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Abstract:

As human-beings are increasingly spending most of their time within office environments, there is a strong need to reconnect them with nature, due to the health, well-being and productivity benefits proximity to nature can have. One of the ways to achieve it, is by integrating ornamental plants as decorative walls, which are commonly referred to as Indoor Living Green Walls (ILGW) within the field of architecture and design.

As this trend in interior design is still very new and developing, there are no proper lighting standards or guidelines as how to correctly illuminate surfaces with the modern LED light sources, such that human visual needs and plant growth requirements are met, while at the same time maximising the aesthetic appearance of the plants and the space overall. Therefore, in view of the context outlined above, the proposed research paper will take both an analytical and practical approach, with the objective of making an original contribution to the state of research in this field. The author's intention is to define the best strategy for creating complex lighting solutions that successfully integrate and balance human visual needs, plant growth conditions and aesthetics, taking into account a number of different parameters including: light intensity, direction, spectrum and correlated colour temperature (CCT).

This study has been supported by a comprehensive review of existing specialist literature across numerous disciplines, as well as discussions with LED luminaire manufacturers, an interview with ILGW expert, a series of lighting test measurements and photographic evaluation.

A NEW LIGHTING STRATEGY FOR INDOOR LIVING GREEN WALLS

Master Thesis

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Aalborg University Copenhagen

Faculty of Engineering and Science

Department of Architecture, Design, and Media Technology
Master of Science

Lighting Design
Master Thesis

A new lighting strategy for indoor living green walls (ILGW)-

How to combine a suitable artificial illumination for ornamental plant's growth with human visual comfort in office environment

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Abstract

As human-beings are increasingly spending most of their time within office environments, there is a strong need to reconnect them with nature, due to the health, well-being and productivity benefits proximity to nature can have. One of the ways to achieve it, is by integrating ornamental plants as decorative walls, which are commonly referred to as Indoor Living Green Walls (ILGW) within the field of architecture and design.

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Keywords: Indoor Living Green Wall (ILGW), LED Light for Plants, Human Centric Lighting (HCL), Visual Comfort in Office Environment, Green Building Standards, Visual Appearance of Ornamental Plants

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“Study nature, love nature, stay close to nature. It will never fail you.“

Frank Lloyd Wright

Dedicated to my brilliant dad and to my brilliant brother.

First of all, I would like to thank my office, Lightsphere GmbH, who supported me by providing the facilities during the entire process, in a very enthusiastic and enjoyable environment.

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Likewise, I would like to express my special gratitude to my closest friends, to my sister and my mother.

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Grazie Mille

DEFINITION OF BASIC TERMS

Indoor Living Green Wall (ILGW) : An Indoor living green wall, is a wall partially or completely covered with greenery that includes a growing medium, such as soil or a substrate. Most green walls also feature an integrated water delivery system. A green wall is also known as a living wall or vertical garden. It could be freestanding or attached to an existing wall.

Biophilic design: (according to a theory of the biologist E. O. Wilson) an innate and genetically determined affinity of human beings with the natural world

Horticultural Lighting: Horticulture lighting is used to support, increase and enable the growth of plants by illuminating them with artificial light.

LED: A light-emitting diode is a two-lead semiconductor light source.

CCT: The correlated color temperature (CCT, Tcp) is the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions

ELECTROMAGNETIC SPECTRUM: The electromagnetic spectrum is the range of frequencies (the spectrum) of electromagnetic radiation and their respective wavelengths and photon energies.

PAR: Photosynthetically active radiation designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.

DLI: Daily light integral describes the number of photosynthetically active photons (individual particles of light in the 400-700 nm range) that are delivered to a specific area over a 24-hour period, and is usually expressed as moles of light (mol) per square meter (m^{-2}) per day (d^{-1})

PPFD: Photosynthetic Photon Flux Density (PPFD).This is normally measured using mol $m^{-2}s^{-1}$

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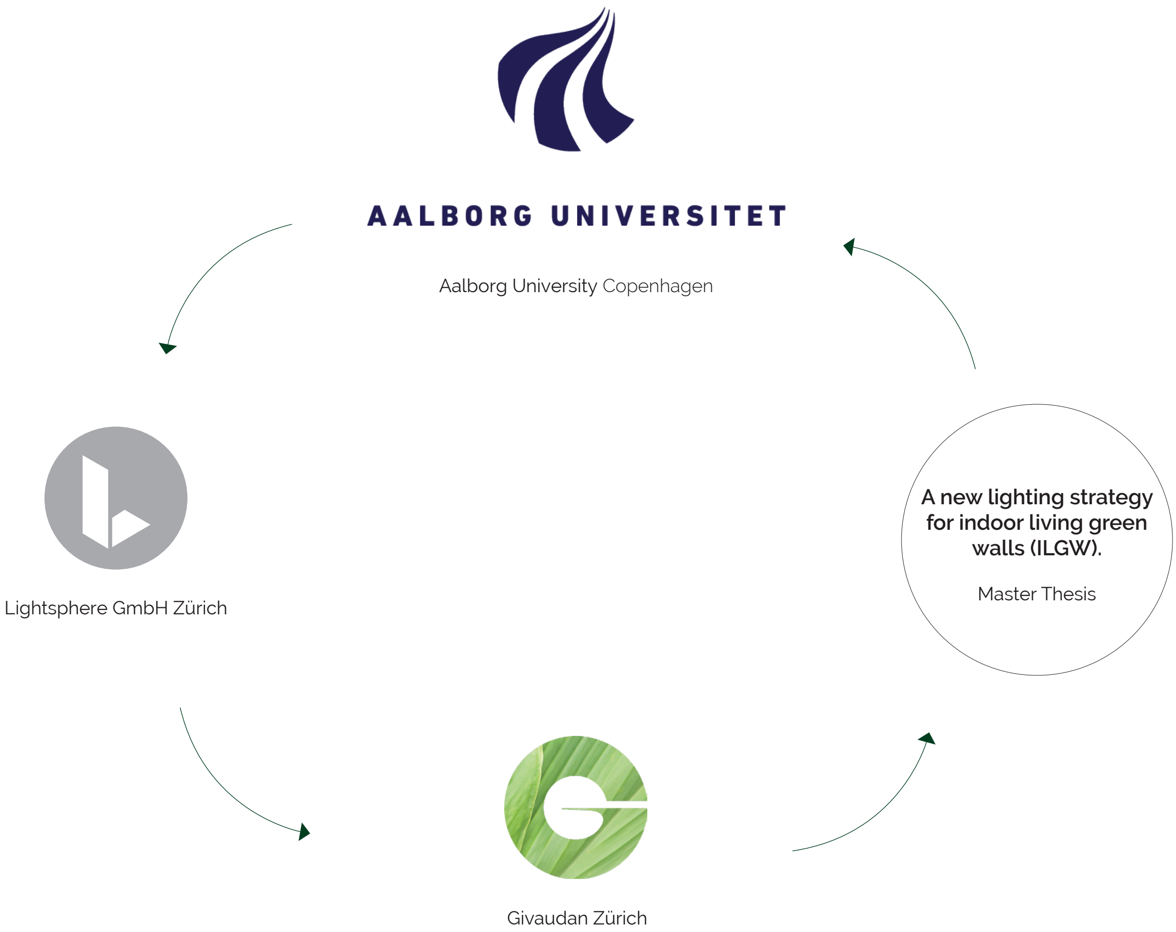

