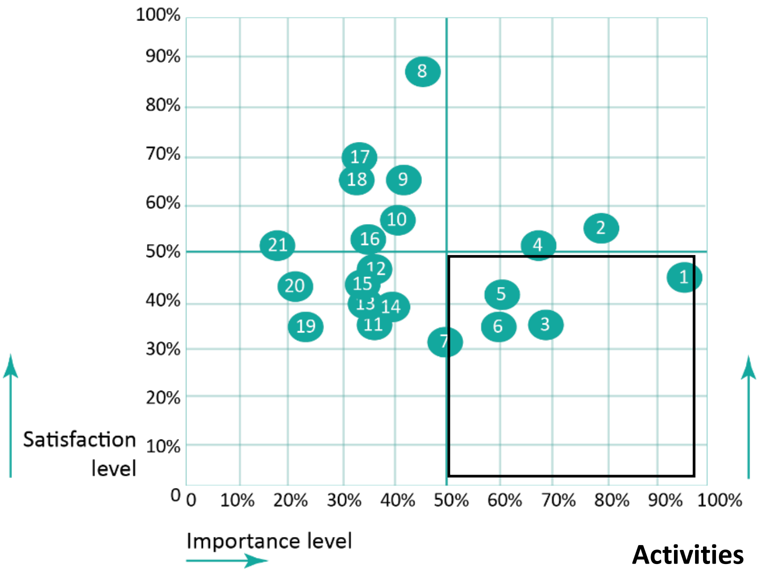
Figure 67. Activity and facility explanation model (Leesman, 2019).

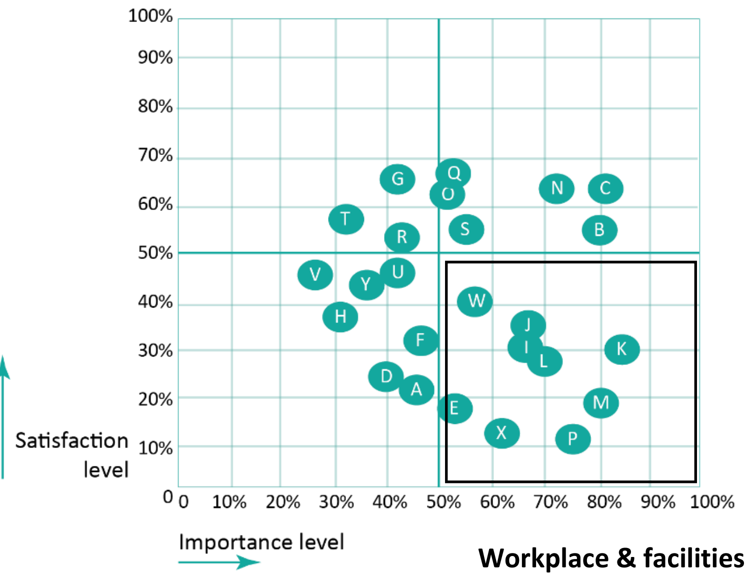
Conclusion workplace facilities
The workplace facilities are mostly not meeting the criteria of the building users. Results show a high amount of workplace facilities which are not meeting the building user satisfaction. Recommended is too pay extra attention to: thermal comfort, acoustic, meeting room small, silence room 1-2 persons and indoor air quality. These results are supported by the Benelux Benchmark and the various departments as well. In addition, the complaints about the indoor comfort are mostly about not controllable or defect systems, which make noise. Furthermore, the systems, products and or materials are difficult to clean, this causes complaints about the building users health.

7.3.5 Survey conclusion

The aim of this survey analysis is to profile the building users, the workspace, activities and facilities of the headquarter of the bank in the Netherlands. These analyses resulted in a building users profile and a priority list about the workspace, activities and facilities to increase the users satisfaction. This information is the start of criteria for designing the floorplan of the case study.

First the activity, workplace and facilities are combined in a figure to find the focus area, figure 68. This focus area, marked in orange consists of a satisfaction level lower than 50% and an importance level higher than 50%. All factors will be taken into account, only the focus area can influence the satisfaction of the building users the most. The top 13 activities, workplace and facilities within the focus area is prioritized with a number and marked in green in the figure below.





Activity

1	**Individual concentration at desk (3)**
2	Scheduled meetings
3	**Phone calls (8)**
4	Informal spontaneous meeting
5	**Collaborate concentration (13)**
6	**Reading (11)**
7	Business confidential conversations
8	Informal social interaction
9	Relax and break
10	Collaborate creative
11	Private conversations
12	Big meetings
13	Audio conference
14	Thinking
15	Video conference
16	Guests meetings
17	Routine tasks
18	Learn from colleagues
19	Individual concentration without desk
20	Paper or materials
21	Use of technical equipment

Workplace & facilities

A	Personalize your workplace
B	Chair
C	Desk
D	Seperation desk and working space
E	**Colleagues passes by workplace (7)**
F	Space between work spaces
G	Accessibility colleagues
H	Audiovisual equipment
I	**Room reservation systems (9)**
J	**Meeting room big (10)**
K	**Meeting room small (4)**
L	**Indoor air quality (5)**
M	**Thermal comfort (2)**
N	Daylight
O	Artifisial light
P	**Acoustic comfort (1)**
Q	Accessibility elevators and stairs
R	Art and photography
S	Atriums and common areas
T	General appearance
U	Informal workplaces break areas
V	Internal signage
W	**Flowers and plants (12)**
X	**Silence room 1-2 persons (6)**
Y	Variety of workplaces

Figure 68. Conclusion satisfaction and importance level for the activities, workplace and facilities, focus area is indicated in green (Leesman, 2019).

The focus area consist of 13 activities, which are not fully supported by the building facilities or the workspace, the activities are illustrated in the table 14 below. The focus in this research of these elements is illustrated in the table 15 as well. The focus is rated from 3, top priority to 1 lower priority.

General conclusion survey					
Rating number	**Identification number**	**Activities, workplace or facilities**	**Satisfaction level**	**Importance level**	**Focus**
1	P	Acoustic comfort	13,9%	75,1%	1
2	M	Thermal comfort	19,1%	80,7%	1
3	1	Individual concentration at desk	45,9%	95,7%	3
4	K	Meeting room small	31,8%	86,3%	2
5	L	Indoor air quality	28,6%	71,0%	3
6	X	Silence room 1-2 persons	13,9%	62,0%	2
7	E	Colleagues passes by workplace	18,3%	53,0%	1
8	3	Phone calls	35,7%	68,2%	2
9	I	Room reservation systems	30,3%	66,4%	1
10	J	Meeting room big	35,0%	67,5%	1
11	6	Reading	35,4%	60,3%	2
12	W	Flowers and plants	43,1%	55,5%	2
13	5	Collaborate concentration	43,2%	60,9%	2

Table 14. General conclusion survey.

Secondly, the satisfaction and importance level of the activities, workplace and facilities together with the complaints show the importance of the renovation. Especially the indoor comfort and the lay-out of the workplace. The focus of this research is the indoor air quality and designing a floorplan lay-out which support the activities of the bank. In summary, developing a system, floorplan lay-out and materials which support the comfort of the indoor air in a circular way. The list below, table 15 is composed from the results of the survey, which is the starting point of the design phase and will be compared with the measurements performed in the case study.

Focus conclusion survey		
Building users	**Indoor air**	**Floorplan lay-out**
Gender, mostly men 59%.	Improving the indoor air; - Takes into account the occupancy rate. - Avoiding cold air stream. - Avoiding smells. - Building user control. - Avoiding ventilation system too much or too less air/ too warm or too cold air. - Avoiding closing ventilation system. - Being able to clean and maintain the system or materials. - Avoid dry air. - Installation above ceiling, especially the ventilation system makes a lot of noise. - Temperature is too high. Flowers and plants - Less plants close by workplace.	Individual concentration at desk.
Equal divided age between 25 and 64 years.		Meeting room small.
Primary working space is a shared space both open or cellular.		Silence room 1-2 persons.
Building most occupied on Monday till Thursday between 10:00-16:00.		Colleagues passes by workplace.
		Being able to make phone calls.
Work at various locations, same department. Adjust to their own needs.		Meeting room big.
		Being able to read.
full-time employed and working for a prolonged period, >50% more than 12 years.		Perform concentrated work in a partnership.
		Material and products that can be cleaned well

Table 15. Focus conclusion survey.

The answers to the questions are composed from various sources. However, the survey questions from Leesman were already asked and could not be adjusted anymore. For this reason some questions are missing in the questionnaire which are valuable to add next time. For example category 'general', subcategory 'work location' does not include working from home yet. Working from home is a policy of the bank. Recommended is to add these adjustment in the next survey of Leesman.

7.4 Measurements

7.4.1 Introduction

The measurement devices started measuring on Tuesday 18 February till Monday 9 March 2020. They were placed in the case study; a bank in the Netherlands, on the pilot floors A11 and Facility Management floor E03. The pilot floor will be one of the first floorplan which will be renovated. A11 consist of 800,1m^2 with 172 building users. The measurement devices are mostly placed in smaller size rooms; between 6m^2 and 30m^2. There are 12 various areas with 90 desks and 82 meeting spaces. 12 measurement devices are taken into account, where 3 areas are measured with air purifying plants. These plant types are Aglaonema Siler Queen (1), Scindapus Aureus (2), Chlorophytum Comosum (3), Hemigraphis Alternate (4) and Hedera Helix (5). The location of the type plant is illustrate in green cycles in figure 53 below. The plants are placed on Tuesday 25 February 2020 till the end of the measurements.

E03 consist of 946,2m^2 with 199 building users. The measurement devices are placed in bigger size rooms; greater than 100m^2. There are 8 various areas with 128 desk and 71 meeting spaces. 12 measurement devices are taken into account, where 3 areas are measured with air purifying plants. The floorplans are illustrated below in figure 69.

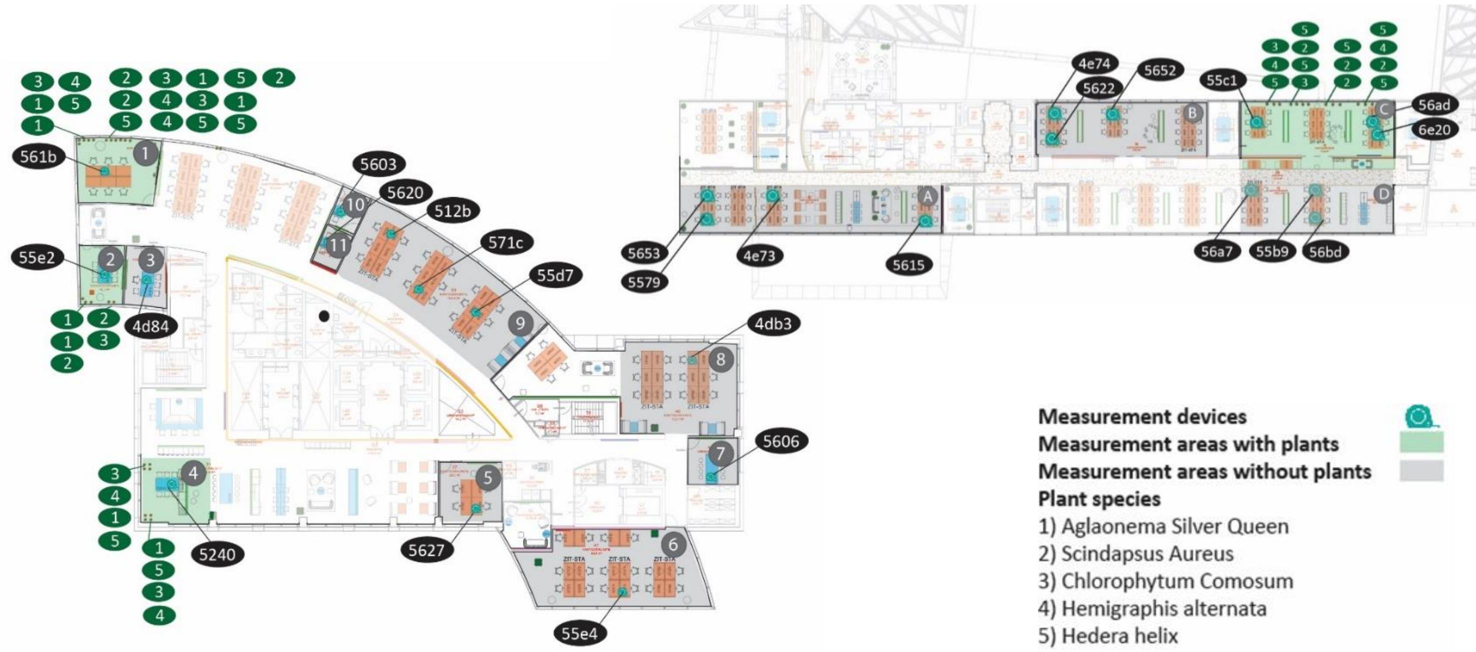


Figure 69. Measurement devices case study; left floorplan A11 and right floorplan E03.

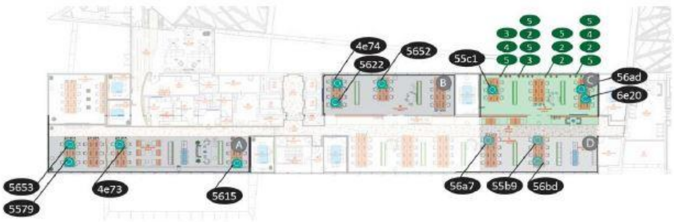
The measurements conditions of the existing situation and the plants are illustrated in figure 70 below. Every plant species has their own air purifying ability and weight. Every area is described with function, occupancy, area and volume. The plant strategy is applied with full of plants, a few plants and mostly no plants. The amounts of plants are important and how much they weight to calculate how much carbon dioxide (CO_2) concentration each plant species can convert to dioxide (O_2). In addition, each plant species have their own volatile organic compounds (VOCs) absorption capacity. This is calculated for every plant species, times the amount of that specific plant species. The CO_2 production and needed ventilation is calculated per person in the specific area. In addition, the existing ventilation capacity per area and per person is described in this figure as well. More information can be found in appendix 16.

A11 General information

Room	Occupancy	Area (m2)	Volume (m3)
1. Working location	6	33	85,8
2. Meeting room	6	16,3	42,38
3. Meeting room	6	16	41,6
4. Meeting room	6	14,8	38,48
5. Working location	4	25	65
6. Working location	16	83,6	217,36
7. Meeting room	8	14,8	38,48
8. Working location	16	80,2	208,52
9. Working location	22	104,4	271,44
10. Meeting room	2	6,6	17,16
11. Meeting room	2	7,2	18,72

Plants							CO2 production			
Plant strategy	Amount of plants	Weight of plants (kg)	Amount plants CO2->O2	Weight (kg) plants CO2-> O2	VOC absorption capacity 1 plant (mg/day)	VOC absorption capacity (mg/day)	Minimum CO2 (g/h)	Minimum ventilation (45 m3 air/h/p.p.)	Ventilation existing situation	Ventilation existing situation p.p.
Full plants	18	25,53	3,07	1,83	0,6	11,1	198,6	270	480	80
Few plants	5	7,52	1,51	0,91	1,3	6,3	198,6	270	260	43
No plants	0	0	1,49	0,89	1,3	0,0	198,6	270	226	38
Full plants	8	7,52	1,37	0,82	1,4	11,0	198,6	270	315	53
No plants	0	0	2,32	1,39	0,8	0,0	132,4	180	105	26
No plants	0	0	7,77	4,64	0,2	0,0	529,7	720	420	26
No plants	0	0	1,37	0,82	1,4	0,0	264,8	360	105	13
No plants	0	0	7,45	4,46	0,3	0,0	529,7	720	420	26
No plants	0	0	9,70	5,80	0,2	0,0	728,3	990	585	27
No plants	0	0	0,61	0,37	3,1	0,0	66,2	90	195	98
No plants	0	0	0,67	0,40	2,8	0,0	66,2	90	Unknown	Unknown

E03 General information



Room	Occupancy	Area (m2)	Volume (m3)
A. Open area	40	167,1	434,46
B. Open area	22	125,2	325,52
C. Open area	26	112,6	292,76
D. Open area	22	120,5	313,3

Plants							CO2 production			
Plant strategy	Amount of plants	Weight of plants (kg)	Amount plants CO2->O2	Weight (kg) plants CO2-> O2	VOC absorption capacity 1 plant (mg/day)	VOC absorption capacity (mg/day)	Minimum CO2 (g/h)	Minimum ventilation (m3 air/h)	Ventilation existing situation	Ventilation existing situation p.p.
No plants	0	0	15,52	9,28	0,1	0	1324,20	1800	Unknown	Unknown
No plants	0	0	11,63	6,96	0,2	0	728,31	990	840	38
Full plants	14	18,84	10,46	6,26	0,2	2,5	860,73	1170	720	28
No plants	0	0	11,19	6,69	0,2	0	728,31	990	840	38

Figure 70. General information floorplan A11 and E03.

The goal is to measure the indoor comfort with the possible stressors; indoor air quality, thermal comfort, light quality and acoustic comfort. The following research questions is asked *'What is the indoor comfort of the case study based on the measurements?'* This chapter constructed into firstly, general measurements results per area per stressors and areas with and without plants. Secondly, the general measurements results per floorplan lay-out including lay-out A11 and E03. Lastly, the criteria are reviewed with every measurement device to review if the measurement device meets the criteria.

7.4.2 General measurements results per area

The indoor comfort levels and concentration are measured in 24 various areas in the case study. The results specific per measurement device are described in appendix 15.

Indoor air measurements

The ventilation capacity is calculated and visualized in figure 71. Ten out of the fifteen areas contain a lower ventilation capacity than 45m^3 per hour per person. This means that the measured indoor air quality will probably exceed the permitted values.

The indoor air is measured with a carbon dioxide (CO_2) concentration and total volatile organic compounds (TVOC) concentration. The results are described and calculated in appendix 17. The minimum CO_2 concentration, during office hours, varies between 400 and 424 ppm. However, the minimum concentration during 24-hours is always around the 400 ppm. The CO_2 concentration in the atmosphere is measured by the KNMI (2017), the outdoor CO_2 concentration is around 400 ppm, because this concentration is measured in 2017, probably the CO_2 concentration in the outdoor air is even higher. This concentration increases over time, because in 1959 this concentration was only 316 ppm.

As opposed to the minimum value, the maximum value during office hours is always exceeding the value of BREEAM, which is a CO_2 concentration below the 600 ppm. Furthermore, the bank, due to climate class B and Well certificate, requires a lower CO_2 concentration of 800 ppm. This value is also exceeded by 12 out of the 24 measurements, illustrated in figure 55. The maximum value differs from 700 ppm up to 2198 ppm, measured on floorplan A11, location room 11 with 6,6m^2 without a window.

The average CO_2 concentration during office hours differs from 444 ppm up to 626 ppm, measured as well on floorplan A11, location room 7, 14,8m^2, where 8 building users can meet. The average CO_2 level is always below 800 ppm and nearly always below 600 ppm, 22 out of 24 measurements.

All measurement devices exceed the 600 ppm CO_2 value during office hours, 12 out of the 24 measurements exceed the 800 ppm, most measurement devices were located on floor A11. This value is difficult to meet and is not always feasible in office situations. Moreover, 4 out of the 24 measurements exceed the 1000 ppm, 2 out of the 24 exceed even the 1500 ppm and only 1 out of the 24 measurements exceed the 2000 ppm, this measurement device is located at A11, location room 11 including 6,6m^2 surface.

Recommended is to improve the indoor air quality regarding the CO_2 concentration level. The CO_2 concentration levels are only too high a few hours per day. This is mostly on Monday till Thursday in the afternoon.