Since 2016, I am a student enrolled at Aalborg University, Copenhagen, in the Master program MSc Lighting design. As of September 2017, I am working as Lighting Designer Intern at Lightsphere GmbH, a lighting design company based in Zurich, Switzerland. During the course of my internship semester, I was involved in a project to develop the lighting design for greenery indoor in the Givaudan Innovation Center located in Kemptthal, Switzerland. I found the subject matter truly fascinating, and I decided to write my internship report about the Givaudan project. While working on the project, I realized how important the role of a lighting designer is in the process of designing greenery for indoor spaces, and how difficult it was to find useful knowledge and insights about artificial light and ornamental plants. It was this realization and the desire to make a positive contribution to the body of knowledge around the lighting needs of ornamental plants and human visual comfort, that led me to pursue this master thesis.

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Fig.1 La città Nuovissima - Illustration - Photocollage. Selina Bächli and Carla Sigillo. Inspired by Antonio Sant'Elia drawing *La città nuova*, 1914

Origin of work

The future of Urbanism and Architecture has taken a clear direction in the days we live, towards sustainable and green cities. Specifically within the field of interior design, a new trend has emerged involving ornamental plants as decorative walls, in order to reconnect people to a natural environment, in an era where humans are spending most of the time working far from nature and daylight.[1]

The decision to investigate the given subject matter, derives not only from my passion for nature, plants and vegetation, but out of a genuine need experienced during the course of my profession(a). Having participated in a project to develop a lighting design for indoor greenery elements for the Givaudan head office in Zurich, Switzerland, I soon realised how limited the knowledge and the specific technical solutions were on the lighting market.

Guidelines and technical standards regarding the design and the maintenance of living walls are rarely available[2] and the existing lighting solutions for indoor greenery are not achieving a satisfying result in many ways.
When a living wall is built outside the building, it will receive an illuminance level above 30.000 lux. In the indoor environment, artificial light is needed, and to thrive, plants necessitate 1000/2500 lux[3]. Apart from the light intensity and the duration, one must also consider the light spectrum and the position of the light source, as these play an important role. Often the light quality is not considered, and as a result, the organic elements appear dull or unnatural, providing an unpleasant atmosphere for the users that live the space.

For this reason, I have decided to focus my research on a new and innovative approach that seeks to improve the lighting for indoor greenery, while simultaneously taking into account the human visual experience in an office environment.

(a) Intern as lighting designer student at Lightsphere GmbH, refer to p.1

Thesis of research work

A new lighting strategy for Indoor Living Green Walls (ILGW).
How can artificial illumination that allows ornamental plants to grow healthily, be combined with illumination that ensures human visual comfort in an office environment?

The Thesis of research starts with an initial research question:

„Is it possible to enhance the quality of artificial illumination to fulfill growing requirements of natural plants and in the same time achieve visual comfort for the end user, creating aesthetically pleasing office environments?“

The aim of this study is indeed to explore the missing link between lighting for plants and the effect on the users.

To gain knowledge about light for plants, it is necessary to explore the horticultural lighting world and the body of knowledge that exists in this field.
What is Horticultural light and how does it work?

To respond to the increasing global population demand, agriculture has developed greenhouse systems to increase the production of crops (vegetables and fruit) by supplementing deficiency or absence of natural light with artificial light. As consequence, between 1961 and 2011, global agricultural output increased threefold[4]. Today a revolution is happening in horticulture lighting, and because the challenge is to produce more food in a sustainable way, thanks to the properties of LED lighting source, it has become the main technology used today. We will explore the properties of this technology, in order to understand its utility and applications within lighting for horticulture and human needs

"We now have exciting possibilities to tune the light to boost yield, customise the plant characteristics and maintain plant health" [5]

The goal in the horticultural research field is to optimise the artificial light spectrum, in order to control the plant's speed of growth, the quality of the food and the flowering period, among other things.

There is still lack of knowledge regarding the use of artificial light for ornamental plants, especially when one considers that the light should be in sync both with the plants and with the people occupying the space.

The key factors for a successful and long-term living ILGW are as follows: air/humidity indoor condition, water and soil nutrition system for the plant, and good quantity and quality of light. This study is focussing only on the lighting aspect, being aware of the importance of the other aspects, and of the interconnection between water and light.

Taking into account the short amount of time, and considering that evaluating the biological effects of an artificial light on a plant would take a longer period (minimum 3 months), the study will explore the different possibilities in terms of visual comfort for the users and the aesthetic appearance of the plants.

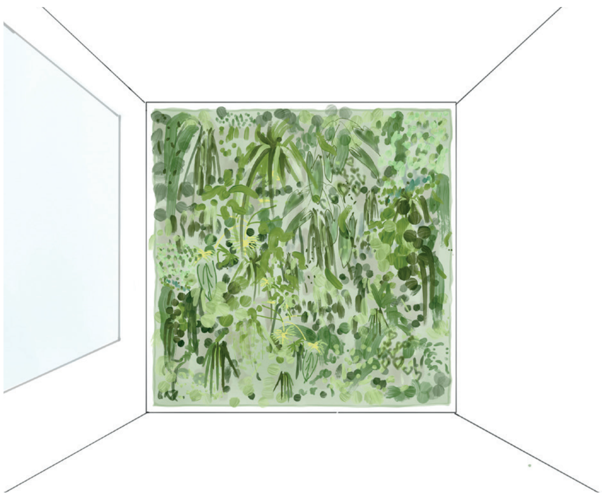

Fig.2 Indoor Living Green Wall (ILGW) - Author's sketch

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Methodology

To examine the above indicated issues and to answer the research question the following research methods were employed:

- The method of critical analysis of literature/ interview

The assessment of existing scientific literature related to research question puts in context the research. To progress a summary of existing work, theoretically and practically, a critical examination is necessary. The literature of the subject includes publications in the form of books and articles in journals or conference materials that present the results of more general or scientific research.

- Interview method

The ability to ask research questions and then develop answers. In this work, the student decided for personal interviews in the form of recorded face to face meeting with Mr, Bulgarelli, ILGW expert with whom she previously worked professionally, with the request for their opinions on the ILGW.

- The method of observation

This method involves deliberate searching for facts. Observation of transformations in the field of illumination of ILGW, it made it possible to put up a new research problem and tries to solve it. Cognitive value of the observational method consists in the description of phenomena. While applying this method, a hypothesis was put forward that it can be found the answer to the question whether „Is it possible to enhance the quality of artificial illumination to fulfil growing requirements of natural plants and in the same time achieve visual comfort for the end user, creating aesthetically pleasing office environments?"
Also, in order to fully illustrate the term 'ILGW', a photographic collection presenting images capturing 'various ILGW according to various locations in the room', was established. Based on the analysis of results findings and conclusions of different types were presented.

- The graphical method

A way of frequently presenting research using a drawing, illustration, graph or photography. Graphic methods logically simplify transferring information and choosing the form of their presentation.

- Empirical / practical method – lighting test experiment

The primary focus of the research is to advance knowledge about practice, or to advance knowledge within practice. Such research includes practice as an integral part of its method. This Master thesis connects theory to practice by analysing the best lighting conditions for ILGW based on 3no. different criteria: plant's needs, human's needs and aesthetic look of plants by using own experience in designing and testing different lighting scenarios

Applications of findings

To design an indoor living green wall that has true benefits for the building and it users, requires a blend of skill-sets and professionals, ranging from architects and engineers, to lighting designers, botanists, landscape and interior designers. To be successful, these key stakeholders must all collaborate to navigate and co-create the complex design process. In the lighting design field, as stated above, there is still a lack of knowledge, and solutions currently are sub-optimal.
The outcome of this research is a guideline for architects, interior designer and other stakeholders that are interested in integrating a good quality of light in the living wall design, and to understand the key features required to create a light concept that creates a pleasant atmosphere, while catering to the biological needs of plants and people.

A new lighting strategy should serve as guiding concept to enhance the natural beauty of plants, and at the same time, defines a hierarchy between daylight and artificial light elements throughout all hours of the day, in the working environment.

Fig.3 ILGW - artificial lighting - Elements, Munchen © by Creaplant.ch

The state of research

Lighting systems usually installed nowadays to provide artificial light for ILGW, consist of linear or punctual artificial light sources (Fig.3) that shoot light from the ceiling towards the plants (from above, as it is happening in nature). The type of technology mostly used is metal halide (MHL), Incandescent (IL) or LEDs at high intensity level, in order to provide enough energy for photosynthesis of the plants.
From the few studies conducted on the optimal light for ILGW[6][7],it can be observed that an important role is played by the position of light source, its intensity and duration.
Tan et Al.[6] underline the importance of light prevision for indoor landscaping, as a strategy to control the building energy consumption and to make the living wall efficient in terms of maintenance. The daylight availability prevision is indeed highly recommended, and measurements of Photosynthetically Active Radiation and the Daily Light Integral (DLI), works better with plants, compared to lux level.

Egea et Al.[7], has conducted an experiment of ILGW under different artificial lighting sources (Incandescent (IL), fluorescent (FL) and metal halide (MHL) lamp. Despite the three identical electric inputs, differences in the growing effect occurred when the distance from the light source was up to 1 meter. This was due to the spectral composition, but the research does not show the relative spectra measurements. The main result was found in the different water consumption, where the MHL was more advantageous compared the other two options. However, these experiments are not providing information about light spectrum composition and how this affects the user's visual experience, and the aesthetic of the ILGW. Furthermore, this study by Egea, did not explore the LEDs technology. It would have been interesting and highly insightful to test also this technology, in order to understand the water consumption resulting from LEDs utilization.