The total volatile organic compounds (TVOC) is measured in ppb, this is 1000 times smaller than the CO_2 measured concentration. A few regulations are written down, this research shows only problems when the TVOC is above the 155 ppb. Mostly, a TVOC of 0 ppb is measured with the maximum value of 215 ppb on floorplan A11, location 2 with 14,8m^2, where 6 building users can have a meeting. The TVOC measured in this research, is nearly never measured above the permitted value, which means that the TVOC does not need to change on these two specific floorplans. The TVOC is only measured short-term with the same conditions; the emission sources are the same. Future research can investigate the long-term exposure to TVOC and the influence of adding new materials.

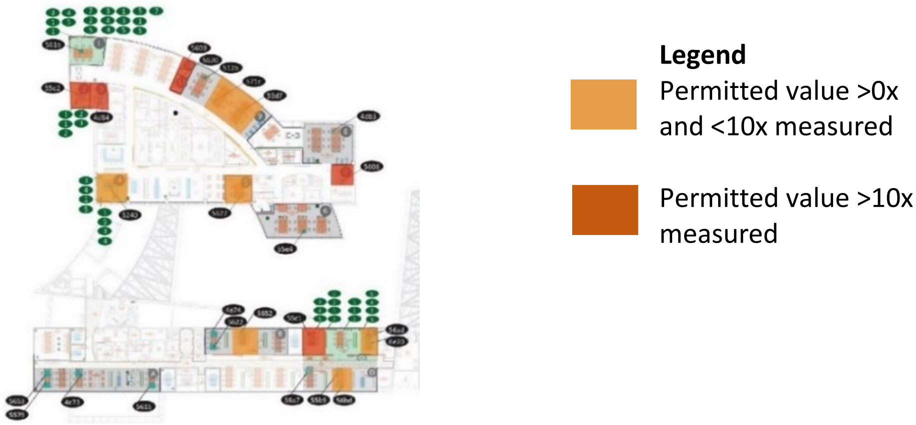


Figure 71. CO_2 concentration above permitted value 800 ppm, marked in orange >0x and <10x measured and marked in red >10x measured. Floorplan A11 above and floorplan E03 below.

Thermal measurements

The thermal comfort is measured with temperature in degrees Celsius (°C) and relative humidity in percentages (%). The results are described and calculated in appendix 18. The temperature level during office hours is measured in 24 areas. The minimum temperature which is measured is 18,7 °C. This value is measured at A11, location 7, including 14,8m^2 for where 8 building users to meet. This minimum temperature varies from the 18,7°C up to very warm areas with 21,9°C as a minimum temperature. This warmer area is located at A11 location 11 with 6,6m^2 and at E03 location 1D with 120m^2 and seating spaced for 22 building users.

The highest temperature which is measured is 26,3 °C at E03 location 3D with 120m^2 and seating spaced for 22 building users. The highest temperature measured during office hours in various areas differs between 23,1 °C and 26,3 °C.

The average temperature during office hours is between the 21,6 °C and 23,7 °C. This 23,7 °C is measured at E03 location 1D with 120m^2 and seating spaced for 22 building users.

The temperature between the 20 °C and 24 °C is exceeded several times in every area. The area where the temperature is exceeded the most is located at E03, location 1C including 122,6m^2 surface, it exceeded 357 times 10 minutes. Recommended is to stabilize the temperature with a maximum lowest temperature of 20 °C and a highest temperature of 24 °C.

The relative humidity is measured next to the temperate as well. The minimum relative humidity is very low, between the 23,3% measured at A11, location 3 with 16,m^3 and 6 building users and the 36,2% at E03, location 2B, 125m^2 with 22 building users. Equally important, it is visible that floorplan A11 contains more measured values, lower than the permitted value, than E03. The minimum measured relative humidity lower than the permitted value at A11 is 12 out to the 12 and at E03 0 out of the 12 measurement devices.

The maximum measured value is always above the 30%, which is the lowest permitted value. The maximum value various between the 39,6%-46,6%. The 39,6% is located at A11, location 6 with 83,6m^2 including 16 building users and located at E03, location 1D with 120m^2 including 22 building users. In addition, the 46,6% is positioned at A11, location 7 with 14,8m^2 and 8 building users. This location contains the highest temperature as well.

The average measured value during office hours is always above the permitted 30%. The values variate from 31,0%-38,4%. The 31,0% is located at A11, location 6 with 83,6m_2 including 16 building users. The relative humidity is always exceeding the 30% at A11 in contrast to E03, where only less than 50 times the permitted 30% is exceeded.

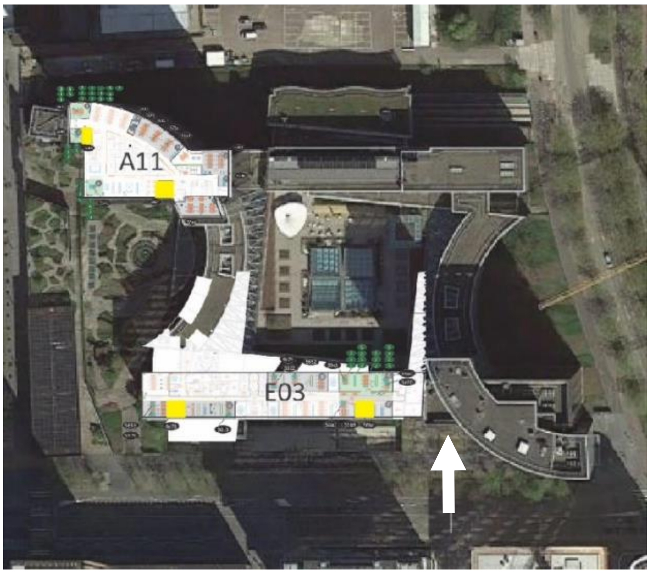
The temperature and relative humidity are compared with each other, illustrated in figure 72. When the temperature increases the relative humidity decreases. The decrease of the relative humidity is stronger than the increase of the temperature, but the connection is visible.

Figure 72. Left temperature marked in orange when <20 and > 24; measured >50x and marked in red when measured >200x.
Right relative humidity marked in orange when <30% and >70%; Measured >50x and marked in red when >200x.
Floorplan A11 above and floorplan E03 below.

Light & visual measurements

The light quality is measured with light level in lux and flicker light in Hertz (Hz). The results are described and calculated in appendix 19. The light level during office hours is measured in 24 areas. Every area consist of at least one measurement below the required 500 lux. The minimum measured values are mostly around 0 lux, this means that the light is off and the space is not used with full capacity. This is mostly early in the morning or late in the afternoon. The measured values difference from 0 lux – 231 lux. The 231 lux is located at A11 location 4 including 16,3m^2 with 6 building users.

The maximum measured light level values differ a lot from each other, because of the daylight entry. Most of the daylight, comes from the South façade of the building, namely measurement devices at A11: 4D84 and 5627, and at E03: 56BD and 5579, illustrated in figure 73. Generally, the highest average temperature has not been measured in these areas. The maximum light level various from 222 lux, positioned at E03, 2B, the North façade till 11866 lux, located in floorplan E03, area 3D.



Legend
Light level
>11000 lux

Figure 73. Measured floorplans positioned in location; maximum light levels above 11000 lux are marked in yellow.

The average measured light level varies from 33 lux till 312 lux, all below the permitted 500 lux. In conclusion, the light level does not meet the prescribed values and contains an average of 400 lux during working hours.

The flicker light level can cause discomfort between the 0 Hz and the 50 Hz. The minimum flicker light of every area during office hours and 24-hours is always 0 Hz. The maximum flicker light differs from each other from 0 Hz up to 94 Hz. The 94 Hz is measured at A11, location 2 with 14,8m^2 including 6 building users.

The average flicker light level is around the 30 Hz. Nearly every area contains light level between 0 Hz and 50 Hz. Notable is the difference between floorplan A11 and E03, where floorplan E03 counts more flicker light. Recommended is to minimize the flicker light, especially on floorplan E03. Specific rooms 5620 and 5622 counts more flicker light than the average areas. In conclusion, the lightbulbs are used a longer lifecycle than designed, therefore the light can flicker more and this needs to be stabilized.

Acoustic measurements

The acoustic comfort is measured with average sound level and maximum sound level in decibel (dB). The results are described and calculated in appendix 20. The sound levels; background noise level and installation sound level during office hours is measured in 24 areas. The installation sound level needs to be lower than 40dB or even 35dB, this is measured by calculating only 50% of 24-hours measured time, to calculated only the night installation sound. This installation sound level is nearly always measured under the 35dB, whereby the installation complies with the permitted installation sound level.

Furthermore, the background sound levels are measured only during office hours with permitted value of 57dB, required by the bank and 59dB, required by Bouwbesluit 2012. These background sound levels exceeding multiple times the permitted background sound levels.

The minimum average background sound level measured values is around 30 dB, between 31 dB up to 39 dB. The 39 dB is positioned at A11 location 9C with 104m^2 including 22 building users. The maximum average background sound level during office hours is between 54 dB up to even 66 dB, measured at A11 location 3,16m^2 with 6 building users.

The average background sound level is around 40 dB, between 38 dB up to 51 dB. The 51 dB is measured at A11, location 7 with 14,8m^2 including 8 building users to meet. Most of the exceeded permitted values are measured at A11 in smaller areas, this is illustrated in figure 74.

The maximum average background sound level is measured as well. The maximum background sound level during office hours various a lot more than the average background sound level. The minimum background sound level between 1 dB till 41 dB.

The maximum background sound level is between 65 dB up to 128 dB. This is only measured for a short period. Recommended is to lower the maximum background sound level till at least 120 dB, this is the pain threshold of sound levels. This pain threshold level is measured at the following rooms at floorplan A11. Firstly, location 10 including 7,2m^2 with 6 building users. Secondly, location 5 with 24 m^2 including 4 building users. Lastly, location 1 including 33m^2 with 6 building users. In addition, it is measured at floorplan E03 as well. Firstly, 1D and 3D with 120m^2 including 22 building users and 3A, 2A and 4A with 167m^2 including 40 building users.

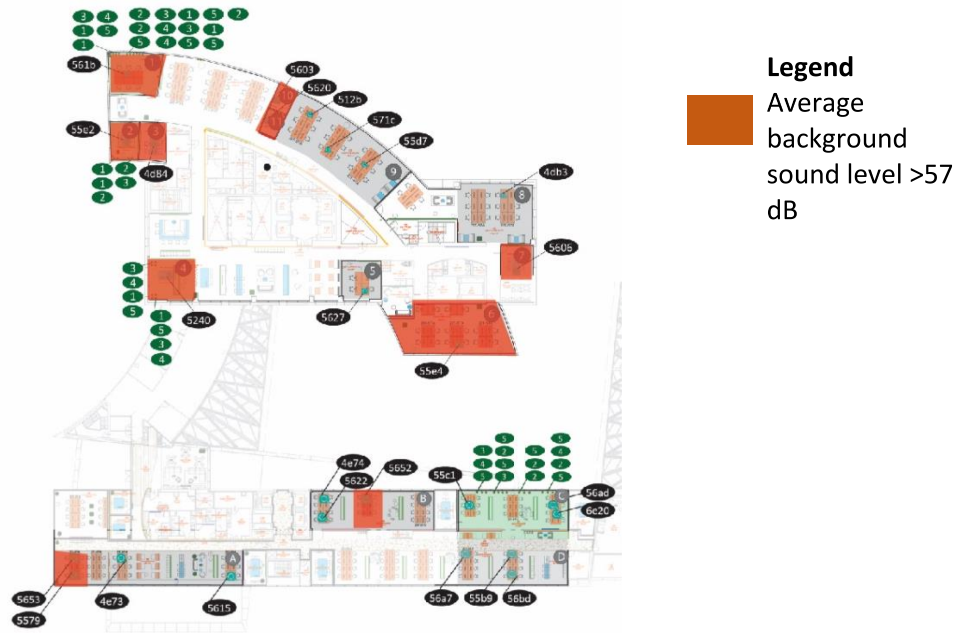


Figure 74. Average background sound level above 57 dB.
Floorplan A11 above and floorplan E03 below.

Plants measurements

The possible indoor comfort stressors can be influenced by indoor plants. These influences are analysed for indoor air quality, thermal comfort and acoustic comfort. The calculations are explained in appendix 24. The first measure week was without plants and the second and third with plants. Floorplan A11 contains plants in small meeting rooms and floorplan E03 contains plants in open areas. The indoor conditions are the same for every plant measurement, only the area size and occupancy differs.

Firstly, the indoor air quality will theoretically be improved by placing plants in the interior. The CO_2 concentration measured on Floorplan A11 improves, these plants are placed in the smaller size rooms of this floorplan, illustrated in figure 75. In opposite to this floorplan, the CO_2 concentration measured on floorplan E03 increase. The use and occupancy rate on this floorplan influence this concentration, instead of the plants. The TVOC concentration which is measured on both floorplans, differs a lot and is less influenced by the plants.

Secondly, the thermal comfort is less influenced by placing the plants in the interior, illustrated in figure 76. The temperature is not clearly influenced by placing the plants in a smaller size or bigger size room. In addition, the relative humidity should increase by placing plants. This is mostly not been shown by the measurements, only the water vapor is a little bit higher.

Lastly, the acoustic comfort seems to improve slightly by placing the plants in the interior, both in the small spaces and in the larger spaces. This is most likely only a few decibels, figure 77. This decrease in sound level can be influenced by other factors as well, like people talking softer.

In conclusion, plants have a greater effect when the plants are placed in smaller spaces than in larger spaces. In addition, the building users appreciated this research and were eager to participate, because the plants in their office gave peace in their minds.

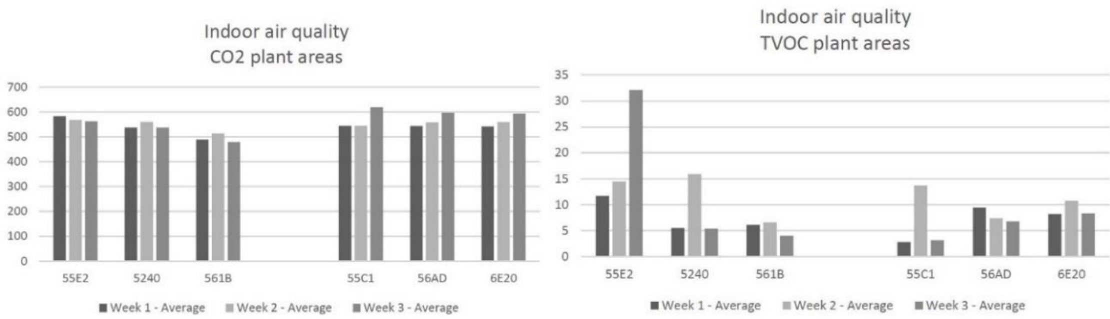


Figure 75. Indoor air quality CO_2 and TVOC, left A11 and right E03 floorplan from 18.02.20 till 09.03.20.

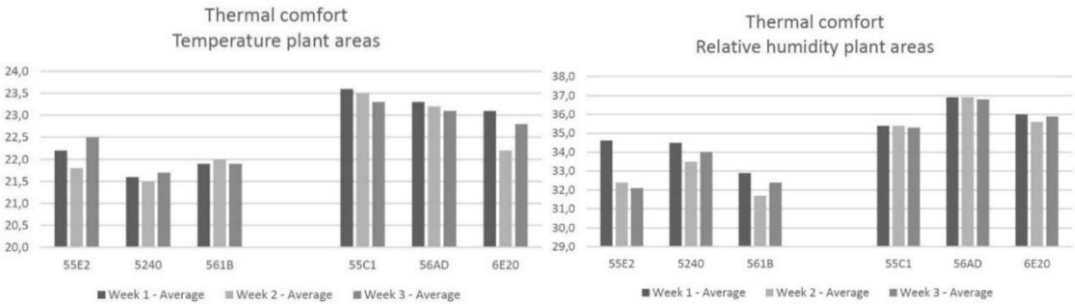


Figure 76. Thermal comfort temperature and relative humidity, left A11 and right E03 floorplan from 18.02.20 till 09.03.20.

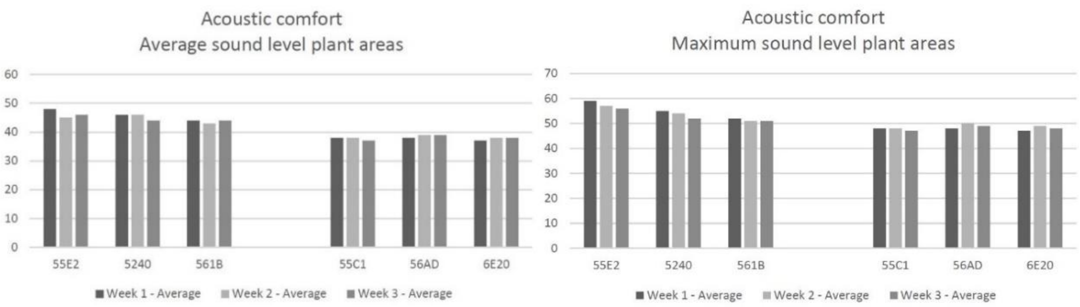


Figure 77. Acoustic comfort average and maximum sound level, left A11 and right E03 floorplan from 18.02.20 till 09.03.20.

Areas including plants	Average relative humidity (%)	Average temperature (°C)	Saturated vapor pressure (Pa)	Actual vapor pressure (Pa)
5240	32,9	21,9	2629	865
561B	33,0	22,0	2645	873
55E2	34,5	21,6	2581	890
6E20	35,4	23,5	2896	1025
56AD	36,0	23,1	2828	1018
55C1	36,9	23,3	2861	1056
Average	**34,8**	**22,6**	**2740**	**955**

Areas without plants	Average relative humidity (%)	Average temperature (°C)	Saturated vapor pressure (Pa)	Actual vapor pressure (Pa)
55D7	30,9	23,5	2896	895
55E4	31,0	23,5	2896	898
571C	31,4	23,2	2844	893
5603	31,5	23,0	2811	885
512B	31,6	23,2	2844	899
4D84	32,5	22,8	2778	903
5627	32,7	22,8	2778	908
5620	33,1	23,4	2879	953
5606	33,7	21,9	2629	886
4E73	33,9	23,0	2811	953
56A7	35,5	23,7	2932	1041
55B9	35,9	22,6	2744	985
5615	36,9	22,7	2760	1018
56BD	37,0	22,6	2744	1015
5579	37,4	22,8	2778	1039
5652	37,5	22,6	2744	1029
4E74	38,4	21,8	2613	1003
5622	38,4	21,9	2629	1010
Average	**34,4**	**22,8**	**2784**	**956**

The water vapor is linked to the relative humidity and the saturated vapor pressure calculated with the air temperature, table 16. The plant areas does not necessarily contain a higher actual vapor pressure (Pa). Building users produce water vapour as well, with 70g/h (ISSE, n.d.).

Table 16. Vapour pressure (Pa) of the measurement areas of floorplan A11 and E03 (klimapedia, n.d.).

7.4.3 General measurements results per floorplan lay-out

Floorplan A11 and E03 have been compared with the exceeding values during office hours.

Floorplan lay-out A11

Nearly every measurement devices exceed the criteria as shown from chapter 5 in figure 78 below. Calculations are written in appendix 22. Lay-out A11 measurements. Only the CO_2 concentration above the 800 ppm was not always exceeded by various measurement devices. The light level, which need to contain a minimum of 500 lux, is non reached most times. In addition, the flicker light did exceed the permitted values by 23 measurement devices. The temperature, relative humidity, background and installation sound level exceeded around the same percentages.