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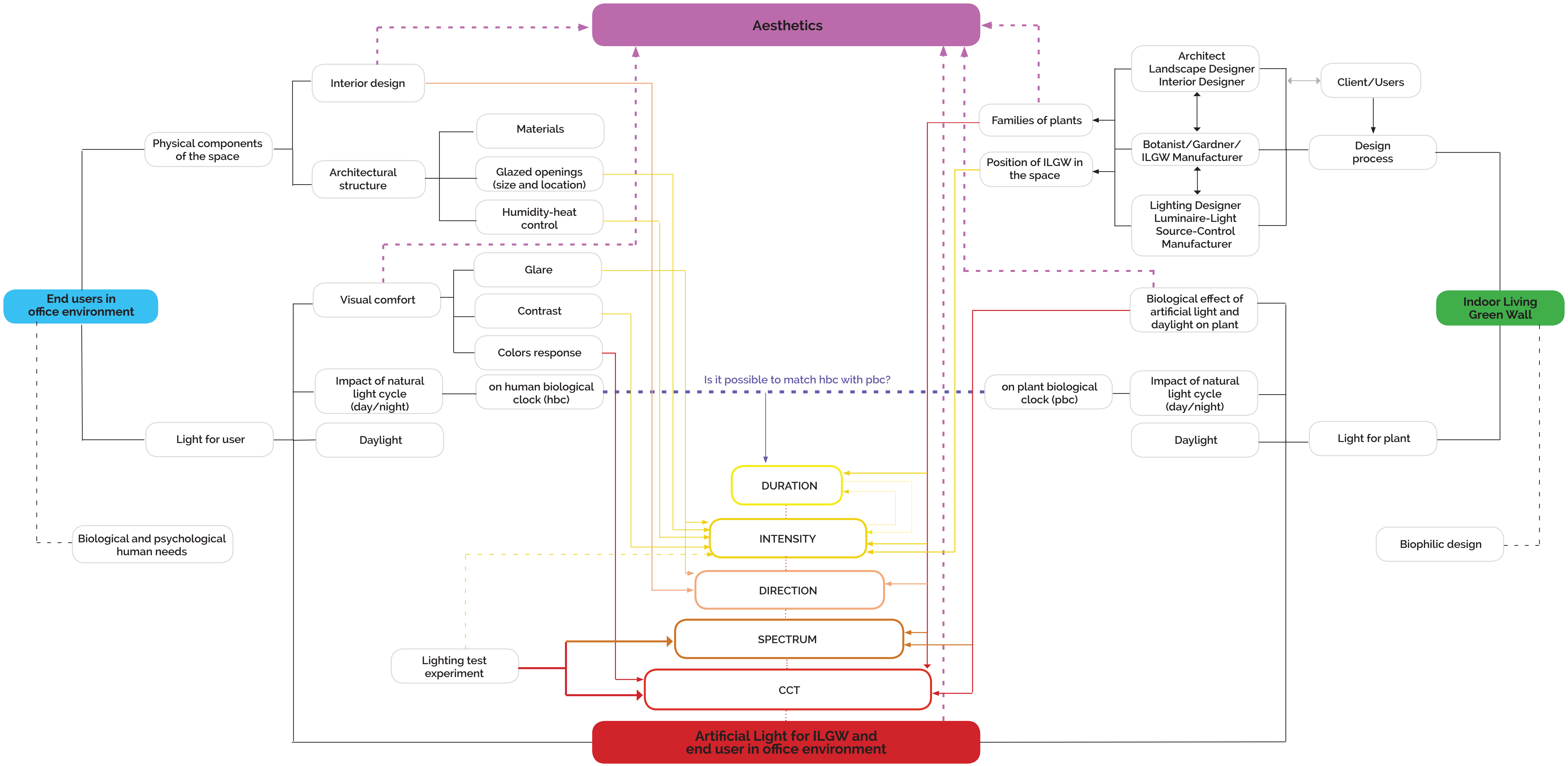
Mind Map. an overview of the Thesis topic



Work Structure

In order to explore the subject matter thoroughly, and arrive at a set of insights and solutions that help bring progress to the field, the following steps will be undertaken:

- First, a review and analysis of the existing knowledge from the array of relevant fields that can potentially influence and improve the living wall design process
- Second, the application of this theoretical knowledge into the lighting design practice, in order to establish a set of criteria and parameters to follow
- Last, an evaluation and assessment of the possibilities for fulfilling the criteria, by designing and conducting tests on plants, applying the available technologies from the horticultural lighting that support healthy plant growth, while seeking to improve the human lighting experience at the same time

The research strategy will comprise the following elements:

-Scientific evidences. The work will explore an array of subjects connected to the main subject, embracing the biological, physical and psychological elements influencing the given subject matter. The complexity and interdisciplinary nature of the chosen subject is depicted in the mind map.
-Interview. The interview is done with a project consultant of ILGW, that is in the business. The objective of the interview is to achieve a deep understanding of the risks to plant health when developing and creating an ILGW, as well as the current best practices observed during his career.
-Scientific evidences. The work will explore the topics that could better address the direction of the study.

-Case study. The objective of the interview is to achieve a deep understanding of the risks to plant health when developing and creating an ILGW, as well as the current best practices observed during his career.

-Lighting test experiment. Mock up test on array of ornamental plants under a monochromatic LEDs lighting source, changing spectral composition and color temperature.

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LITERATURE REVIEW

1.1 INDOOR LIVING GREEN WALL (ILGW)

1.1.1 Biophilic Design

Biophilic design offers an extraordinary array of „societal" benefits, particularly as the world population increasingly moves into urban centres. From stress reduction, improved cognitive function and creativity, as well as improved health, well-being and even healing. In consequence, it is of vital importance that biophilic design continues to develop and grows in importance, as it allows people to improve health and overall quality of life.
But what exactly does biophilia mean?
Biophilia: *„(according to a theory of the biologist E. O. Wilson) an innate and genetically determined affinity of human beings with the natural world"* (Oxford dictionary).
Since the ancient times, ornamental plants were used as decoration inside private and public spaces, and also as ornaments for religious and spiritual rituals.
In many civilizations you can find references to nature in architectural and object design.
One of the oldest historical examples can be found in one of the seven wonders from the ancient world, the hanging gardens of Babylon. The pensile paradise planted, as described in many cuneiform books and from historical writers[1], was a huge suspended garden where many trees, flowers and plants of every species were producing this agreeable pleasure for the eyes. As supposed in many studies, the system of watering was depending from the Euphrate river, and as a result, this big terrace full of soil and plants was always kept moist and became a perfect environment for plants growth and thrive.

Fig.1 The Hanging Gardens of Babylon - Digital Art - ©by Sergey Likhachev (Behance)

In the classical orders of ancient Greek and Roman architecture, the Corinthian order was characterized by the use of sculptural acanthus leaves as decoration on the capitals of the temple's columns. This decoration is still visible in many archaeological sites spread all over the Roman Empire's territory, from Rome to Jordan.