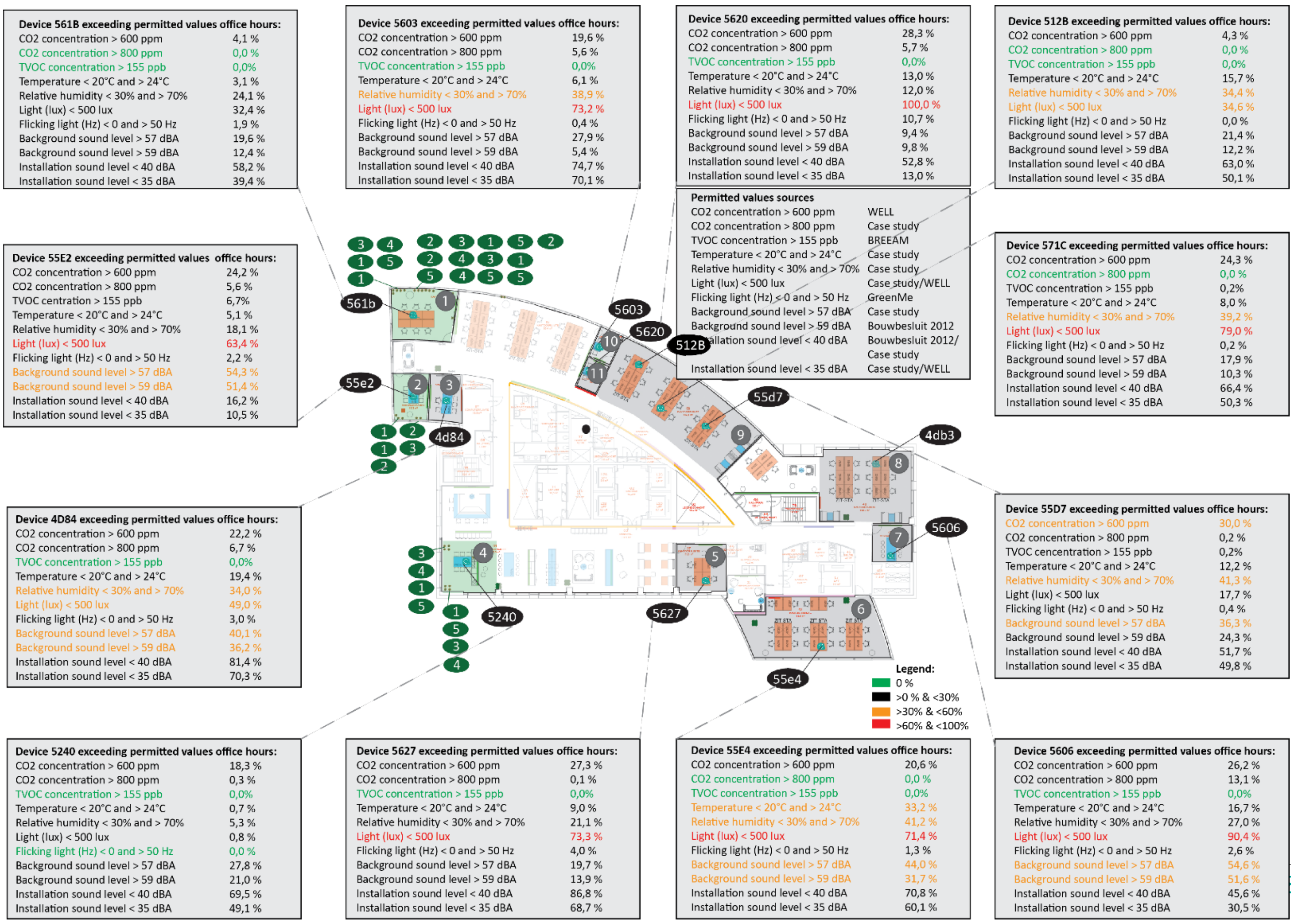


Figure 78. A11 Measurement results exceeding permitted values during office hours.

Floorplan lay-out E03

The floorplan lay-out E03 exceeded less times the permitted values compared with floorplan lay-out A11, described above. The exceeded measured values of lay-out E03 are displayed in figure 79. Calculations are written in appendix 23. Lay-out E03 measurements. Mostly, all criteria contain exceeded values, only the CO_2 concentration below 800 ppm is measured in nearly every area as 0,0%. One criteria is nearly every time exceeded; the light level below the 500 lux. In addition, some criteria are multiple times exceeded. Firstly the temperature, secondly the noise level and lastly the CO_2 concentration below 600 ppm.

The rooms with a higher CO_2 concentration contain mostly a higher temperature level. In contrast to the temperature level, the relative humidity is not lower than in other spaces. These results show a connection between the higher CO_2 concentration and the higher temperature level.

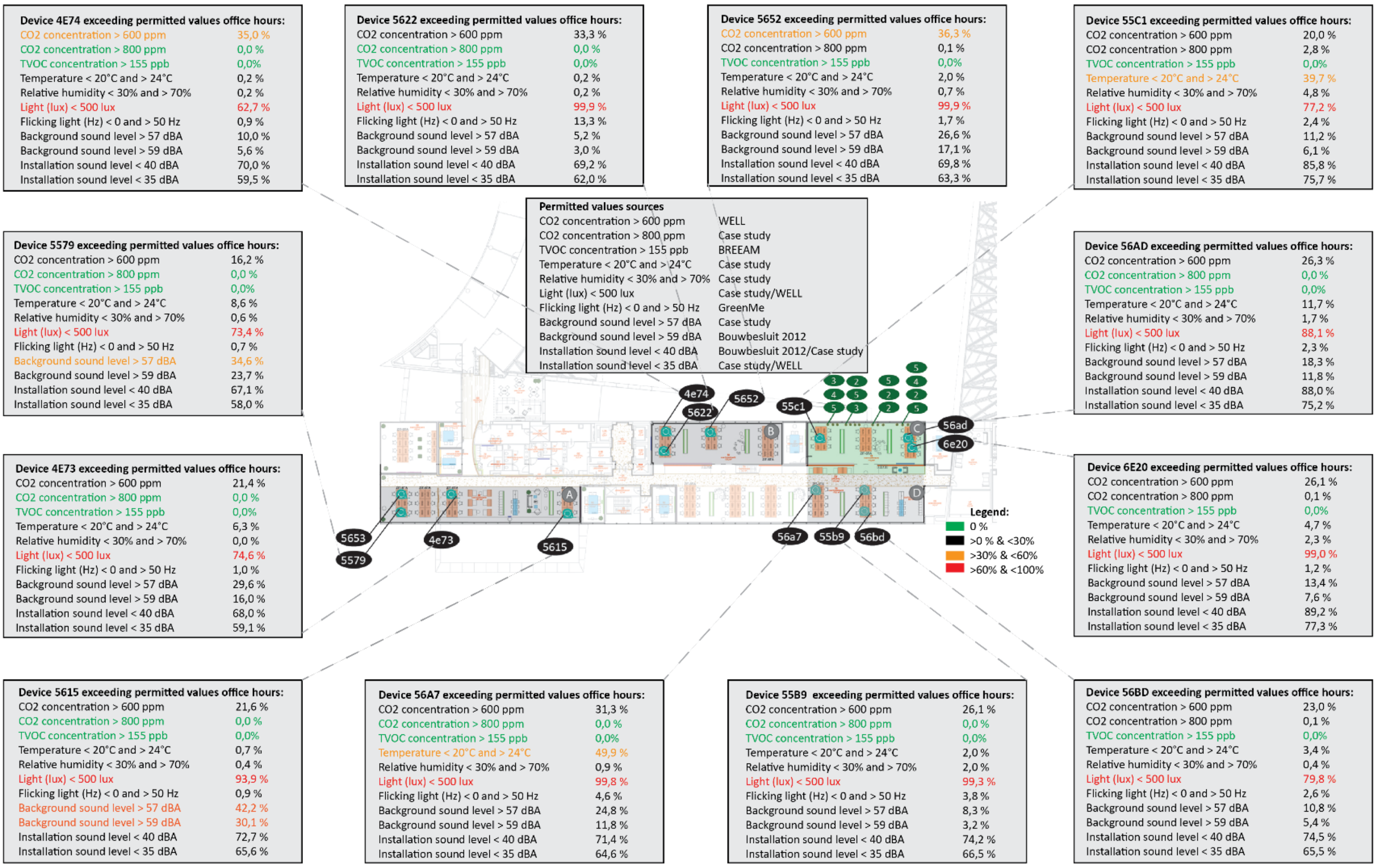


Figure 79. E03 Measurement results exceeding permitted values during office hours.

KNMI weather measurements

The measurements took place from 18th February till 9th March 2020, whereby the relative humidity was measured lower and the temperature higher, therefore these values are compared with the KNMI measures. The KNMI measured the weather in the Netherlands in the Bilt since 01-01-1901. The results of the KNMI measurements, are summarized in table 17, explained in appendix 21. The temperature was overall higher, the sun hours and the relative humidity was lower than usually measured. This partly explains the deviating values, displayed in figure 78 and 79, measured in the case study.

Date	Average T (°C)	Normal T (°C)	Sun (hours %)	Normal sun (hours %)	Average RH (%)	Normal RH (%)
Week 1 Average	7,8	3,3	20	33	78	83
Week 2 average	5,4	4,1	23	32	81	83
Week 3 average	6,5	5,0	33	31	81	83
Total average	6,6	4,2	25,4	32,0	80,1	83,0

Table 17. KNMI weather measurements 18th February till 9th March 2020 (KNMI, 2020).

7.3.4 Conclusion

The individual areas and floorplan lay-outs are not meeting the criteria described in chapter 5. The criteria are measured in each specific area when and if they exceed the permitted values. The measurement devices which exceed this values during office hours (08:00-18:00) are marked as negative or how many of the measurement devices are not meeting the permitted values. The results are illustrated in the tables 18 and 19 below.

Measurable criteria						
Category	**Subcategory**	**Requirement**	**Equipment**	**Accuracy**	**Type of result**	**Not meeting results**
General	Spatial	Per person office space >4m^2	Floorplan	-	Floorplan lay-out	A11: Positive
			Floorplan	-	Floorplan lay-out	E03: Positive
Visual & lighting control	Emergency lighting	Emergency light <75 occupants	Floorplan	-	Floorplan lay-out	A11: Positive
			Floorplan	-	Floorplan lay-out	E03: Positive
Acoustic comfort	Contact sound level	>59 dB	GreenMe cubes	± 3 dBA	Individual measurement device	24 out of 24
		>57 dB	GreenMe cubes	± 3 dBA	Individual measurement device	24 out of 24
	Building installation sound level	<40 dB	GreenMe cubes	± 3 dBA	Individual measurement device	0 out of 24
		<35 dB	GreenMe cubes	± 3 dBA	Individual measurement device	1 out of 24
Nature	Plants	Reduce VOC	GreenMe cubes	> 0,1 ppm	Individual measurement device	6 out of 6
		Reduce CO_2	GreenMe cubes	> 0,1 ppm	Individual measurement device	4 out of 6
General	Spatial	Kitchens, chemical storages & printers in another room	Floorplan	-	Floorplan lay-out	A11: Positive
						E03: Positive
Visual & lighting control	Illumination	Minimum 500 lux	GreenMe cubes	± 2%	Individual measurement device	23 out of 24
	Light flickering	Smaller than 0 Hz, bigger than 50 Hz	GreenMe cubes	± 2 Hz	Individual measurement device	16 out of 24
	View	50% view from desk	View plan	-	Individual area	1 out of 24

Thermal comfort	Temperature	Winter 20-24 °C Summer 20-26 °C	GreenMe cubes	± 0,2 °C	Individual measurement device	20 out of 24
		Variation of at least 3 °C across open space over 200 m^2	GreenMe cubes	± 0,2 °C	Floorplan lay-out	A11: Positive
						E03: Positive
	Relative humidity	30-70 % or ventilating heat exchange wheel	GreenMe cubes	± 2%	Individual measurement device	16 out of 24
	Thermal zone	Maximum thermal zone per $60m^2$ or 10 occupants	Floorplan	-	Individual area	Negative, per area
Air quality	VOC concentration	<100 µg/m^3 per 30 min.	GreenMe cubes	> 0,155 ppm	Individual measurement device	3 out of 24
	Carbon dioxide concentration	<600 ppm	GreenMe cubes	± 30 ppm		24 out of 24
		<800 ppm	GreenMe cubes	± 30 ppm		6 out of 24

Table 18. Results measurable criteria.

Subjective criteria			
Category	**Subcategory**	**Type of result**	**Results**
General	Occupancy distribution	Floorplan lay-out	The occupants are distributed over the available areas and are not too close to each other.
	Activity of the building users	Individual area	Meeting areas: Talking to other people, mostly not concentration work
			Working areas: Various activities are done. Talking to other people via phone or colleagues sitting close by and reading and concentration work.
			Other areas: Talking to other people or relaxing.
Visual & lighting control	Which view	Individual area	Meeting areas: Half of the time no view, otherwise buildings from other companies or the train.
			Working areas: Buildings from other companies or the train.
			Other areas: Buildings from other companies or the train.
Thermal comfort	Clothes	Floorplan lay-out	The measurements were done from Tuesday 18 February till Monday 9 March 2020. The building users were warm clothes. Always a long trouser, long sleeves.

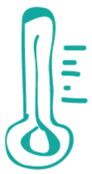
Table 19. Results subjective criteria.

The measured indoor comfort problems are described below per stressor during office hours with the official occupancy. Some factors influences these conclusion, like outside conditions, installation capacity, occupancy and the activities of the occupancy.

Indoor air quality

- CO_2 concentration highest in smaller rooms
- CO_2 concentration >600 ppm measured at all measurement devices
- CO_2 concentration >600 ppm measured as a percentage of time is 23,6%
- CO_2 concentration >800 ppm measured at half of the measurement devices from Monday till Thursday between 10:00-16:00
- CO_2 concentration >800 ppm measured as a percentage of time is 1,7%
- CO_2 concentration highest measured value is 2198 ppm
- TVOC concentration is measured mostly <155 ppb, measured as a percentage of time is 0,0%
- The VOC concentration can be higher when new materials are added to the interior, this will increase in time.
- Plants measured values improves only CO_2 concentration in smaller areas. In addition, the calculated values were higher than the measured values

Thermal comfort



- Temperature minimal measured value 18,7 °C and maximal measured value 26,3 °C
- Temperature level <20 °C and > 24 °C measured as a percentage of time is 10,5%
- Relative humidity is measured a few times below 30 % in every room or area at A11
- Relative humidity level <30 % and >70 % measured as a percentage of time is 14,6%
- When the temperature decreases, the relative humidity increases. The increasing relative humidity value increases by twice as large values compared to the decreasing value of the temperature
- The relative humidity is low, where the temperature is too high. When the temperature is brought down, the relative humidity will most likely go higher above the minimum permitted values
- Plant measured values is not shown as improving the temperature or relative humidity
- KNMI measured the outside conditions; temperature was overall higher, the sun hours were lower and the relative humidity was lower than usually measured.

Light and visual quality

- Light level >500 lux measured at all measurement devices
- Light level average around 400 lux
- Light level caused by daylight is highest measured at south façade
- Light level >500 lux measured as a percentage of time is 72,2%
- Light flicker measured at all measurement devices, highest values at E03
- Light flicker <0 Hz and >50 Hz measured as a percentage of time is 2,6%

Acoustic comfort

- Noise sound level highest in smaller rooms
- Average sound level >57 dB measured at half of the measurement devices
- Average sound level >57 dB measured as a percentage of time is 2,0%
- Average sound level >59 dB measured as a percentage of time is 1,0%
- Installation sound level measured always below 40 dB
- Installation sound level <40 dB measured as a percentage of time is 68,2%
- Installation sound level <35 dB measured as a percentage of time is 56,4%
- Maximum sound level >57 dB measured as a percentage of time is 25,5%
- Maximum sound level >59 dB measured as a percentage of time is 18,5%
- Plant measured values improves slightly the sound level

General

- Plants have a greater effect in small spaces (5-30m^2) compared to larger spaces (> 100m^2) and building users appreciated to participate in this plant research
- Minimum space per person in an office space is 4,7m^2, this needs to be 5m^2
- The occupants are distributed over meeting rooms, working spaces and relaxing spaced
- Activities in meeting rooms is talking to other people, mostly not concentration work
- Activities in working areas are talking to other people via phone or colleagues, reading and concentration work.
- Activities in relaxing areas are talking to other people or relaxing.
- The building users wore warm clothes. Always a long trouser, long sleeves.

7.5 Conclusion

The material, survey and measurement results are compared with each other, with as main factor the building users. The comparison of the results are explained in the category lay-out, figure 80 and indoor comfort, figure 81. Some problems can be substantiated by both the building users questionnaire and complaints, the measurements and the material research. Other problems can only be explained from one of these three parts. These problems are translated into framework elements and measures which are adapted in the floorplan design of the case study.

Lay-out				
	Category	Survey	Measurements	Material
Challenges	**Office space**	Too little plants closeby the working spaces	Plants improve CO_2 concentration, mostly in smaller size rooms Plant measured values improves slightly the sound level	
		Shared working space 84%	4,7m2 surface per person	
		Same place at various locations	Yello floorplan concept	
	Occupancy	>3000 building users on Monday till Thurdsay from 10:00-16:00 hours	Stressors above permitted values calculated by occpuncy Stressors not regulated per occupant	
	Building user control	Being able or not being able to open a window		
		Building systems can be adjusted by Technical management	Building management systems can mainly be operated by FM	
	Lay-out Working space	Need for individual concentration places at a desk	Activities in working areas are talking to other people via phone or colleagues sitting close by and reading and concentration work.	Individual height adjustable desks and chairs
		Need for silence rooms for 1-2 persons		
		Begin able to read		
		Distracting by colleagues passing by workplace		
	Lay-out Meeting space	Need for small meeting rooms	Activities in meeting rooms is talking to other people, mostly not concentration work	
		Being able to have phone calls		
		Need for big meeting rooms		
		Need for concentration places to work together		

Figure 80. Conclusion lay-out analyses.

Indoor comfort

	Category	Survey	Measurements	Material
Challenges	**Cleaning**	On top of the light lies dust		Some installation systems are not reachable
		Products and materials are not cleaned well	TVOC concentration is always <120 ppm, % of time is 0,0%	Some parts of the furniture are not demountable
		Carpet keeps dirty after cleaning		Older or not organic materials can include VOCs
	Indoor air	Cold air stream		
		Smell from the canteen, a fire or sewer system		
		Ventilation system provides too much or too less air	Too low ventilation rate calculated per person	
		Ventilation system is defect, provides warm air or no fresh air	CO_2 concentration highest smaller rooms above 600 ppm	
		Ventilation grill is closed		
		The filters are not cleaning the air enough	CO2 concentration >600 ppm measured as % of time is 23,6%	
		Dry air, eye irritation or headache	Relative humidity <30 and >70 % measured as % of time 14,6%	
	Temperature	Temperature is too low or too high	Temperature minimal measured 18,7 °C and maximal 26,3 °C	
		Temperature is higher than thermostat	Temperature level <20 °C and > 24 °C measured as % of time is 10,5%	
		Sensors falling down or are not working		
		Sun shading system is not working		
		Relocating the sensors, because of relocating furniture	South facade higesth daylight measured up to 11866 lux	
		Temperature difference with adjacent rooms	Temperature difference below 3°C between adjacent rooms	
			Every area can control their own temperature not per occupancy	
	Light	Light remote control is defect or lost	Light flicker <0 Hz and >50 Hz measured as % of time is 2,6%	
		The fittings are defect		
		Automatic light control is not working		
		Activating the light multiple times		
		The ability to dim the light or adjust height	Light level >500 lux measured as % of time is 72,2%	
		Some of the fittings provide less light than others	Light level average around 400 lux	
		Power failure, emergency lighting		
	Acoustic	The light and ventilation systems make a sounds	Installation sound level always below 40dB, mostly below 35dB	
		Noise from the ceiling Loud buzzing noise in the space	Installation sound level <40 dB measured as % of time is 68,2%	
		Continuous beeping sound		
		Follow conversations in another room	Average sound level >57 dB measured as % of time is 2,0% Average sound level >59 dB measured as % of time is 1,0%	Sound insullation by felt space divider panels and wall finish and floor finish carpet

Figure 81. Conclusion indoor comfort analyses.

Chapter 8. Framework

8.1 Introduction

How to improve the indoor comfort in an office in a circular and energy-efficient way? Following Smorenburg (2019) it is important to create awareness for a healthy indoor comfort to stimulate health, environment and prosperity. In addition, increasing knowledge level about the indoor comfort and circular and energy-efficiency way of building. Moreover, combining theoretical study with field study; the material, building users and indoor comfort conditions analyses of the case study.

In Germany, the open office in other words Bürolandschaft was created in the 1950s (Van Noorloos, 2019 & Van Weerdt, 2018). From the 1970s this principle was applied in the Dutch offices, also called an activity based office. This principle entailed various advantages and disadvantages. The advantage following Van Dijk (2019) is stimulating conversations. Nevertheless Van Dijk's and Van Noorloos (2019) disadvantages are less square meter per person, lack of privacy and concentration, disturbing phone calls and conversations between colleagues and more distraction. Another view from Van Weerdt (2018) on the disadvantages of an open office are noise, visual and audio distraction, less concentration and stress. Moreover according Pullen (2020), the disadvantages are even more health related, for example an open office increase headaches, stress and burn-out complaints. Besides the health challenges of an open office, it stimulates extroverted characters, only a floorplan needs to stimulate every kind of character.

In addition, a building can influence the energy and materials use, as well as the building users behaviour (pwnet A, 2019). For example firstly, generating energy for the building and building users can be done technically and mentally. Secondly, health can be stimulate the building users physically and mentally. Thirdly, zero waste of materials and talents and lastly, creating a dynamic working space, where the building users are central, while using green, light and natural materials.

Furthermore, the financial situation of a company is affected by the health and environmental impact of an open office (Pwnet B, 2019). Companies are investing in health and environment, because they want to stimulate their employees, they have the responsibility towards the board including laws and sick leave, attract new employees, it brings the company financial benefits and small investments can make a difference.

Studies (De Been & Beijer, 2013; De Been, Van Yperen, Moback & Albers, 2016 & Van der Voordt, Hoekstra & Van Sprang; 2019) shown that improving the indoor comfort and reorganize the activity-based working environment can lead to a higher building users satisfaction. However, studies (De Los Rios & Charnley, 2016) also show that a circular and sustainable economy requires a changing role in the design process. As it has been noticed, the indoor comfort is minimal related to the environmental and financial impacts and its changing approach toward a design.

The aim is to develop a step by step approach to influence the health and circular approach in an office building. This improves the wellbeing of the building users. This development goes along with creating general knowledge about the indoor comfort and circularity. The sub research question is stated *'What kind of framework can influence the indoor environment in a circular way?'*

The methodology, to gather the required information, is literature study and reference research. This information consists of principles and existing strategies how to improving the indoor comfort and designing it in a circular way. These principles and existing strategies are structured and combined or separated into a framework.

This chapter is structured in subchapters. Firstly, the healthy and circular office framework is illustrated. Secondly, the interventions within this framework are explained per element.

8.2 Healthy and circular office framework

The building users, who need to work in a healthy and circular office, are central to the framework. The general elements; indoor comfort possible stressors, building users, location and existing materials influences the three focus areas; health & wellbeing, nature and business case. These focus areas need to be in balance with each other. The healthy and circular office framework is illustrated in figure 82.

This framework consists of five steps that must be approached per element. Each element consist of various strategies to achieve step by step a healthy and circular office. These strategies are illustrated in symbols and described in the next chapter.

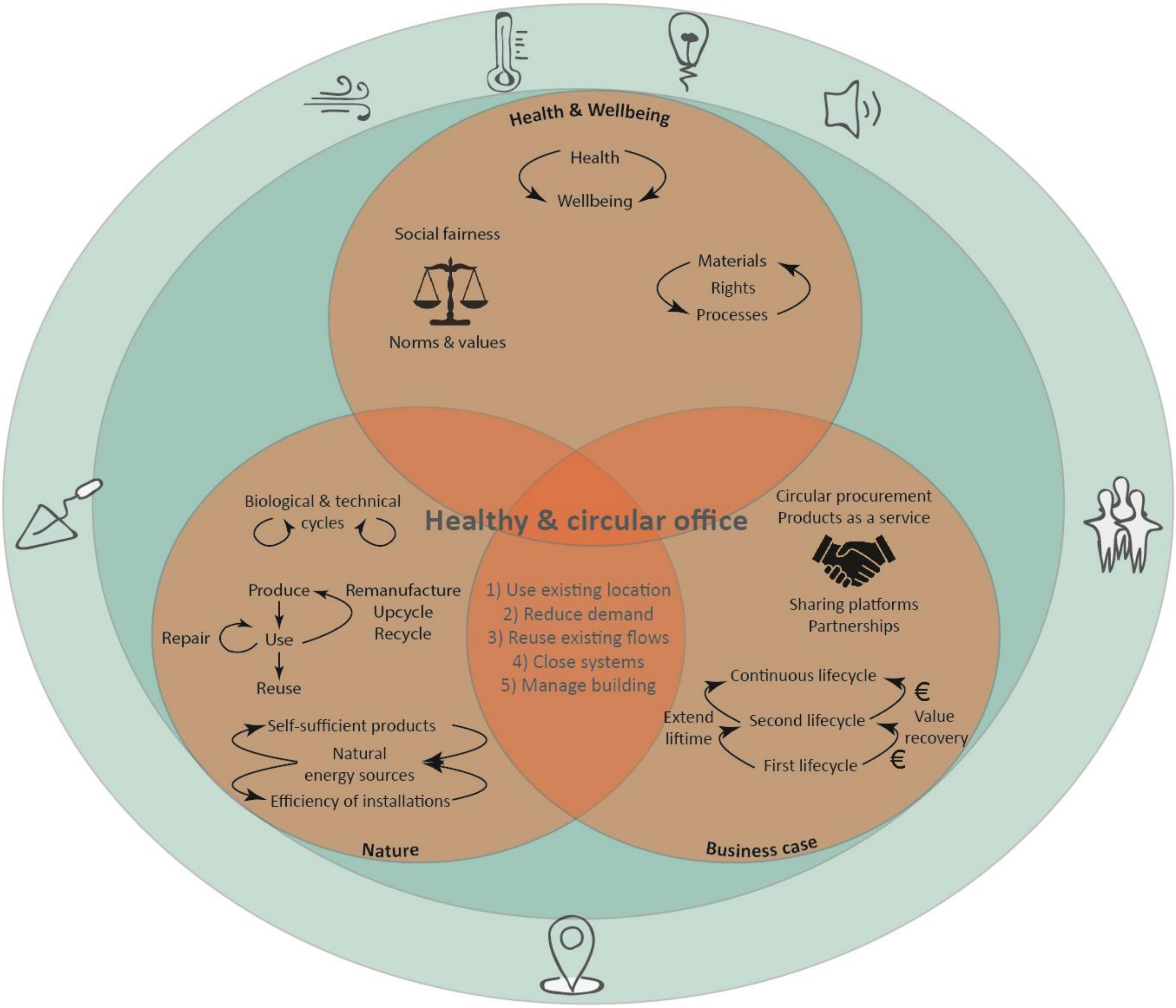


Figure 82. Healthy and circular office framework.

8.2.1 General elements

The general elements apply to every intervention, starting with 5 steps, illustrated in figure 83 to improve the indoor comfort in a circular way.

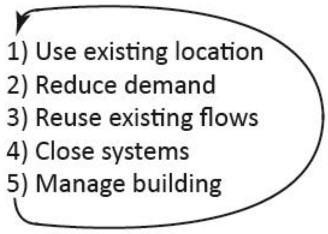


Figure 83. 5 steps toward a high indoor comfort satisfaction level in a circular way.

The first step, using existing location, uses natural sources and orientates the building towards these sources. The second step, reduce the demand, ensures the least possible demand for material, water and energy flows. The third step, reuse existing flows, all flows can be characterized and identified, so that they can be reused or recycled. After using all existing natural sources and flows and reducing the demand, only a small demand for materials, water and energy is required. The fourth step, close systems, use as few materials, water and energy as possible. After these interventions the building meets the required materials, water and energy flows and the building can be maintained. The last fifth step, manage building, keeps all the flows within the system. In addition, all flows will be reuses, remanufactured or recycled. After a certain period, when the building users preferences and needs or building regulations are changed the steps are followed again.

The first general elements are the possible stressors of the indoor comfort, including indoor air quality, thermal comfort, light & visual quality and acoustic comfort, illustrated in figure 84. These elements influence the indoor comfort from a building technology point of view.

Figure 84. Framework indoor comfort parameters.

Firstly, the indoor air quality is influenced by the outdoor air, furniture, customer products, tobacco smoke, office equipment and building materials. The indoor air quality can affect the subcategory health and wellbeing, especially the nose and the respiratory tract. It can influence the subcategory nature with substances such as, VOCs, CO_2, CO and NO_2. Finally, financially refreshing the indoor air needs energy for installation. In addition, materials or plants can filter the air as well.

Secondly, the thermal comfort is determined by air & vapor, human body and the local climate. Thermal discomfort can cause hypersensitive or damaged skin. The subcategory nature can be affected by air movement with various temperature and vapor levels. Lastly, energy is needed to heat up or cool down the air. This has financial consequences.

Thirdly, the visual & light quality is influenced by the façade, amount of sunlight or artificial light and the local weather. Light can affect the eyes in the subcategory health and wellbeing. Furthermore, light can disturb day & night rhythm for living organisms in nature. In addition, it impacts nature and light needs energy and affects the financial situation as well.

Lastly, the acoustic comfort is determined by the sound of people and traffic, installation noise, the properties of materials and the location of the sound. The human ear can be affected when the sound is too loud during a certain period. Sound influences the life of living organisms as well. Lastly, financially an investment in sound absorbing materials can influence the financial situation.

The second general elements are the location, building users and material & products, illustrated in figure 85. These elements define the existing situation. If the existing situation consists of a greenfield only the location and building users can influence the design. In contrast to a renovation, when all three elements influences the design, because the existing building including materials & products, they can be reused or recycled.

Figure 85. Framework influence factors indoor comfort.

Firstly, the location determines the natural sources and the orientation of the building. Secondly, a profile of the building users refers to the preferences and needs of the people in the building. Lastly, material & product of an existing building can be reused or recycled. These materials can contain toxic substances that can influence the health of building users.

8.3 Elements within the healthy and circular office framework

The healthy and circular office framework illustrates interventions to improve the indoor comfort in a circular way. This framework consists of general, healthy & wellbeing, nature and business case elements. The elements are explained in more depth in the following subchapters.

8.3.1 Health & wellbeing element

Health and wellbeing is the main topic of the indoor comfort of building users, people are central to this framework. Firstly, a healthy environment must be calculated and designed. A healthy environment means nearly zero healthy complaints, caused by the indoor comfort stressors, location, building users and materials and products. Secondly, wellbeing can be designed when the office environment is healthy, see figure 86. The health and wellbeing is related to materials and their processes.

Figure 86. Relation between health and wellbeing.

Figure 87. Materials, processes and their rights.

Materials contain certain processes to which rights can be linked, figure 87. The processes of materials are production, use, reuse and recycling. During the production process the raw materials are composed to a new or reused product. These raw materials, or the product as a whole, may contain rights. As explained by Rau (2016) the Universal Declaration of Material rights, where raw materials are recognisable, have an unique identity and stay available. In addition, strategies for waste behaviour, long-term vision and recovery to its original state. Furthermore, materials need protection and administration.

The use and reuse process is a deposit for the raw materials. These materials need identification on location and can go back, any time in the process, to their original state.

The recycling process brings the raw materials back to the use and reuse phase. These raw materials are disassembled and each raw material can be reused in the production process, the process starts over again.

Social fairness and norms and values influence the human health and wellbeing, figure 88. Firstly, social fairness is about the human rights, mostly focused on the building users. The building needs to facilitate these rights, for example break areas and toilets. Secondly, the norms and values of the company are visualised in their office building. These norms and values need to match with the human rights.

Figure 88. Social fairness And norms & values.

8.3.2 Nature element

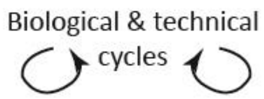


Figure 89. Biological and technical cycles.

The nature elements minimalize the impact on the environment. The nature consists of biological cycles, where only elements from nature are used to compost products, figure 89. These elements are for example, from the earth, from plants or from animals. After the use and reuse of these products, these biological elements can go back to their original state into the nature. This process goes via composting.

In addition, the mankind added technical cycles, where products are composed from raw materials. Combining these raw materials form new products. After the use and reuse, these products can be disassembled. These dissembled raw materials can be manufactured in new products.

It is recommended to keep the biological and technical cycles separated, to be able to recycle and reuse the biological elements and raw materials.

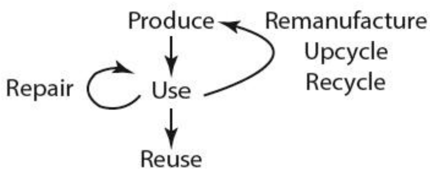


Figure 90. Cycle of materials.

The process of a raw materials influences the environment, where emissions and toxic gasses may arise. A product is produced and used. It can be reused after its lifecycle, figure 90. If the product is damaged, it can be repaired and reused again. In addition, a product may not meet the requirements anymore or innovations took place. The product can be disassembled and remanufactured, upcycles or recycled.

It is recommended to design a product in such a way that it can be reused, repaired or disassembled to meet the future needs of the building users and to make the products circular.

Energy sources are required in an office building. These energy sources can influence the environment. There are many energy sources which use natural sources, like wind, solar and water energy. These natural energy sources are favored to use. In addition, reducing the energy use, less natural energy sources are needed. The products can be self-sufficient, where they are not using any energy or producing it by themselves.

Furthermore, design the installations as efficient as possible. These installations use less energy and are only used when building users are using the office building or an area within this building, figure 91.

A suggestion, to use only natural energy sources, where the energy need is limited and reduced by the products and the installation systems itself.

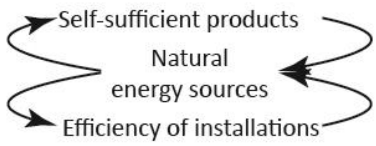


Figure 91. Optimizing energy sources.

8.3.3 Business case element

Figure 92. Cooperation to achieve circularity.

A business case is important to record all financial documents, this business case can include how to procure raw materials or products. Equally important, is the ownership and the associated responsibilities. Next to that, the knowledge which is created in all these process can be shared, even biological elements, raw materials and products can be exchanged. Lastly, partnership within circularity is important. Financial processes and forms of cooperation are changing, this requires more communication and cooperation, figure 92.

First, circular procurements by minimizing the environment impact. Furthermore, closing flows in processes when buying products and investigate multiple lifecycles. Next to that, it is important to build partnerships including long-term contracts and local suppliers.

Secondly, ownership and responsibility using products as a service model. In this model, the producer keeps responsible for the raw materials that are incorporated in the product. The consumer only rents the product as a service. For example, if a technical manager want to increase the fresh air in the building. The manger is not building the ventilation ducts and installation, but only the amount of fresh air which is needed. The ventilation ducts and installation remains to property of the producer. In this way the producer insures fresh air to the consumer and designed the system as efficient and circular as possible. This brings benefits for both the producer and the consumer. The producer owns an optimal system and the consumer is not concerned about the technical specification of the system.

It is advised to keep the ownership at the party who can influence the process and keeping track and identify the biological elements and raw materials.

Thirdly, sharing platforms bring parties together, where knowledge, supply and demand are exchanged. These platforms can speed up the circular process, by exchanging materials, products and knowledge. The more companies are connected to those platforms the more exchange take place.

Lastly, partnership promotes cooperation between companies. It is required, because of the changing processes, responsibilities and financial situations.

The amount of lifecycles of a biological element, raw material or product influence the financial situation, already when its procured.

Firstly, every biological element, raw material or product can be valued for its first lifecycle, as well as for the following lifecycles. Reusing it every lifecycle, means an added recovery value. These value can be calculated on how much the biological elements or raw materials are worth on that specific moment or in the future. Prediction models can assist the calculation value in the second and continuous lifecycles. When procuring the product, the raw materials may be worth less than in the future.

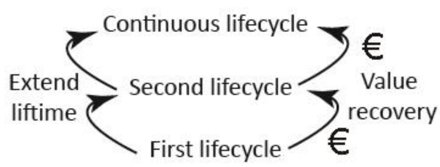


Figure 93. Economic cycles.

Secondly, the biological elements and raw material are used for an extended lifetime. If a material can be reused after the first lifecycle, no manufacture or repair cost are made. This can be added in the business model as cost saving, figure 93.

It is recommended to take all added values for the circular system compared with a linear system into account when a business model is composed. These added values can be cost-saving in the future, requiring a smaller investment to realize the same product.

8.4 Conclusion

This healthy and circular office framework creates a tool to start a renovation or a new construction process following steps and the elements. This tool is applied in Chapter 9.

Chapter 9. Case study design

9.1 Introduction

The case study design brings analyses and the framework together to practical measures to renovate the pilot floor A11 of the case study. Both the interior and technical aspects to improve the indoor comfort in a circular way and whereby the energy consumption is taken into account. The design is based on the A11 floorplan because the timeline of the renovation process starts with this floorplan after this research.

The design measures are developed with the framework, explained in chapter 8, to described the basic approach of the proposed measures. The design measures are detailed on the following aspects: technical aspects, social aspects and financial aspects. Firstly, the technical aspects contain the indoor comfort including the improved stressor(s) and how each measure improves the health. In addition, the technical aspects described circularity of each measure including the raw materials, the process and how it improves the environment. Moreover, the technical aspect explains the energy efficiency of each measure including how the energy use can be improved. Secondly, the social aspects consist of social fairness and how it improves the behaviour of the building users. Lastly, financial aspects contain the investing cost, maintenance cost and the next lifecycles revenue.

The aim is to create a design that provides various perspectives to approach the challenges mentioned in chapter 7 case study results. The following sub-research questions will be answered: 'How to improve the measured indoor comfort of the case study in a circular way, while taking the energy consumption into account?' and 'How does the floorplan, which improves the indoor comfort of the case study looks like?' Chapter 9.2 described how the healthy and circular office framework is applied to the case study. Chapter 9.3 analysed and described improvements on the material and product use for in the case study. Chapter 9.4 shows in sketches the measures to improve the existing situation and chapter 9.5 illustrates where these measures are located on the floorplan.

9.2 Healthy and circular office framework applied to the case study

The healthy and circular office framework is applied to describe the first steps of the renovation of the case study. The proposed measures, described below, are functional and improve the case study' indoor comfort in a circular way, by creating an optimal floorplan including the interior and technical aspects taking the energy consumption into account.

9.2.1 Five steps approach

This five steps approach described the existing situation and the improvements for the case study.

Step 1) *Using the existing location*; existing situation is using solar panels to generate energy from the sun to create renewable energy and apply sun shading system to regulate the thermal comfort.