The ancient Chinese tradition of "pun-tsai", handed down to Japanese culture as "bonsai", is the art that uses trees grown in small vases. The origin of this tradition derives from the ancient Chinese belief that the miniature of natural landscapes was a tool to empower the human spirit. In the Japanese literature, we have a significant passage on the book Classic Bonsai of Japan[2] that explains the interrelationship between humans, plants and beauty:

"A tree that is left growing in its natural state is a crude thing. It is only when it is kept close to human beings who fashion it with loving care that its shape and style acquire the ability to move one."

In the middle age, after the end of the Roman Empire, the only institution that survived was the Church, the guardian of instruction and culture, where people were focused on keeping the chaotic situation of the barbaric invasions stable. In this period, inside the monastery and churches cloister, the culture of herbs and plants became a truly important and permissible source of pleasure, work and contemplation[3].
More and more examples could be added to this historical list. Today biophilic design manifests itself in different ways through the usage of plants in outdoor and indoor environments, and also by copying nature's footprint and patterns in the design of architectural styles, furniture and objects.

The subject of the study, the living wall, is an element classified into the biophilic design.

Fig.2 Acanto leave - Pantheon, Rome ©by geometriefluide.com

Fig.3 Bonzi - Olive tree bonsai - Private collection

Fig.4 Cloister - San Giovanni in Venere Abbey, Vasto Italy ©by tripsinitaly.it

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1.1.2 Indoor Living Green Wall components

The Indoor Living Green Wall (ILGW) is a device that brings a pleasant and natural environment into the atmosphere. It is useful to clean the indoor air pollution, it is also giving a contribution to the noise attenuation and to the temperature as well as humidity improvement [4], among other benefits.
A "Green wall" is a vertical garden and refers to a vegetative surface made with different species of plants and flowers. It could exist in the outside of a building wall, called "green Facade", or it could be installed inside (Indoor Living Green Wall)

The ILGW is a system that is composed of vertical modules, where the vegetation is positioned. It can be freestanding, or fixed into a drywall (main/partition wall). Nowadays there are several technologies which bring substructure, soil, plants and watering system together. We can identify two main constructive systems for ILGW:

1. The modular living wall, is a "library-shelves" shaped structure, with modular containers for soil and plants (Fig.5). Many manufacturers of ILGW offer a fixed size component, that could be repeated as many times as needed, to cover the size of the existing wall. The base is usually made in aluminium, and the watering system is integrated along all the levels of the wall. This is a flexible and easy to maintain ILGW. The only issue is, that it shows the construction behind the plants, losing some of its "natural appeal". The advantage is that the plants are pre-growth, and the installation on site provides the final "look" of the ILGW, without waiting time for the growing process.

Fig.5 Modular system ILGW - ©by ANS Global

Fig.6 Modular system ILGW - Verticalis 2.0 Green picture with integrated water storage system ©by Hydroplant.ch

2. The "Mur Vegetal", is patented by Patrick Blanc, a real pioneer and experienced french botanist. The origin of the design of the Mur Vegetal is very interesting, and connected to water. Patrick Blanc was prototyping a biological filter for his tropical aquarium. As the plants have incredible filtering properties, he developed this idea of using plants as filter, placed on a vertical surface. This is how the vertical garden was born. The Mur Vegetal is made with three different parts: a metal structure, a PVC panel and a layer of not biodegradable felt made by polyamide. The metal structure could be hung on a wall, or freestanding. The plants are installed as seeds, or cuttings or already developed in their normal growth size. They will develop their roots inside the felt. The watering is coming from the top, and homogeneously distributed by the capillarity of the felt. A collector is usually placed in the bottom part of the wall and collects the excessed water. After that a mechanism with a pomp, brings the water back to the top, optimizing the water consumption. Low concentrated nutrients have to be added to the water, if tap water is used. This system that doesn't necessitate any soil, allows the construction of very high living wall, since its weight doesn't go over 30 Kg for square meters [6].

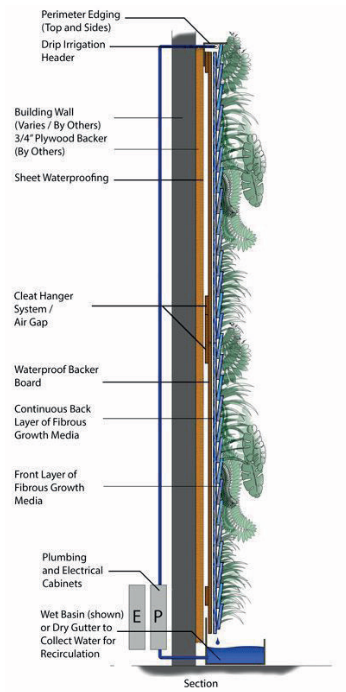

Fig.7 Mur Végétal - Section Drawing - ©by 3rd yr-Pinterest

Fig.8 Mur Végétal - Indoor vertical garden Patrick Blanc home after four years growth © by Patrick Blanc

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As explained in the introduction, the key factors for a successful and long-term living ILGW are air/humidity indoor condition, water and soil nutrition system for the plant as well as good quantity and quality of light.

Water and light are strictly dependant on each other and the more heat is produced by the light source, the more water the ILGW needs to prevent an overly dry substrate/soil. The excess of water also has a negative impact on the plants growth, because it could produce mold, which might affect negatively the plant's ecosystem. That's why the maintenance of a ILGW is usually provided by the company that installs the system and monitoring of the first weeks is required to set optimal air/water/ light conditions.

The following images show some examples of ILGW installed in office environment.

Fig.9 Smeg Offices – Abingdon Green Walls for Meeting Area - ©by homedit.com

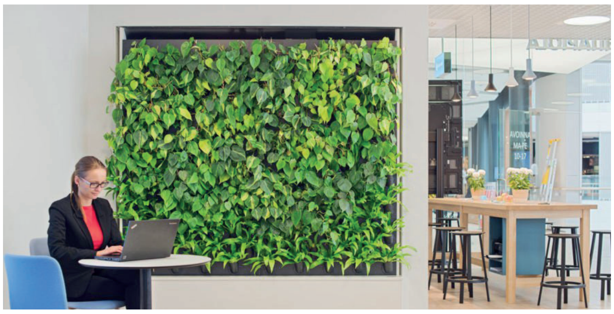

Fig.10 ILGW Naava in office space - ©by Inhabitat.com

Fig.11 Naava green wall - open office space ©by Naava

1.1.3 ILGW design process

Loh[5] summarises the current researche on the ILGW and lists the benefits produced for buildings:
• keeping low energy consumption and gas emissions
• increasing the thermal performance of buildings(lowering energy costs)
• improving of Indoor Air Quality (IAQ)
• reducing the noise pollution
• improving health and well-being.