Step 2) *Reduce demand*; proposal for the renovation is to install and use only efficient products. One measure is adding capacity to the air handling unit. Secondly, replace the existing lightbulbs and lastly, use the existing sun shading system to reduce heating capacity.

Step 3) *Reuse existing flows*; identify the applied materials during the renovation and store the information in a material passport to be able to reuse the raw materials in a later stage. In addition, measure to procure demountable furniture, desks and chairs where the materials can be reused for another purpose or product. Furthermore, reuse the existing ceiling plates and when parts of plates are damaged use only biological material to fill up the gaps.

Step 4) *Close systems*; recycle the existing waste from building users. The waste is already collected separately, to find company who can make recycled products out of these raw materials.

Step 5) *Manage building*; by updating the drawings with asset management; People Power, who are managing all documents of the case study and reuse or repurpose materials or products which are not used anymore in the existing situation. They can be sold on market places, like Excess Material Exchange or upcycle the material. The last option is to recycling the products.

9.2.2 General elements

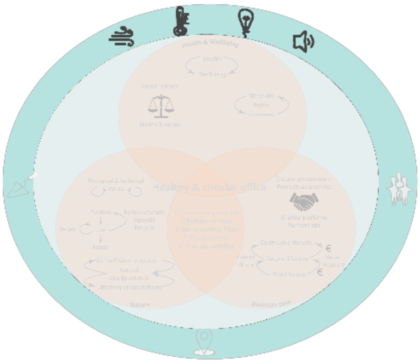


Figure 94. Framework-stressors.

Stressors

The possible stressors are measured and improvements can be made within this category, figure 94. Firstly, indoor air quality by engineering a higher ventilation capacity and addition products which can filter the air. One measure is adding a plant wall and cleaning the textile ventilation system ducts. Secondly, thermal comfort by creating a constant temperature and a higher relative humidity. Thirdly, light quality by procuring light bulbs with a minimum capacity level of 500 lux and more stable light, without flickering. Lastly, acoustic comfort by adding circular sound absorption materials.

Building users

Making a profile of the building users is to identify their changing preferences and needs, figure 95. This changed over the last twenty years, whereby the building users are doubled and the outdoor conditions changed. In addition, they complain more about the indoor comfort, building facilities and lay-out. The building users are mostly men, 59%, equal divided age between 25-64 years, primary working space is shared office and they work from various locations. Moreover, the building is most occupied on Monday till Thursday from 10:00 till 16:00 hours and most employers work fulltime, whereby 50% over more than 12 years. This means to create more meeting rooms and team working places, to accommodate all building users

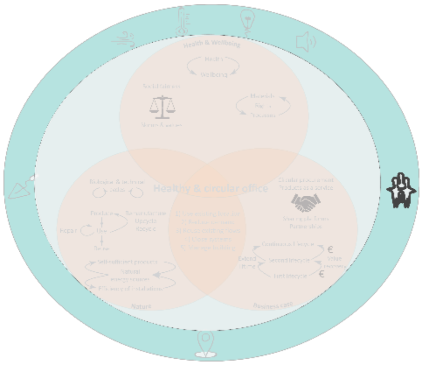


Figure 95. Framework-building users.

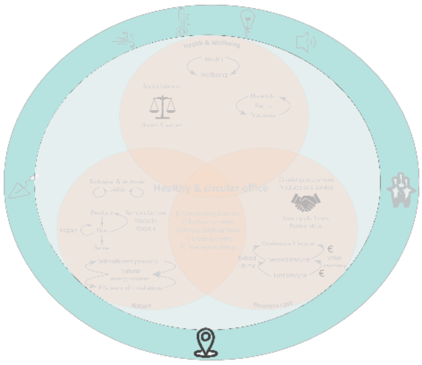


Figure 96. Framework-location.

Location

The building are multiple tower with various heights. The highest tower, building A, is 105 meter high and is located next to the road and the train station, figure 96. The top and middle floors of the building do not receive shade from the surrounding trees. Furthermore, the train, cars and trucks can cause noise, whereby the cars and trucks pollute the outside air as well. This need to be solved with the existing façade and the installation system, whereby the installation systems to have a higher capacity to meet the indoor comfort criteria influenced by the location.

Materials & products

The case study is a renovation project, whereby the structure and façade remain in their original condition. Only the installations and floorplan lay-out will be adjusted during this renovation process, figure 97. In addition, most of the materials are used for over twenty in the building, this means that the VOCs are mostly emitted from the materials. When adding new materials, the VOC concentration in the air can be higher than the current situation. This needs to be taken into account, whereby only materials without VOCs and environmental harmful additives are recommended.

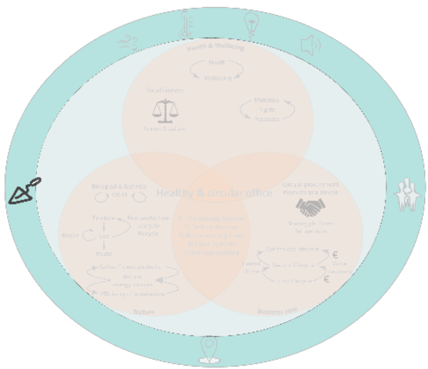


Figure 97. Framework-materials & products.

9.2.3 Health & wellbeing

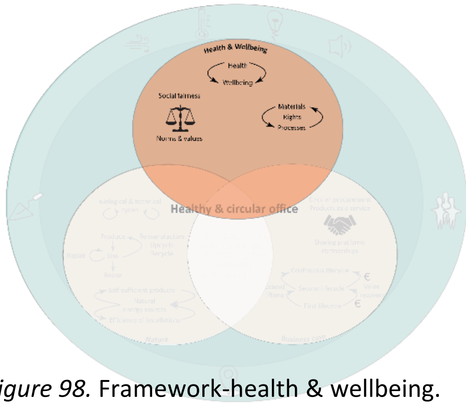


Figure 98. Framework-health & wellbeing.

A full overview of the environment involvement within the proposed measures will be created, figure 98. This will be done by including for every measure, recommended in this research, a company who can provide this measure explained in chapter 9.4, to be able to check the materials and process of this product. Moreover, a material passport, which is recommended for every measure, provides insight in this as well. This is described in the framework as a combination of the *material and processes cycles* and *health and wellbeing*. The social fairness, including the human rights, includes the *norms and values* which are taken into account in this floorplan to create relaxing places and toilets close to the working spaces. In addition, the building users are educated by dashboard on their computer which shows the indoor comfort values measured at that moment. This is illustrated in the framework as the *norms and values.* The case studies norms and values are presented in the floorplan as well. For example, their sustainable approach, described in the norms and values in this framework is, among other things, visible in separating the waste of the building users and make them aware of this process.

9.2.4 Nature

The nature is very important for the case study, figure 99 and the *biological and technical cycles*, described in the framework, are separated in all recommended measures. The measure plants, from the plant wall, are easily demountable from the plant holders. Which means a separation in biological and technical cycle. The case study is using *natural sources*, solar panels, to heat and cool the building and providing fresh air. In addition, a recommended measure is to connect the installations to the occupancy of that specific space to inform the building management. These people counter sensors are placed above every door. Described in the framework as *efficiency of installations*.

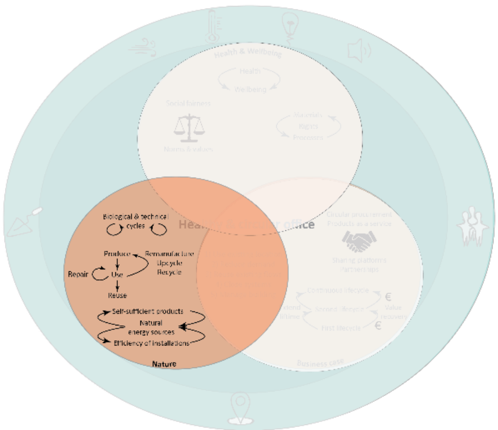


Figure 99. Framework-nature.

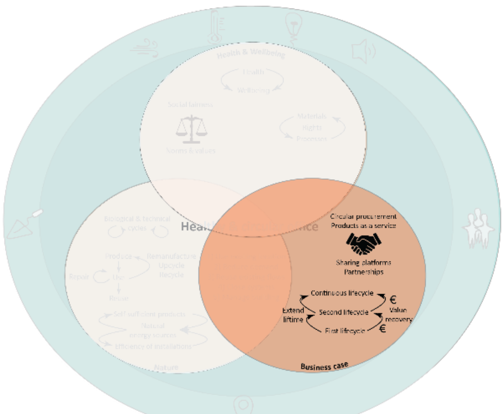


Figure 100. Framework-business case.

9.2.5 Business case

Every measure contain a business case, figure 100, explained in appendix 26. A proposed measure is to filter the air by plants and creating a higher ventilation system capacity. The company of the case study wants only fresh air and not to install and maintain these products and systems; the plant walls and the ventilation systems. Therefore, the producer keeps ownership and installs and provides *a service* for these products, while the consumer; the company of the case study, only pays for the service. Moreover, the investment needs to be updated including *recovery value and extended lifetime*. Furthermore, stimulating *partnerships* and using the same producers and suppliers. For the proposed measure filter the air by plants. The already existing plants are maintained by the company Ambius. Recommended is to give them the privilege to provide the plant wall as a service as well. In addition, renovating the pilot floors provides lessons learns of the process. These lessons can be shared on *sharing platforms*, mentioned in the framework, with companies via the website of the case study.

9.3 Materials and products improvements

9.3.1 Improvements

The analysis of the top five used products in the interior of the case study are described in chapter 7, figure 101. This information, the improvement per product, is validated with information from articles displayed in ScienceDirect or the Cradle to Cradle Certified Products Registry. The improvements per product are described in table 20.

1 Floor finish-carpet
2 Wall finish-felt wall
3 Space divider -panels
4 Workplace-desk
5 Workplace-chair

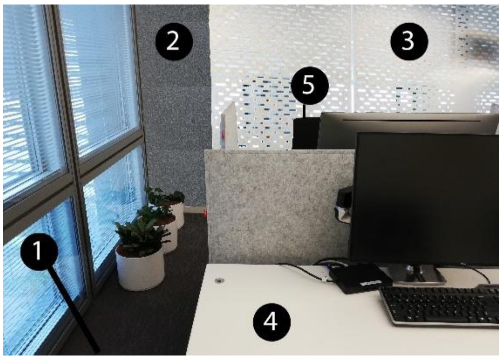


Figure 101. Interior materials case study.

Category	Circular				Indoor comfort	
	Raw materials & lifespan	Demountable or detachable	Remanu-facture	Recycle or upcycle	Influence factor health	Toxic gasses & cleaning
1 Improvements Floor finish carpet Wave-B754 (Desso)	Using mono-material from recycled or organic materials	Develop detachable connection method with glue that works like a screw	Reuses first layer and first backing layer within the process	First layer and first backing layer recyclable	Improving indoor air quality by filtering small particulates	Create product without VOCs
2 Improvements Wall finish felt wall 1001 Natural White (Viltex)	No improvement is needed on this specific point	Develop detachable connection method with glue that works like a screw	No improvements are needed on this specific point	No improvement is needed on this specific point	Improving indoor air quality by filter air and thermal comfort by mass	No improvement is needed on this specific point
3 Improvements Space divider panels In-Felt Wave (In Zee)	Use recycled material add value to sustainability	No improvement is needed on this specific point	Reuse felt panels in manufacture process	Begin able to recycle felt panels to PET	Improve visual comfort by variation of holes	More info about colouring process
4 Improvements Workplace desk TMNL Dual workstation (Gispen)	Identify which recycled materials are used for every product	No improvement is needed on this specific point	No improvement is needed on this specific point	Begin able to recycle the 24% waste	Improving visual quality by using the colour without glare	Required more information
5 Improvements Workplace chair Futu NPR (HAG)	Identify raw materials and its origination	Identify components, make them demountable	No improvement is needed on this specific point	Required more information	No improvement is needed on this specific point	Identify raw materials and its toxicity

Table 20. Improvements existing interior material analysis.
(Adjusted from Arc edition, n.d; Cradle to Cradle, 2019; Desso, n.d.; Gispen, n.d.; Health2work, n.d.; In Zee, n.d.; Przybylek, n.d.; ScienceDirect A., n.d.; ScienceDirect B., n.d. & Vilton, n.d.)

This analysis shows how the interior products can improve the meet the circularity and indoor comfort criteria described in chapter 5.

Firstly, the floor finish carpet Wave is a product whereby the second backing layer can be recycled. The other layers of the carpet are difficult to reuse, which means that the raw materials and attachment method need to change in order to recycle or reuse every layer and material of this product. Recommended is to use a product whereby all layer are detachable and can be reused.

Secondly, the wall finish felt wall is a already a very circular product. A mono raw material wool is used, the product is fully recyclable and the raw material can be reused. Only the connection method of the product is difficult to demount. Recommended is to connect the felt to the wall with temporary detachable connection system, like tape.

Thirdly, the space divider panels In-Felt is partly a circular product. The product is made from recycled PET bottles, which is a recycled not sustainable raw material. The supplier produces its products with a raw material which is not endlessly in stock. In addition, the raw material is circular only the producer is not taking the product back to its production process. The reason is unknown and not described on their website. Recommended is to produce a product with infinite raw materials and which can be recycled and reused.

Fourthly, the workplace desk TMNL Dual workstation is demountable and made from recycled products. Limited information was available about which raw recycled materials is used, therefor the influence on the human health is unsure.

Lastly, the workplace chair Futu NPR consist of many components. The raw materials which are used and the connection methods could not be found. His makes it complicated to analyse this product, only the producer provides 'long service life'. Which means that the component can be demountable, only the reusability or recyclability is unknown.

These improvements are described in products in the next subchapter or have not yet been invented. The case study uses partly circular products within their interior. They can play a role by asking questions and improvements to their suppliers products and processes. This is an ongoing process, whereby the market is constantly changing.

9.3.2 Innovations

Innovations are time specific and need to suit the materials and products, which are needed for the building users or the building itself. This needs to be analysed case by case and depends on several factors. Innovations are for example, Cradle to Cradle certificated products and reused or recycled materials and using demountable connections. A division has been made into products that are recommended for the renovation at the moment 'proposed measures case study' and products that are recommended after the lifecycle of the existing products 'proposed measures after end-of-life existing products'

Proposed measures case study

Ceiling	Mushroom Material ceiling acoustic panel. It transforms agricultural waste with mushrooms roots to look alike plastic foams, only biobased. After 7 days growing, the product can dry and keeps its form. In the garden compostable; Cradle to Cradle gold (Paradis Packaging company, n.d.). This process is a root-like structure, named as mycelium, whereby the raw materials can be grown or searched locally. The growing process depends on the 'biological algorithm' of mushroom roots. The method is developed by Eben Bayer and Gavin McIntyre as Ecovative in 2007 to create compostable packaging material. By using this method the ceiling plates made from mycelium and agricultural waste are compostable after its lifecycles (Geldermans, Tenpierik & Luscuere, 2019; Archdaily, 2014 & Kim & Ruedy, 2019).
Floor finish	DSM Niaga production method creates mono-material polyester carpet which is fully recyclable. The adhesive between the layers can be decoupled on demand, it works like a screw. The first production process is bonding the surface fibers to the primary backing by using heat and pressure. The next production process is bonding this layer with the surfaced fibers and the primary backing to the second backing by using the Niaga adhesive technology, which is not public available. This carpet is made without

latex, therefore the air can flow better through the carpet, because of this with an vacuum cleaner more surfaces can be reached than by a traditional carpet, which is denser because of the latex bonding. Another added benefit of a non-latex bonding is a free volatile organic compounds adhesive (VOCs), whereby the carpet from installation no VOCs releases (Niaga, n.d.).

Wall finish — Clay plaster is a natural products mixed from clays and sand. This material is non-toxic, durable and recyclable. This wall finish moderates humidity by absorbing and release moisture from the air, this amount depends on the relative humidity and the temperature (Cascione, Lim, Maskell, Shea & Walker, 2019). In addition, it contributes to the indoor air quality by not releasing any VOCs, no addition binders are added and sound absorption by the mass. Clays is an available raw material from the earth and contains a low environmental impact. Moreover, the production process use little amount of energy (Construct, n.d.).

Proposed measures after end-of-life existing products

Ceiling — Honext ceiling plates from cellulose waste, without releasing any VOCs. The plates contains sound insulation, the higher the thickness the higher the sound insulation and thermal insulation depends on the density of the plates. Cradle to Cradle silver (Honext, n.d.). The cellulose fibers forms the main component of plants. This fiber can be obtained from natural plant sources like, wood pulp, cotton or hemp (RIVM, 2012).

Wall finish — Ecolith interior natural lime-based paints; the raw materials off these paints are gain form plants and fruit, where only the natural cycle of materials are used. They use the cellulose of the stems, the leaves delivers colours and the protein, fragrances and resins from fruit. Cradle to Cradle gold (Auro, n.d.).

Furniture — A 2020 Desk chair is adjustable height, is modular, recyclable and produced with renewable energy. The desk chair belongs to furniture as a service, they are reselling it or disassemble the desk chair and reuse raw materials; Cradle to Cradle silver (Ahrend A, n.d.).

Furniture — Desk Balance Lift working standing or sitting, the movement bottom is easy to handle and works without energy; gas spring. Including acoustic plates under the desk for sound absorption; Cradle to Cradle silver (Ahrend B, n.d.).

9.3.3 Conclusion

The aim of this research is to identify the interior products and how these products can be inproved both circular and the effects on the human health. The analysed products are: Desso carpet, Viltex felt wall, In Felt panels, Gispen desk and HAG chair. These products contribute to the human health and contains a certain level of circularity. Recommended is to improve, with a specific product, more indoor comfort stressors. In addition, redesign some of the products, so that they contain only biological or technical cycles and that it can be demountable, recyclable or remanufactured to be able to reuse it.

The material and product innovations are very broad. As it has been noticed that more and more companies develop products which are good for the environment including negative carbon footprint and better for the human health without any toxic gasses or VOCs. DSM Niaga is one of the most developed products, whereby the product, the production and remanufacture process are circular. These materials and innovations will be used in the Chapter 9.4.

9.4 Case study measures

The case study measures are categorized in possible stressors; indoor air quality, thermal comfort, light and visual quality and acoustic comfort. Furthermore, the floorplan lay-out and improved processes. These measures are illustrated in a sketch of the section of the current case study situation, illustrated in figure 102 till figure 109. Next to the sketches, the measures are explained how they can improve the indoor comfort in a circular way, while taking the energy consumption into account. In addition, nearly every possible stressor contains a principle sketch of how the systems are connected to each other and the existing case study situation.

The following steps 'Circular Indoor Comfort Step Strategy', adjusted from the circular 'New Stepped Strategy' according to Geldermans (2016), are used to describe the strategies per measure for the case study:

1) Improving the source
2) Improving situation without energy
3) Improving situation with renewable energy
4) Improving processes

9.4.1 Case study sketch with measures

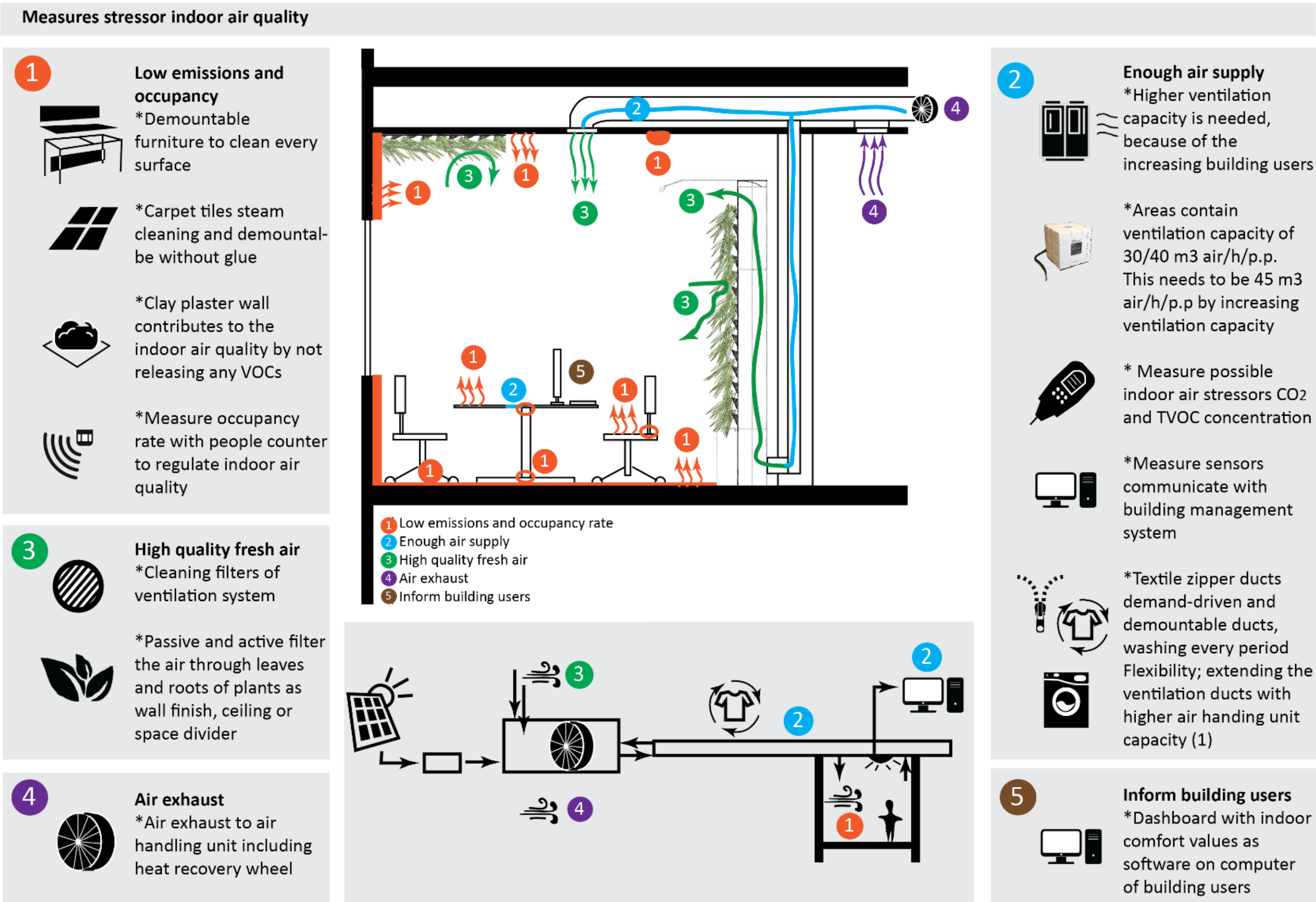


Figure 102. Measures indoor air quality ((1) BTLluchttechniek, n.d.).

Living plant wall

Plant purifying capacity
*CO2
*TVOC

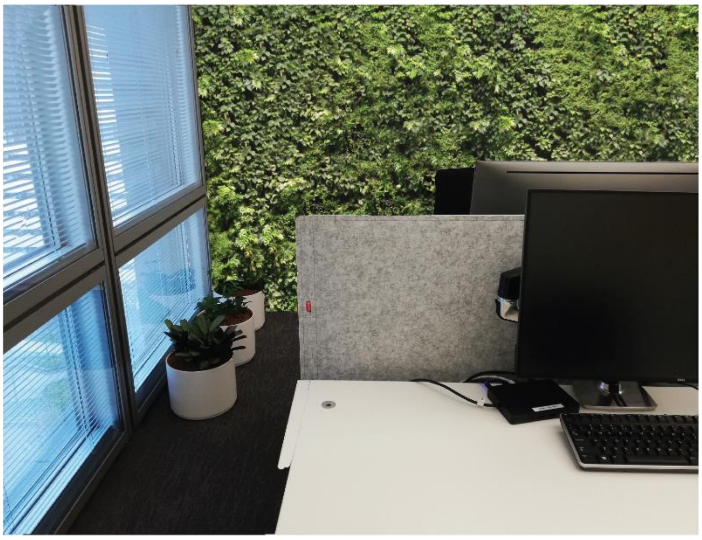
Asorbed by leaves, filtered through roots

Measured -> reduction CO_2 concentration in smaller size rooms

Characteristics leaves
Larger leaves, higher CO_2 absorption capacity & mute the sound better (1)

Productivity
Higher view on green, lower sick leave
An average of 1,6 fewer sick days per employee per year (1)

Building users were enthusiastic about the plant experiment



Relative humidity
Average 5% higher relative humdity, up to 17% during the winter (1)
Measured -> slightly higher relative humdity in smaller size rooms

Circularity
Biobased, without toxic gasses; after lifecycle function as compost

Service and maintenance provided by the producer

Combination
Ventilation installation brings down average pollution concentration

Plants absorp peak pollution concentration

Measured -> lower peaks CO_2 concentration in smaller size rooms

Sound level reduction
Plant absorbs sound and reduces reverberation time (1)

Substrates positively affect the speech area of humans (1)

Measured -> lower average sound level in smaller size rooms

Cost and flows (2)
Investment ± €1250/m2
Maintenance ± €195/m2

Energy and water flows

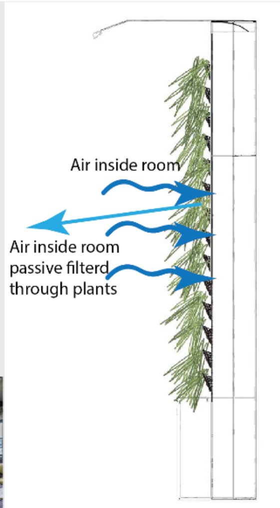
Figure 103. Living plant wall ((1) Starmans, 2020 & (2) Ambius, 2020).

Living plant wall systems and plants spieces

Passive living green wall system
The leaves and roots absorb VOCs and other substances and convert CO_2 to O_2. (1)

Advantages
* low maintainance system

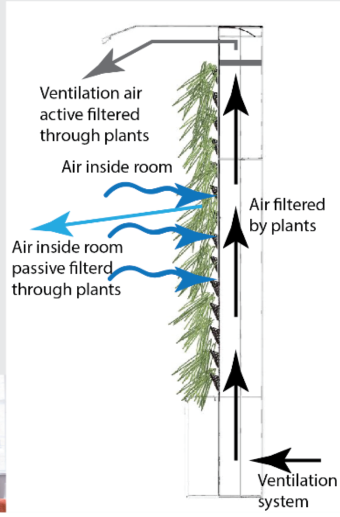
Disadvantages
* Mostly not modular system, difficult to dissasamble and uses more materials



Active living green wall system
Ventilation system is connected to the active living wall system.
The air supply will be filterd by the plants before entering the room.
In addition, the leaves and roots absorb VOCs and other substances and convert CO_2 to O_2. (2)

Advantages
* Higher CO_2 and other substances reduction

Disadvantages
* Uses more energy



Plant species

									
Plant type	Silver Queen	Scindapsus Aureus	Chlorophytum Comosum	Hemigraphis alternata	Aglaonema	Sansevieria trifasciata	Spathiphyllum hybride	Dracaena deremensis	Hedera helix
Absorbs substances (3)	Nicotine and formaldehyde	Methanal, benzene, ethylene	Harmful gases	Benzene, toluene, octane, trichloroethylene terpene	Ammonia and formaldehyde	Benzene, toluene, Xylene	VOCs	Benzene, toluene, Xylene	Benzene, toluene, octane, trichloroethylene, terpene and formaldehyde

Figure 104. Living plant wall systems and plant types ((1) Ambius, n.d.; (2) NAAVA, n.d. & (3) Aihong, 2019).

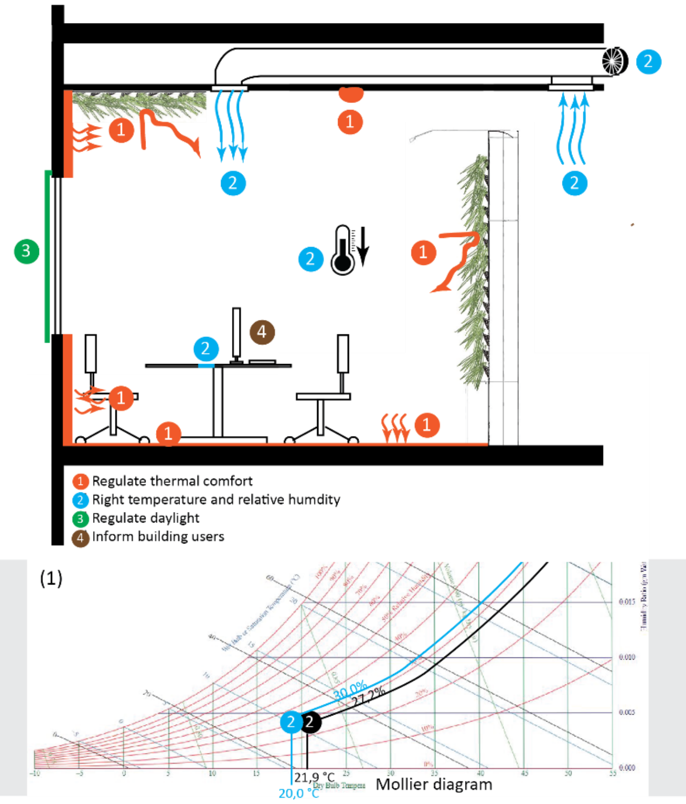
Measures stressor thermal comfort

1

Regulate thermal comfort
*Clay plaster wall moderates humidity by absorbing and release moisture from the air, it depends on temperature and relative humdity

* The plants regulate the relative humdity through the leaves and roots
The plants are function-ing as wall finish, ceiling or space divider

*Measure occupancy rate with people counter to regulate the thermal comfort



2

Right temperature and relative humdity
* Measure possible thermal stressors temperature and relative humdity level

*Measure sensors communicate with building management system

*Lowering temperature to increase the relative humdity.

*Engineer humidification system in the air handling unit

3

Regulate daylight
*Automatic sun-responsive solar shading and manually controllable

4

Inform building users
*Dashboard with indoor comfort values as software on computer of building users

Figure 105. Measures thermal comfort ((1) Hanna, 2010).

Measures stressor light quality

1

Renewable and efficient energy use
* Renewable energy generated with solar panels on the roof

*LED light react on movements and daylight level, existing situation 8W/m2 to renovated situation 5W/m2

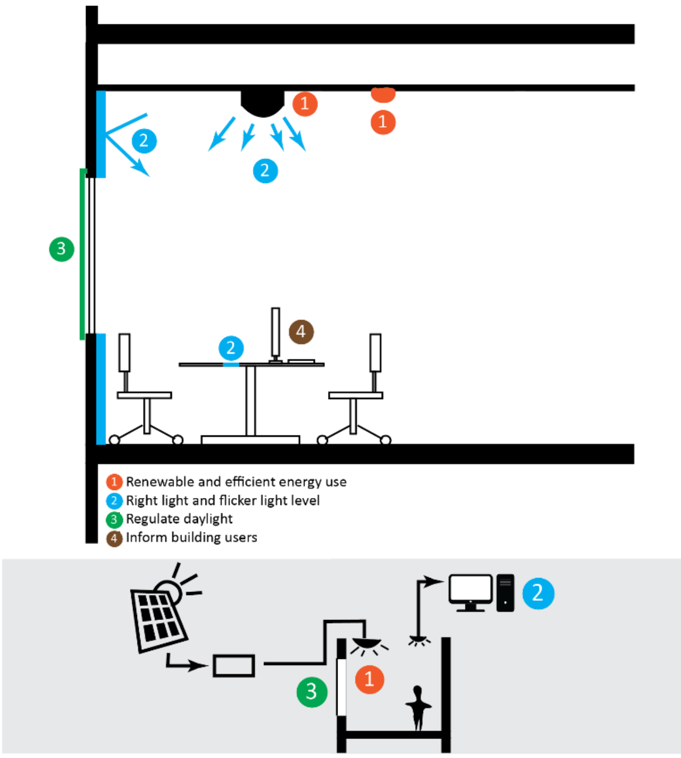
*Measure occupancy rate with people counter to regulate the light

3

Regulate daylight
*Automatic sun-responsive solar shading and manually controllable

4

Inform building users
*Dashboard with indoor comfort values as software on computer of building users



2

Right light and flicker light level
*LED light with minimal capacity of 500 lux

*Clay plaster wall decreases glare

* Measure possible light stressor light and flicker light level

*Measure sensors communicate with building management system

Figure 106. Measures light and visual quality.

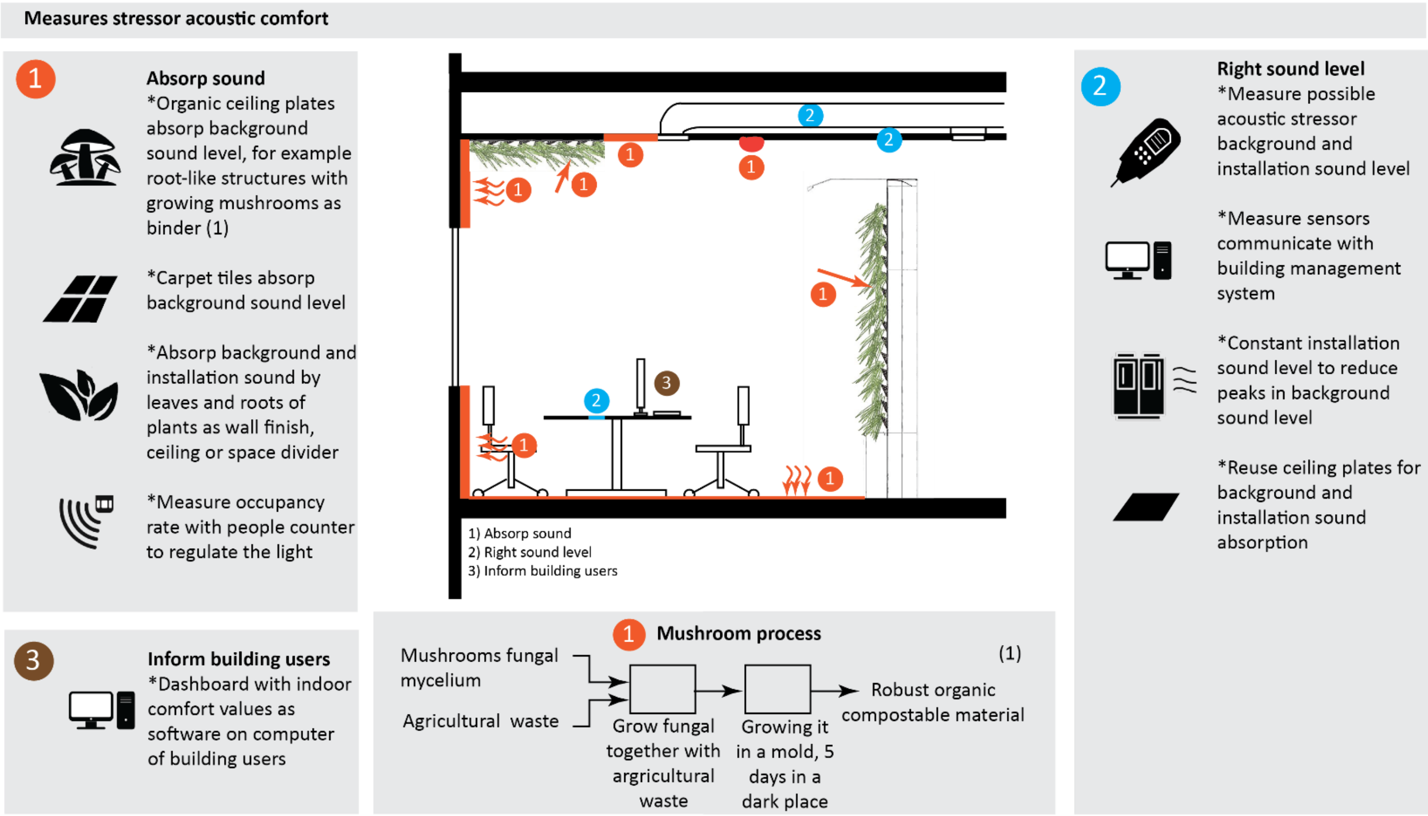


Figure 107. Measures acoustic comfort ((1) Kim, & Ruedy, 2019).

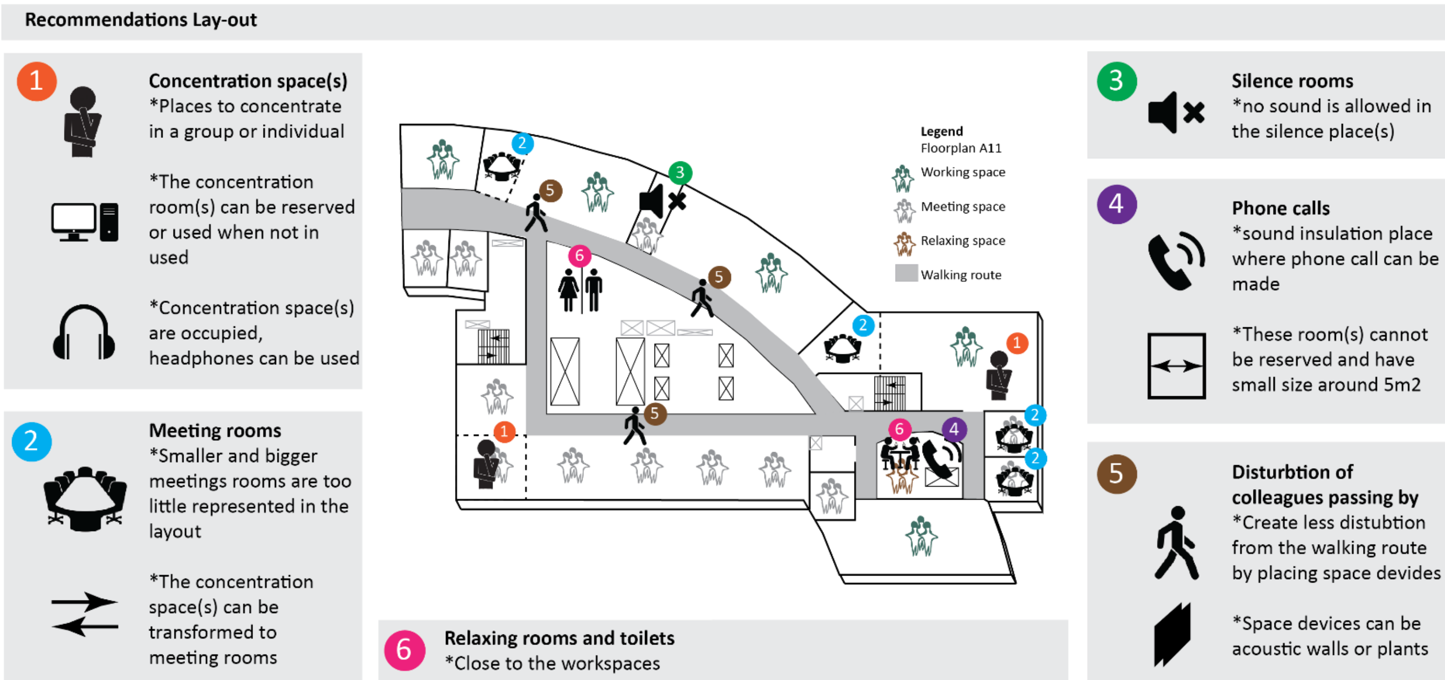


Figure 108. Measures floorplan lay-out.