The design of a living wall is a process that involves a wide range of experts and professional figures from the different fields. Today it is very common to find green walls in many different types of buildings. From Public to private contexts, ILGW is a new tool for architects and designers to give a modern and green imprinting to their project.
In the specific case of working places, the ILGW is implemented in the architectural design, and can be requested by the client in small, medium or big size, thought for a refurbishment/renovation of an existing building, or for a new construction. In the latter case, when the design is involved in a new building, the consultants for the ILGW are engaged at an earlier stage, and it could become a parameter for the definition of architectural component of the space.
ILGW can meet the interests of private/public stakeholders, and for this reason a valuable parameter is the maintenance of it in the long term.
There are several international programs that regulate the building performance rating and certification system, to increase the property's value, to promote a more efficient and conscious way to to construct a building, which is very important in determining the environmental impact. The living wall provides points to achieve this green building standards certification, such as the two certifications discussed below.

The LEED program (Leadership in Energy and Environmental Design), is a green building certification developed in the U.S., with the aim of converting the construction of eco-friendly building. The office places belong to the Building Operations and Maintenance section of LEED. There are several parameters to be fulfilled, that can be summed up with the following list:
- Innovation
- Indoor environment quality
- materials and resources
- location and transportation
- sustainable sites
- energy and atmosphere
- water efficiency

The WELL standards, promoted by The International WELL Building Institute (IWBI), is more human well-being oriented.
The rating system aims to preserve the everyday quality of life for people living in public-private spaces. The seven point promoted by WELL are:
- Air
- Water
- Nourishment
- Light
- Fitness
- Comfort
- Mind

In the office environment, the main actors of the process are the company (client) and the final users (employees). On one hand, the client is interested in having a living wall to ensure a pleasant atmosphere that supports the well being of the employees. On the other hand, this interest is a business strategy itself, since studies[7] have demonstrated the improvement of attention capacity in office with indoor plants. The productivity increases, the performance improves, and this is financially sustainable for the company that invests up front in the interior design, and as return,

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benefits from the employee's productivity and presence at work with less sickness days.

The design of ILGW starts from the site analysis, and after numerous phases and the installation, necessitates maintenance.
The steps for the design of the ILGW are:

- Site condition analysis. Measurements of physical components of the space, including the light condition (Daylight factor, artificial light in the room, shading system), the finishes material (ceiling, walls and furniture) and the size/shape of the room.
- Definition of size/shape/position of the ILGW according to the site conditions.
- Definition of species of plants, according to light condition and to the aesthetics of the interior design. Different shades of green and/or flowering colors to enhance the atmosphere of the space
- Air/humidity/light control. When the daylight impact is not sufficient to ensure the plant's growth, a design for additional artificial lighting is needed. Considering the type of lighting source used and the heat produced it's important to adjust the air/humidity condition by using system for water/humidity control.
- Installation. Depending from the ILGW construction system, the plants are pre growth and installed on site, or in the other case there is a period within a range of 1-3 months when the plants will grow, filling the empty part of the ILGW.
- Maintenance. This is the most difficult part of the ILGW, and usually the company that installs the living wall, is also offering a maintenance service for the whole time after the installation. The maintenance is strictly connected to the light condition, and in the next chapters it is explained how the light affects the biology of the plants.