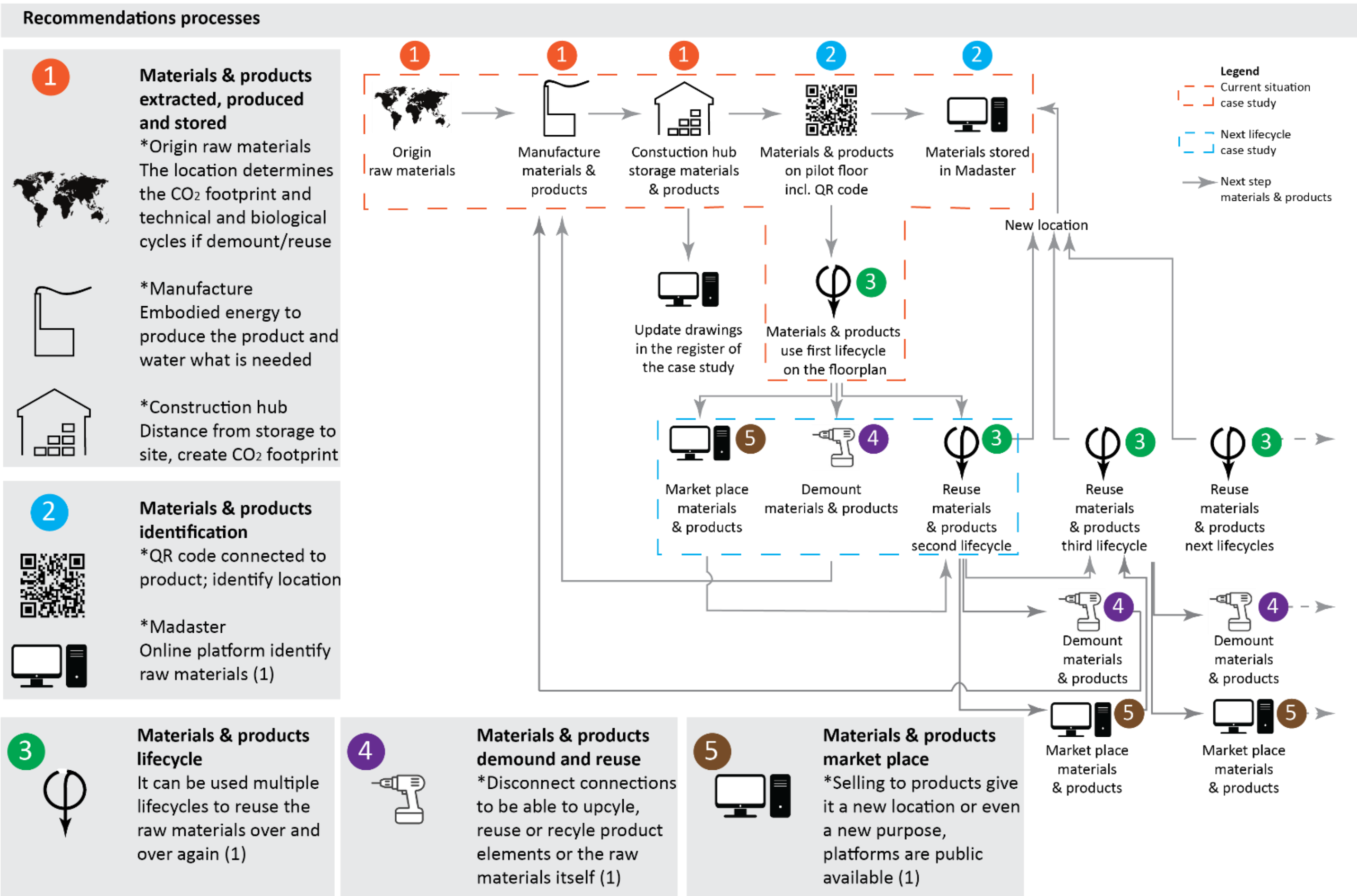


Figure 109. Improvements material processes ((1) Rau & Oberhuber, 2016).

9.4.1 Case study measures

The measures proposed and explained in the case study sketches chapter 9.3 are listed below and illustrated in chapter 9.5 in the floorplan A11 design of the case study. Th measures contain a category and name, belong to one of the steps from the 'Circular Indoor Comfort Step Strategy' and the measure is described in the table 21 below.

Category and name measure	Steps 'Circular Indoor Comfort Step Strategy'	Description measure
Stressor sensors	1) Improve source	Adding sensor on the desks of the building users. Sensors are measuring; indoor air quality (CO_2 and TVOC concentration) thermal comfort (temperature and relative humidity level), light (light level and flicker light level) and acoustic comfort (background sound level and installation sound level).
People counter sensor	1) Improve source	The people counter sensors are placed on the ceiling. When there are too many people in the area, the sensor warns the building users when the climate system cannot provide a healthy environment. A notification will be given to the buildings users and the facility managers as well.
Demountable furniture	2) Improve situation without energy	Furniture can be demountable with an easy movement. The materials are low-emission materials, which do not included VOCs.
Clay wall finish	2) Improve situation without energy	The clay wall finish regulates the relative humidity and the mass functions as sound absorption.
Natural plant wall	1) Improve source	Natural plant wall finish purifies the air, adding water vapor and absorbing sound.
Natural plant space divider	1) Improve source	Space divider which takes care of meeting areas or concentration areas, purifies the air, adding water vapor and absorbing sound.
Textile ventilation ducts	3) Improve situation with renewable energy	Textile ventilation ducts are connected with zippers to adjust or demount the ventilation duct. The textile ducts can be washed every period to clean the ducts from small particulates or dust. Every area contain their own exhaust and the system is demand-driven. The ventilation capacity is above the needed capacity, because if the function changes the ventilation capacity can be adjusted fast. The ventilation is demand-driven and differs per area and occupancy rate.
Building management system	1) Improve source	The building management system gets information form the stressors sensors and the people counter sensors. This system is managed by the technical managers and regulates the indoor climate. The indoor climate can be regulated on the basis of occupancy rate. To provide the highest possible indoor comfort and save energy on the days when the installation is less needed.
Smaller size rooms	1) Improve source	Creating smaller size rooms on the floorplans to be able to have a phone call and create a concentration and silence areas. Normally every area can be thermally adjusted, creating smaller areas each can be thermally controlled to the preferences of the building users.
Cleaning ventilation filters	1) Improve source	Filters that clean the ventilation system automatic.
Plant decoration	2) Improve situation without energy	Planters as decoration, air purifying, adding water vapor and absorbing sound.

Sun shading system	3) Improve situation with renewable energy	Automatic sun shading system which reacts on daylight (lux level), energy use (kWh/m^2) and indoor comfort (light and temperature level). It can be controlled manually by the building users as well. Among other things, this measure takes care of overheating of the building and minimalize the sun radiation when needed.
Demountable carpet tiles	1) Improve source	Carpet tiles connected with double sided tape. Therefore the carpet tiles can be removed and be deep steam cleaned every period. DSM Niaga invented an production method with only pressure and heating, whereby all layer are demountable and every individual raw material can be reused in the same production.
Printer room	1) Improve source	Printers in a separate room on the floorplan with a ventilation system.
Dashboard software about indoor comfort values	1) Improve source	Inform the building users about the real-time indoor comfort, measured with stressor and people counter sensors via a software program on their computers.
Humidification system + heat wheel to ventilation system	3) Improve situation with renewable energy	Add water vapor to the air.
Constant installation sound level	1) Improve source	Stabilize the installation sound level, to reduce the various sound levels produced by the building users.
Lower temperature	1) Improve source	Lower the temperature when it is possible (not lower than 20°C) to save energy and the relative humidity react and goes higher. Heating only with low temperature heating 50°C - 30°C. Repair and use the heat cold storage for heating and cooling next to the district heating and cooling and cooling towers.
Renew light bulbs with sensors	3) Improve situation with renewable energy	Renew the light bulbs with an energy efficiency light bulb with a capacity of 500 lux. The desks area minimal of 500 lux and corridor area minimal of 50 lux. Light bulb are reaction on daylight and movements of the building users.
Reused waste	4) Improve processes	Give the waste, that is already separated on the floorplans, an identity and sell the waste on 'Excess Material Exchange' platform, which is a marked place for raw materials.
Reuse ceiling plates	2) Improve situation without energy	Wash and clean the ceiling plates and reuse them.
Biological ceiling based on mycelium growth	2) Improve situation without energy	Replacing the damaged ceiling plates with plates created with mycelium and agricultural waste.
Material passport	4) Improve processes	Give identity to materials and products.
Update drawings in system	4) Improve processes	Asset management, keeping the drawing up to date in the case study systems, with the company People Power.

Table 21. Case study measures.

9.5 Case study floorplan

The existing floorplan A11 lay-out is illustrated in figure 110. In addition, the proposed measures explained in chapter 9.4 are added to the floorplan A11 lay-out and illustrated in figure 111. These visible measures, on the floorplan, are mostly, interior aspects which improve the building users activities. Moreover, the technical aspects, which improve the indoor stressors, are less visible on the floorplan. These technical aspects, which are not visible on the floorplan, are: installation capacities and installation systems, processes, reuse of materials and products, information dashboard for buildings users and building management system for technical managers including the sensors on the floorplans. Every measure contributes to environment and half of the measures use only embodied energy during its lifecycle.

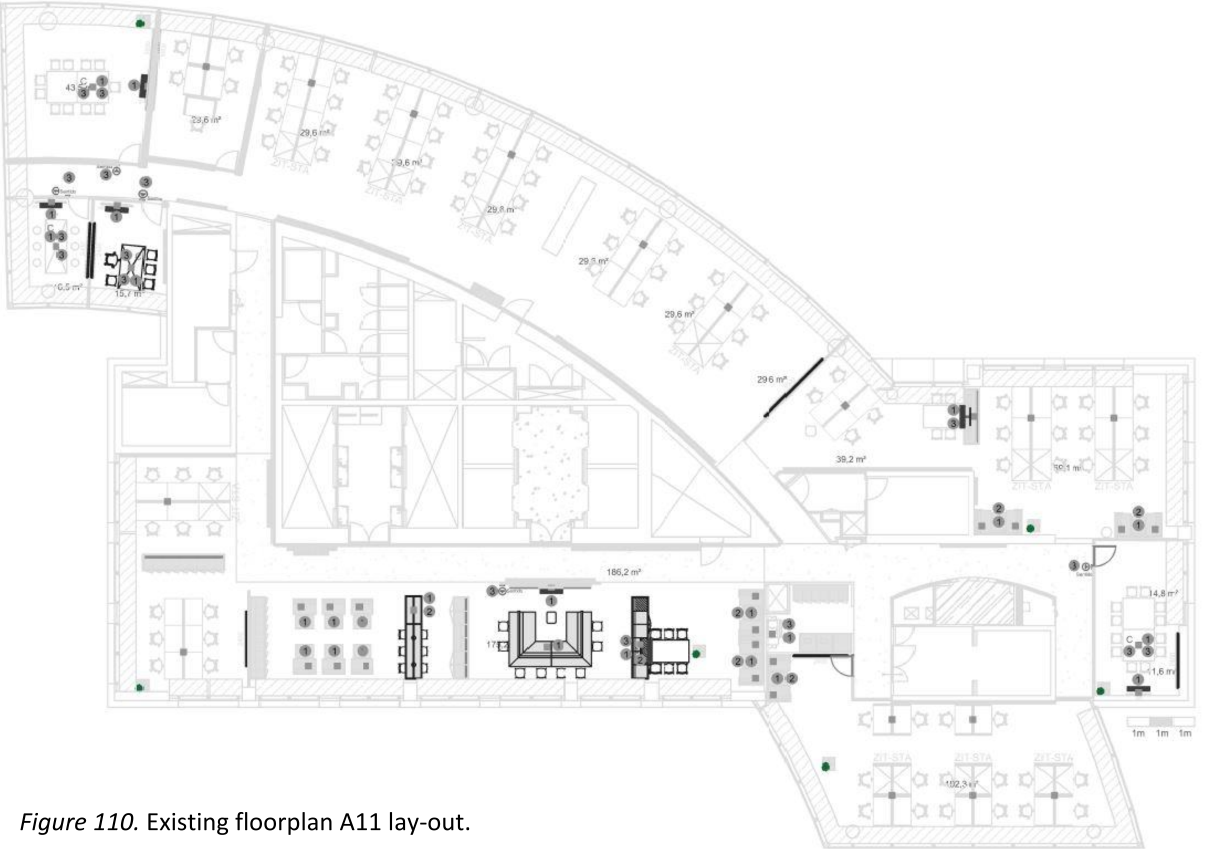


Figure 110. Existing floorplan A11 lay-out.

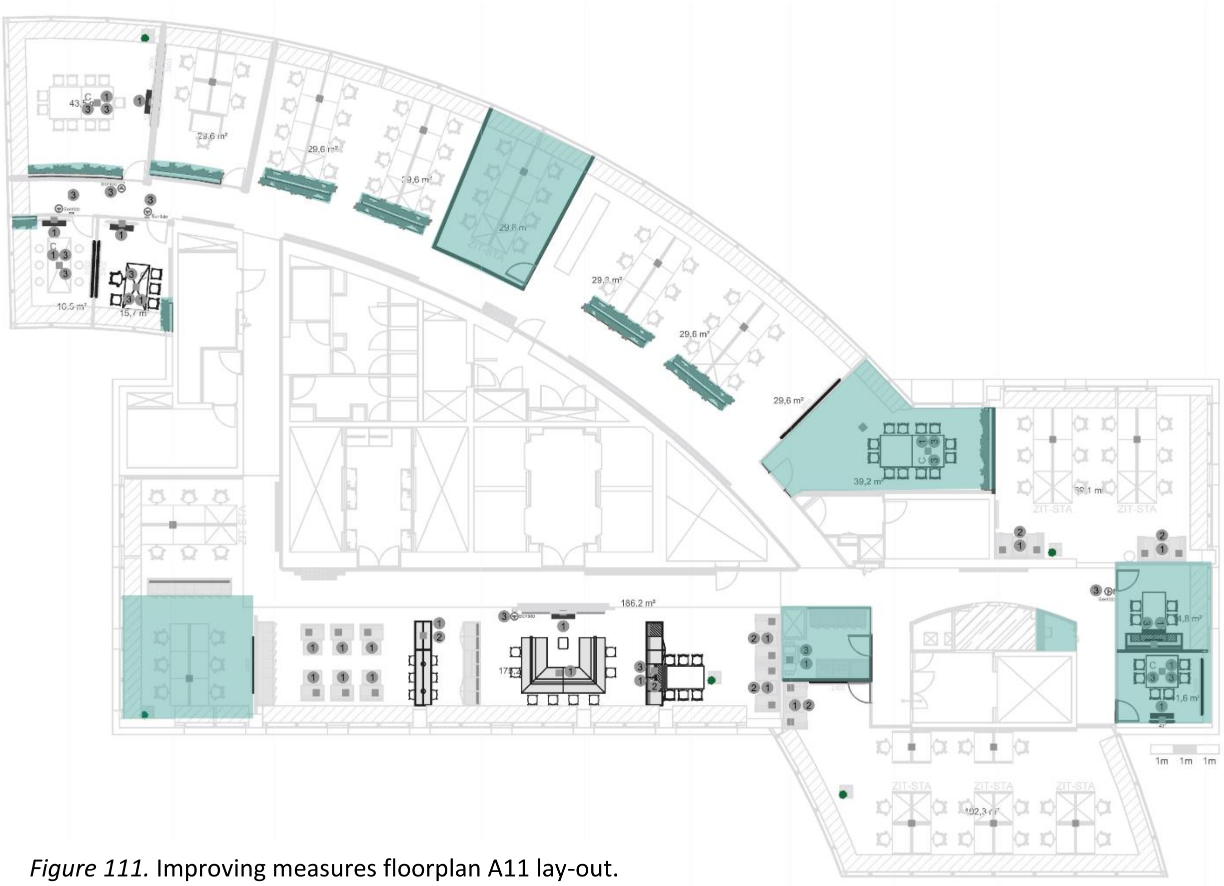


Figure 111. Improving measures floorplan A11 lay-out.

9.6 Conclusion

Various measures are recommended to renovate the case study to achieve a higher indoor comfort satisfaction by the building users, while using a circular approach and limit the amount of energy use. The proposed measures for the case study, the pilot floorplan lay-out A11, are illustrated in figure 85 below. In conclusion, nearly all measures, which are illustrated, improve multiple or all possible indoor comfort stressors, whereby the lay-out and material processes are connected to these proposed measures. The measures are developed with the framework and following the created 'Circular Indoor Comfort Step Strategy' by firstly improving the sources. Secondly, improving the situation without energy. Thirdly, improving the situation with renewable energy and lastly, improving the processes to optimise the identification of the used materials to improve the case study. The lay-out measures can be realised by renovating the possible stressors, illustrated with categorized A till E measures in figure 112.

The challenges analysed during the materials, survey, measurement are approached with a technical view to renovated the floorplan with the aim to not exceed the permitted values during office hours. The social aspect of these measures are covered by notifying the technical managers and building users with a building management software on the their computers. This shows the real time indoor comfort values, which can positive influence their physical, psychosocial and physiological state. Financially, the measures are feasible with an circular procurement approach, whereby the products are procured with the following business model 'Product as service', where the producer is responsible for the maintenance and reuse or recycling after its first lifecycle at the case study. For example, the green wall cost around ± €1250/m^2 investment costs and ± €195/m^2 maintenance costs per year and a green space divider cost around ± €2160/m^2 investment costs and ± €285/m^2 maintenance costs per year. Due to the different costs, it is important to specify the purpose of the products and what is needed to achieve the highest satisfaction level of the building users with a positive contribution to the environment.