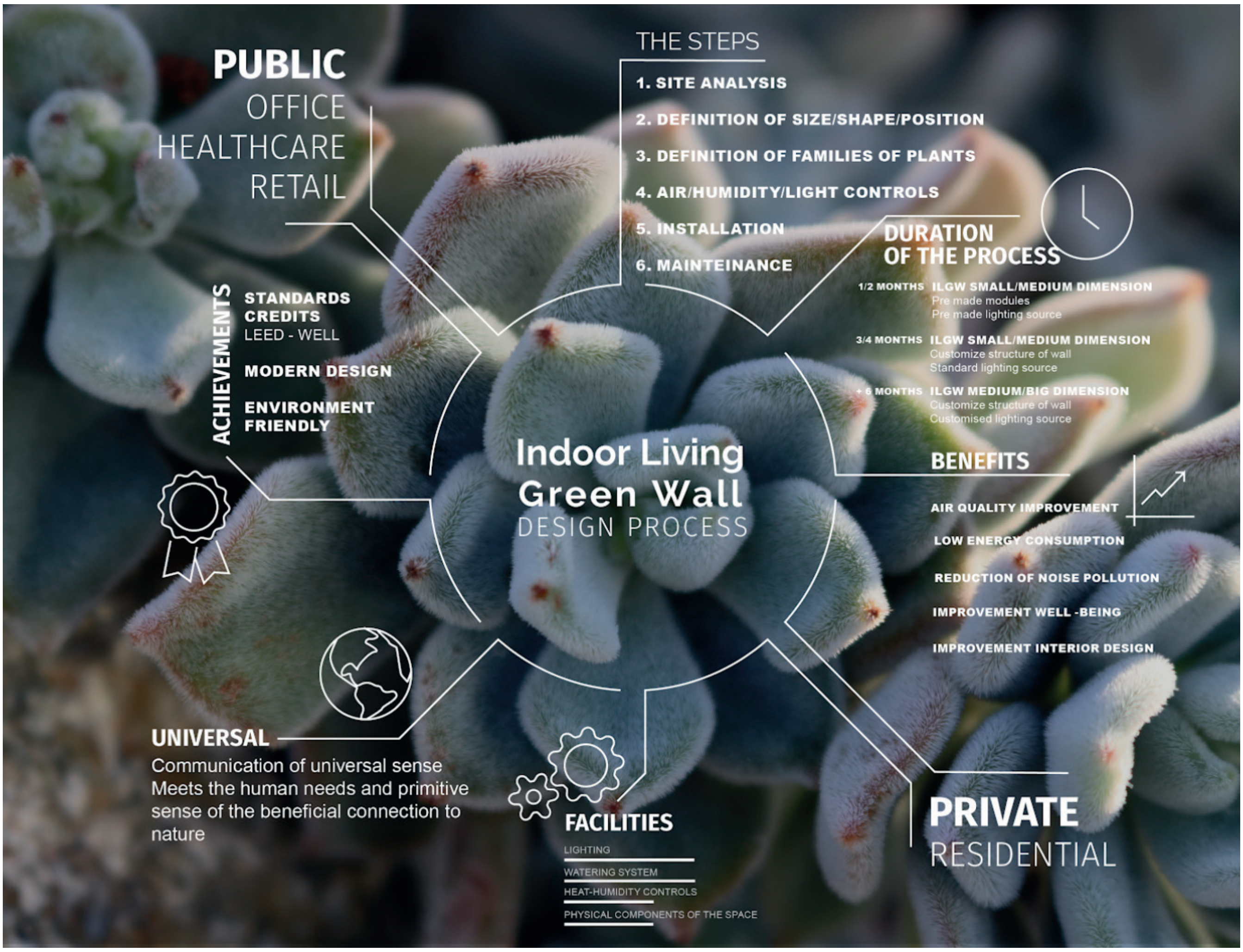

Fig.12 Author's Illustration: the ILGW design process: an overview

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1.1.3.1 Stakeholders Involved In the design

The figures involved in such a complex design are summarized in the following list:

- ILGW manufacturer
- Botanist/Gardner
- Architect/Construction Engineer
- Interior designer
- Landscape designer
- Lighting designer
- Lighting manufacturer company
- Watering/humidity control system manufacturer
- Electrical planner/ Electrical installation company
- Client
- End user

The relation between the stakeholders will depend on the complexity of the ILGW and from the phases of the process. The earlier the parts communicate, the easier and sustainable the maintenance of the ILGW will be as the outcome.
The lighting designer is a figure that should be involved at the first stage, during the site analysis. As explained in the introduction (State of the research), a prevision of the light availability should serve as a tool to optimize the energy consumption of the additional artificial light installed.

Furthermore, the final appearance of the wall will depend on the light that falls on the organic wall, from its direction, intensity and CCT, and for this reason it is not possible to leave this to chance, but rather to a professional within the field of lighting. A lighting designer can study a concept that is better suited to the overall context, which fulfils the requirements for plants and the final users of the space. .

The following image (Fig.13) shows the interdisciplinary connections between the lighting designer and the other key stakeholders.

"Transdisciplinary: beyond the disciplines, not staring within any particular discipline but with a problem or issue, and then bringing various disciplines to bear on solving the problem or addressing the issue – knowledge is transformed"[8]

From the figure, the vital role of the lighting design in the ILGW design is clear. Furthermore, it is clear that all parts need to participate in the decision making process throughout the design and implementation phases, so as to keep the performance of the living wall high, and post installation costs low.