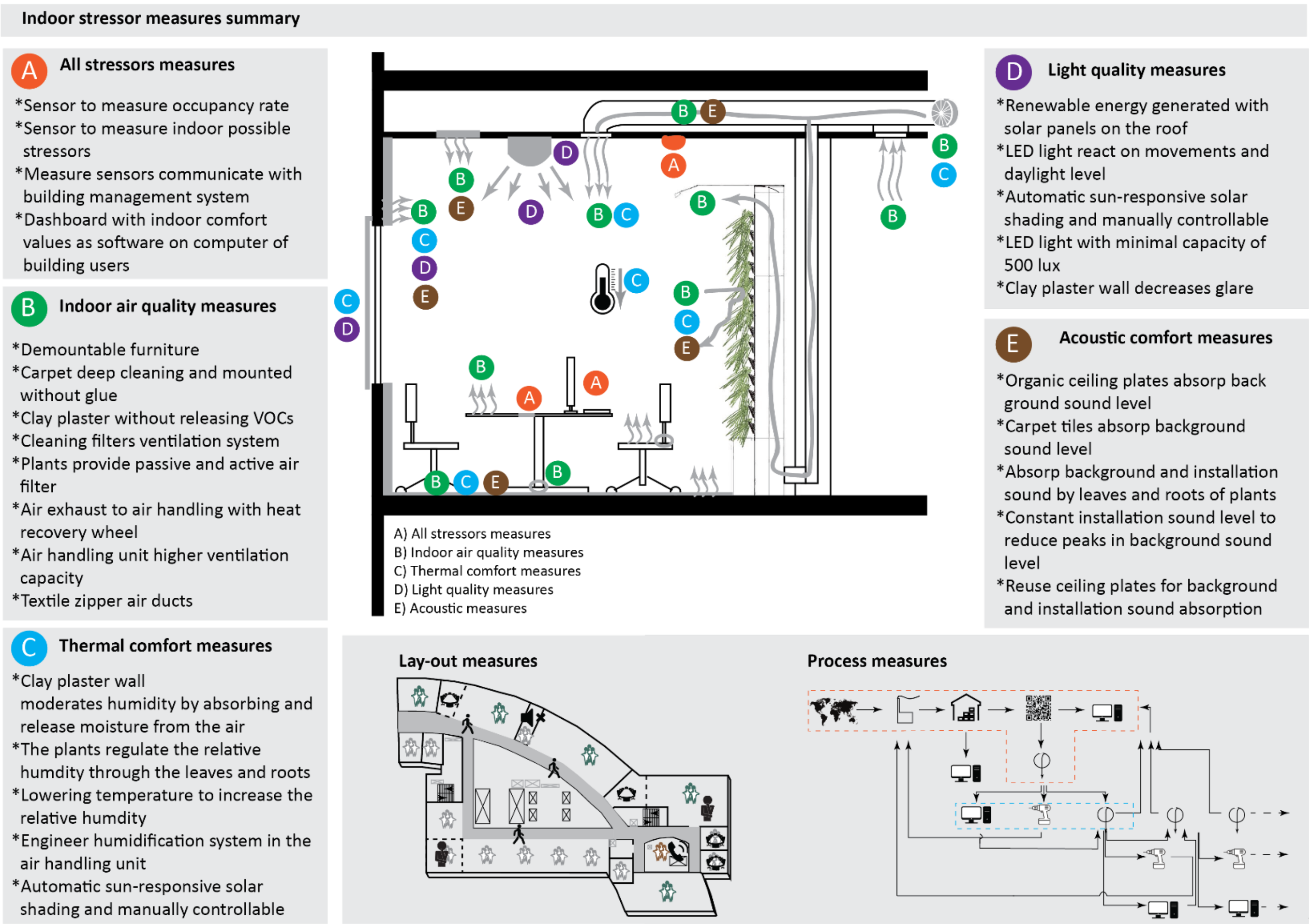


Figure 112. Conclusion measures indoor comfort.

Chapter 10. Discussion

Literature study

The study mentioned the Sustainable Development Goals, these goals were difficult to compare and connect with the literature, because the goals are very broad and can be interpreted in various ways. In addition, the reference projects are chosen from a broad range of reference projects, only one per chapter is analysed, to implement the learning lessons in the criteria. Future research about this topic, can include multiple reference projects for every chapter to be able to compare the various implementations of those projects.

The literature study containing the indoor comfort, was mostly about the four possible stressors: indoor air quality, thermal comfort, visual and light quality and acoustic comfort. Other factors are mentioned, only minimal taken into account by creating the criteria and measures. Furthermore, this study was focused on the indoor air quality. However, the other three stressors were mentioned as well, because the literature showed that they are interconnected. It is recommended to perform future research to find specific information about those three other stressors.

The requirements are extracted from Bouwbesluit 2012; consulted in 2019, BREEAM, WELL, TNO and WHO. Other requirements or rating systems are considered, but they are comparable with the criteria mentioned from the sources above. For example, the LEED certification system contains several elements which are mentioned in BREEAM as well. Recommended is to analyse more requirements from other countries and ratings systems to provide even a bigger overview of criteria.

The literature study about circularity contains mostly requirements focused on the Cradle to Cradle principle. The criteria from other sources are taken into account by adding those criteria to the existing Cradle to Cradle principle.

Methodology

The survey was performed by the company Leesman in 2019, the way how this survey is executed was not included in the scope of this research and therefore could not be adjusted anymore. In addition, some measurement devices from the TU Delft were not available. Therefore, other measurement divides were searched and procured, whereby the small particles, flow finder and air velocity could not be measured during this research. This limits the amount of data of the indoor air quality.

Moreover, the data was collected from only one brand of measurement devices, the GreenMe cubes. The accuracy of the GreenMe cubes, different per stressor, was the least for the acoustic with a difference of plus or minus 3 dB. Next to that, the location of the measurement devices was based on a division between open and closed office space. This division was also based on the available space within the case study and on which department floor it was allowed to place the measurement devices.

The plants purifying capacity were calculated and resulted in procuring 48 new plants and removing the 34 existing plants. On location, it was not possible to remove all 34 plants. The calculation was performed again and even with 48 plants, a clear difference between the measured rooms must be seen. A recommendation is to take, for next time, the existing situation more into account and the possibilities within a large organisation.

Materials

The material analysis is studied by using various sources, like information from suppliers, databases and internal documents of the case study. In addition, the information about the products was limited and therefore assumptions were made. These assumptions stem from the interpretation of existing data. Only five interior elements are analysed, due to time limits. For future research, it is recommended to analyse the entire interior of the case study and not only the most common interior elements. In addition, the criteria were an indication without numbers, this made it more difficult to compare the various products. This subject is very broad, the scope of this research was to analyses only the materials which can improve the indoor comfort. Other materials, which are for example demountable can increase the value of the building as well. Following research can be done on the performance of materials, which do not influence the indoor comfort but are circular.

Survey

The survey performed from 11th September till 27th September 2019, got a responds rate of 21%. The bank was pleasantly surprised with these numbers, because with a population of 6184 people and 1311 respondents with confidence level of 95%, the margin of error is only 2,40%. The smaller the margin of error, the more reliable the results. Some of the respondents did not answer all questions, which were asked in the questionnaire. Those respondents are eliminated from the results, to increase the reliability and comparability of the results. This means that the respondents rate is even a little bit lower than showed in the margin error of 2,40%. The survey is performed in a specific season, which can influence the answers of the respondents. The answers are more valid when the questionnaire is done in all four seasons and during the same time when the measurements are taken.

In my opinion, some questions were missing in the questionnaire, for instance subcategory 'work location' working from home. The respondents could only chose various office locations. This does not represent the reality, because the bank stimulates to work from home. Some of the respondents who filled in to work from a certain office, are probably working from home as well. This could influence the analysis on this specific question, where not all possibilities were taken into account. In addition, there was no possibility to make any additional notes.

Measurements

The measurements are performed from 18th February till 9th March 2020. This timeframe varies unfortunately from the survey analysis. This analysis was already done before this research started. Another point to mention is that the measurements are only performed every ten minutes for three weeks long. It is more reliable when these values are measured every season in the year. At the moment, the conclusion is drawn from those three weeks of measurements. In addition, only one brand 'GreenMe' cubes are used to measure these results. However, the 24 measurement devices have been compared to each other.

Moreover, the measurements are performed in 24 different areas, every area has its own dimensions and occupancy rate. Nevertheless, the measurements are performed on the same days and a description per area is given next to the results. Next time it is important to calculate, in the areas where the plants are standing, the amount of water which is given to the plants. This information was needed to be able to calculate the water vapor and find variations in the relative humidity between areas with and without plants. In addition, the small particles and the air flow in the area can be measured when the measurement devices are less expensive and the results are more reliable.

Framework

The framework was created with the information gathered from the chapter above. The more research will be performed, the more accurate this framework will be. It is recommended to analyse more reference projects to make the framework even more realistic.

Floorplan design

The recommended measures cannot be copy past on every floorplan lay-out. These measures are recommended for the A11 floorplan and need to be adjusted when applying on the other floorplans. This needs to be adjusted due to the building users preferences and needs, various dimensions of areas, the occupancy rate and the activities of the buildings users on that specific floorplan.

In addition, limited information about the materials and costs of each measure was available. Therefore, this could only be described for a few recommended measures. If more time was available, the measures could be developed in-house, whereby the raw materials could be chosen by the Technology Refresh Program team of the case study, while taking into account the costs.

Chapter 11. Conclusion

This conclusion answers the following research question: ‘How can the indoor comfort be improved in a circular way, by creating an optimal floorplan including the interior and technical aspects for, the case study, one the pilot floors of the headquarter of a bank in the Netherlands, while taking the energy consumption into account?’.

Indoor comfort

The indoor comfort is influenced by many factors, which makes it difficult to determine what the problems are. In offices the outside conditions, indoor materials, indoor air quality, thermal comfort, light and visual quality and acoustic comfort influence the building users satisfaction level concluded from the survey and visualised in figure 113. According to the material analysis, the use of certain materials and connections can influence the indoor comfort stressors and therefor the building users satisfaction. In addition, materials can contain VOCs, which release short term emissions and long term emissions. This values can exceed the permitted values, especially during the first using phase. Therefore, stricter values, about the first using phase of the materials, need to be written down in legislations and producers need to test their own products if they meet these legislations.

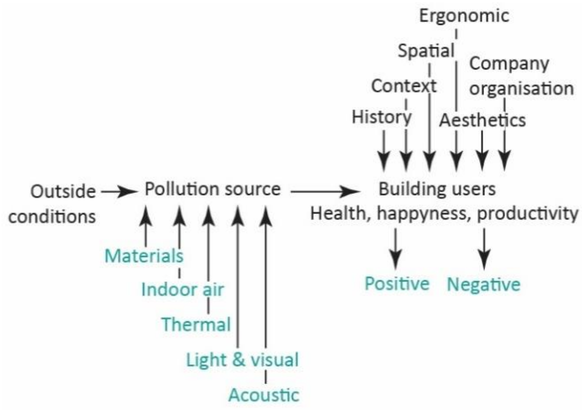


Figure 113. Indoor comfort approach.

In conclusion, to analyse the influence of materials and occupancy rate to the indoor comfort, the stressors need to be measured. Unfortunately, measurement devices are expensive and for small particulates hardly available or developed.

Circularity

A circular design includes different perspectives and consists of multiple processes. A design is not circular when only one process of the product is circular. In conclusion, most of the case study products are not meeting the criteria to be fully circular. This is hardly possible, because the market is in a transition from a linear to a circular production. The criteria when a product is circular is a conclusion from this research. A product is circular when the following criteria are met. The first criteria, the products and materials, which are applied during the renovation process, are extracted in a sustainable way, such as recycled or biological material which are locally available, whereby the characteristic of the raw materials are known. The second criteria, the processes on how these raw materials are processed and connected to each other to create the product plays an important role as well, to use as less as possible water and energy, while creating no waste. The third criteria, the way how it is connected on the floorplans of the case study, it needs to be demountable or detachable. Demountable means taking it apart by removing the connections and detachable means taking it away by removing the connection without leaving any traces at the location where the product was disassembled. The fourth criteria, includes the use of the product by the building users. If the product needs additional flows like energy and/or water or if it creates flows like waste and how the building users can be educated by using the product in a sustainable way. The fifth criteria, the reuse of the raw materials or product, by demount or detach the individual raw materials, remanufacture or upcycle elements of the product or reuse it as how the product was. This process is shown in figure 114 below.

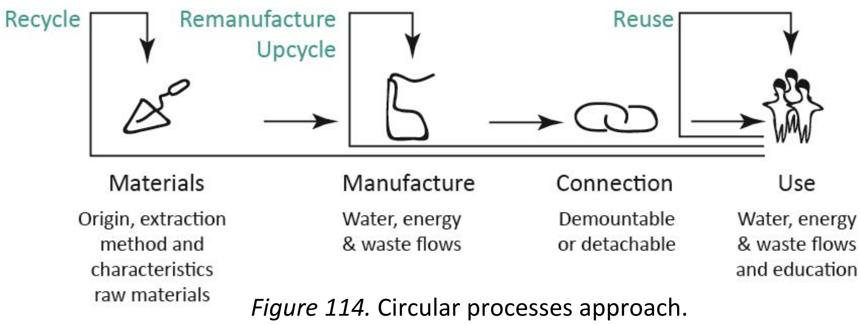


Figure 114. Circular processes approach.

Energy consumption

The energy consumption is based on the 'Paris Proof' ambition, including less than 50 kWh/m^2 energy use per year. This is a challenge because nearly every element on the floorplan design needs energy to be able to perform their function. Measures without using energy or using renewable energy are preferred. Therefore, the following 'Circular Indoor Comfort Step Strategy' based on the 'New Stepped Strategy' by Van den Dobbelsteen (2008) and the circular approach of the 'New Stepped Strategy' by Geldermans (2016) is used to develop the recommended measures on the floorplan. In conclusion, following this strategy, the recommended measures will use none or as little as possible renewable energy. The 'Circular Indoor Comfort Step Strategy' is as follows and is used to form the proposed measures:

1) Improving the source
2) Improving situation without energy
3) Improving situation with renewable energy
4) Improving processes

The pilot floor

The renovation proposed for the pilot floor A11, which is located in the headquarter of a bank in the Netherlands, is desired. There are multiple reasons which support this statement. Firstly, the building users are doubled since the design is built and they are criticizing the indoor comfort. In addition, the building uses a large amount of energy on average 120 kWh/m^2 per year. Moreover, the building materials are more than 20 years old, therefore they are at the end of their first lifecycle.

In addition, the building users rated the indoor comfort as lowest compared to all rated building facilities. This includes a satisfaction level of 20,5% with importance level of 75,6%. Furthermore, a large amount -21,6%- of measurement devices exceeded the permitted indoor comfort values during office hours. Along with the material analyses, whereby the products are mostly not sustainable raw materials, demountable or recyclable.

Therefore, various measures must be taken to meet the goals of the bank. Improving the indoor comfort to meet the headquarter office program of requirements and improve the satisfaction level of the building users. Moreover, lower the energy consumption from 120 kWh/m^2 energy use per year to the 'Paris Proof' agreement of 50 kWh/m^2 energy use per year.

Framework

The 'healthy and circular office' framework creates the first steps towards the renovation process. In conclusion, it broadens the possible measures which contribute to a healthier and circular office. It is a tool to start a renovation or a new construction process following the steps and elements.

Optimal floorplan including interior and technical aspects

The recommended measures are categorized in interior and technical aspects. Whereby the interior aspects improve the building users activities and the technical aspects improve multiple indoor comfort stressors. The proposed measures are aesthetics, circular without any environmental harmful additives and improve at least one indoor comfort stressor. In conclusion the following measures are proposed:

Firstly, improving the source: placing indoor stressors sensors and people counter sensors which are communicating with the building management system and dashboard software for the building users. In addition, placing natural plant walls, space dividers and ventilation filters. Moreover, creating smaller size rooms and placing the printers in a separate room. Furthermore, placing demountable carpet tiles, constant installation sound level and lowering the temperature when its above 24°C.

Secondly, improve the situation without energy by procuring only demountable furniture, placing clay wall finish layer and adding plant decoration. In addition, cleaning and reusing the existing ceiling plates and replacing the damaged ceiling plates with biological products based on mycelium growing agricultural waste.

Thirdly, improving the situation with renewable energy by placing textile ventilation ducts and sun shading system. In addition, engineering a humidification system and adding a heat wheel to the ventilation system. Moreover, replacing the existing light bulbs for LED light bulbs with sensors.

Lastly, improving processes to maintain the circular renovated situation by reusing the collected waste, identify every raw material in a material passport and asset management by updating the drawings in the system. These measures will improve the measured indoor stressors and the experience of the building users of the case study.

Circularity in combination with innovation and indoor comfort

This research showed that there is an increasing amount of studies showing that, the last few decades, the building environment is changing. In the case study this change is mostly focussed on circularity by reusing existing building products and adding building products which contain multiple lifecycles. This process could be supplemented with innovations to improve the circular way of thinking by creating optimal spaces for the building users, illustrated in figure 115.

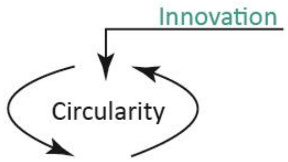


Figure 115. New way of thinking circular building process.

In addition, the additives to meet among other things the fire safety regulations are mostly not insightful for the consumer, this also applies to the products within the case study. These additives can make a difference on if the product is demountable or detachable, and if toxic gasses can be released. This determine whether a product is circular or not.

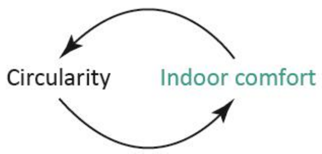


Figure 116. Benefits circularity and indoor comfort

In conclusion, the proposed measures are circular and improving the indoor comfort. This provides benefits for both the environment and the human health. When adding a plant wall system, the ventilation and humidification system can contain a smaller capacity. Because the plant wall filters the peak CO_2 concentration and add humidity to the air. This means that the indoor comfort will be improved by adding natural fresh air supply, absorb background sound level and increase the relative humidity level. In addition, the installation systems use less material, energy and space because the capacity is lower, which concludes a lower CO_2 footprint and a higher indoor comfort. Consequently, the proposed measures in this report contain multiple functions, both aesthetic, supporting the building users activities, improving the indoor comfort and users satisfaction and lowering the CO_2 footprint.

Chapter 12. Recommendations for the case study

The recommendations for the case study are adding criteria to the bank's program of requirements. Moreover, recommending renovation measures which are already applied in the design of the current floorplan renovation process or which will be applied in the design for the future floorplans. In addition, performing again the questionnaire and measurements to evaluate the recommended changes in the program of requirements and the renovation measures on the floorplans.

Program of requirements

The current program of requirements about the headquarters of the bank is very detailed and explains nearly every topic. After performing this research, it is recommended to add flicker light in the indoor comfort section. The flicker light is comfortable when the value is 0 hertz or above the 50 hertz. In addition, the indoor comfort requirements are not describing permitted exceedances. Some of these exceedances are added in the calculation when the requirement was drawn up, like the temperature. This value is calculated with the 'Adaptive Temperature Limits' method including the following parameters: the characteristics of the façade, clothes, occupancy rates, heating and cooling system and users control. These extensive calculations, with regard to exceedance, have not been performed for the indoor air, light and acoustic stressors. Therefore, it is recommend to add an exceedance for these indoor comfort values during office hours.

Design measures

During the last phase of this research, a contribution was made to various Technology Refresh Program teams of the bank to improve the floorplan design. Recommendations and meetings have been held with the mechanical team about the humidifier installation, which appeared to be necessary from the measurement results. In addition, the plants measurements results show that they contribute to the carbon dioxide concentration, the relative humidity level and the background sound level. This is discussed with the mechanical team, the interior team and the producer of the plants how we can potentially integrate a green wall in this renovation process. Furthermore, materials which are described in this research, which can contribute to the indoor comfort, are considered by multiple teams within the Technology Refresh Program.

Moreover, this research recommends to add more sound absorbing materials, especially in the meeting rooms, where the survey contains multiple complaints about the background sound level and the measurements indicate high peaks in the background sound level. Together with this research, Peutz and the engineering team within the Technology Refresh Program are investigating solutions, based on this research, to apply in the renovation process.

Results from this research indicated that the light and temperature level is not comfortable. In consultation with the control Technology Refresh Program team the sun shading system is optimized to improve the indoor comfort and the energy use to meet the Paris Proof agreement.

In addition, new products can contain more emissions, the short term emission. The first weeks or months it can harm the health of the building users. It is recommended to measure the VOCs when applying new materials within the existing floorplan to ensure the safety of the building users. On average this product will meet the Dutch legislations, but may exceed these values during the first weeks/months.

Questionnaire and measurements

After completing the renovation of the first pilot floors of the case study, the questionnaire and measurements can be performed again. Preferably during the same period and in the same months when the measurements of this research were performed; mid-February and beginning of March.

Recommended is to add a few questions or answer options to the existing questionnaire, like adding answer option: working from home and at the end an open question how the building users experience the indoor comfort. In addition, the questionnaire gives a better overview when it is answered in every season. In order to identity the differences between the seasons.

Performing the measurements, it is suggested to place the measurement devices on exactly the same location as where they were placed in this research. To be able to compare the results with the new performed survey and measurements and the results of this research.

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