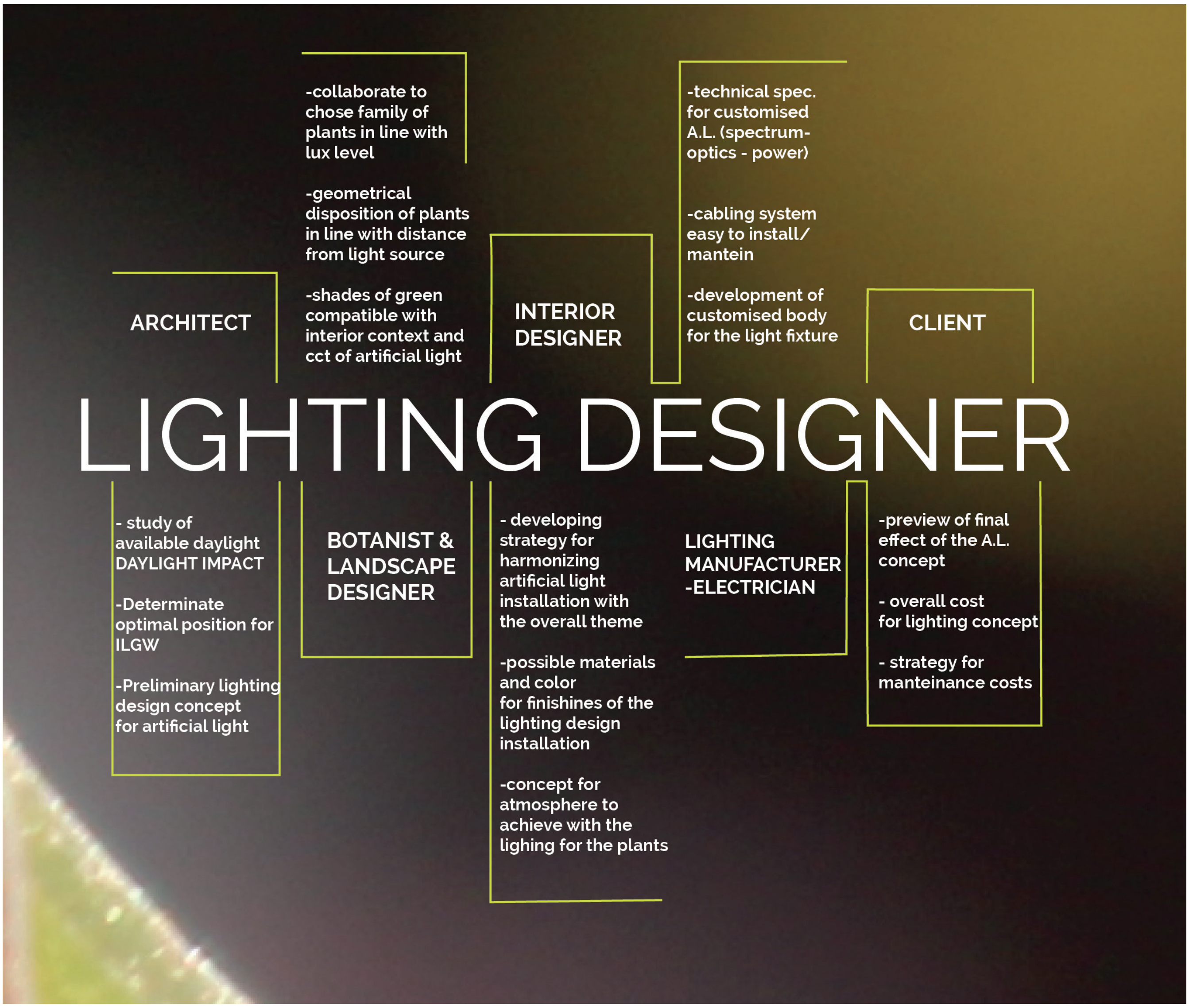

Fig.13 Author's Illustration: Lighting designer transdisciplinary approach

1.1.3.2 Interview with ILGW expert

Zurich, 30.04.2018

Master Thesis - Carla Sigillo - AAlborg University student, Copenhagen - Intern at Lightsphere, Zurich.

Interview with Samuel Bulgarelli, Project Consultant at Hydroplant AG, Zurich.

The objective of this interview is to collect knowledge about the design process of an Indoor Living Green Wall (ILGW), and about the difficulties faced by a plant that lives in an ILGW, with a particular focus on the aspects related to daylight and artificial light conditions. Due to a lack of standards and guidelines relating to the design and maintenance of ILGW, the author will utilize, during the course of the master thesis, the knowledge and insights gleaned during the interview, referring to these as "good practices" in the field.

1. Can you kindly give a quick introduction about yourself, your background, and your role in company?

I am originally an educated outdoor gardener (landscape horticulturist), and I am a plant specialist. I have worked for Hydroplant AG as a project consultant for the past 6 years. What we do in our company, is to bring plants into environments for people to enjoy indoors, such as offices, residential and commercial buildings. What we experience every day is the challenge in balancing what is good for people and what is good for plants. We have a distinction in the FUNCTIONAL *aspect of plants, that help the moisture of the air, clean the air and also work as acoustic insulation. There is also an* AESTHETIC *aspect of it, the beauty of nature that is brought into an indoor space. But the most important one is the* PSYCHOLOGICAL *effect of plants, that calm down people, helping people work in a more relaxed, focused and creative way. If there is no light in such spaces, we proceed in three ways:*

- *We bring lighting, to help the growing process and the health of the plants.*
- *We change the plants every 1 or 2 years when they are not green anymore*
- *We provide artificial plants when requested from the client, to create a placebo effect for the users.*

2. How many people do you interact with on your average ILGW project? (Client, final user, architect, interior designer, landscape designer, lighting designer, luminaire manufacturer company, light source manuf., lighting controls manuf., professionals from other sectors)

Depends on the projects. In the company we have our own planning department for projects. Often we do the planning by ourselves.

In many cases, we are in touch with the person in charge of the outfitting (furniture), all kinds of architects as well as technical experts from various fields, but also with the final users directly.

Compared to the past, nowadays we are involved in projects at an earlier stage. This allows us to give advice on how the room should be, to help the ILGW performance. In the best case, we can plan a project a year in advance. We prefer to be involved in a project as early as possible, we then are able to influence the room features which are necessary for the ILGW. But this is not a customary practice. Sometimes we are the last ones involved in the project.

-With the lighting manufacturer, usually we ask for High-intensity discharge lamps (HID lamps), they deliver the luminaires, and the Electrical consultant does the installation.

We use LEDs, but currently the HID are often better for the plant's appearance.

3. Plant choice: Do you have any database to collect information regarding optimal/sub-optimal performance of species of plants in ILGW, in order to improve your personal portfolio?

We have some lists of plants, to organize the work. But we don't have a database with info about plants performance.

We use acclimatized plants.

The type of plant makes the difference in the speed/way of growing process.

We choose the species of plants depending on the room position and the light impact.

We have tested many families of plants, and out of experience, we have a list of plants that are stable in indoor life.

Another factor that influences the choice of plants is the humidity of the place. There are some species of plants that, during the growing process, necessitate dry air, otherwise there is the risk that the mold will grow and the plant won't survive (producing a bad smell).

Everything depends on the light. When we have too much light the plants age too fast, so we change the intensity of light when possible or simply reduce the time of exposure.

The process of growing has to be good for the plants, and at the same time not too fast for maintenance sustainability.

We have 4 different structural systems to build an ILGW, and the choice of the size of plants depends on the dimension of the substrate utilized in the specific system and on the watering system too.

In the living wall, is important to choose species.

There are usually two ways of proceeding:

- *When the light distribution is not uniform, we collect data, measuring the quantity of light in each point of the wall. From this layout we decide which species in which position on the wall (complex process).*
- *We instruct the Architect/lighting designer as to how much light we need and they provide that condition. Uniformity of light is the best for us to proceed with the installation.*

4. Longevity of ILGW: how much does the daylight impact the longevity of plants in the ILGW? From your experience, have you developed any approach, methodology or model to follow, where illuminance levels and geometry of the room, gives you a threshold indicating where and how plants thrive? How much are you involved in determining openings in new building design phase, to fulfil ILGW needs?

The plants will grow towards the light source and the various plant layers will compete with each other.

Subsequently, longer or wider growing plants will cause shading of the lower levels causing them to grow less dense.

This does not help the overall appearance of the ILGW. For this reason, we prefer to bring light anyway, and have the chance to control the evenly growth and morphology of plants.

Furthermore, in the office the problem is that is the daylight impact depends also on the users of the space, and the way they use shading system, especially in summer time. If they forget the roller shutters are down, the plants won't receive light for an entire weekend, and this will impact the ability of the plants to thrive.

There is another phenomenon that is to be considered regarding the daylight. When, due to changed location situation, direct sunlight is shining on leaves, it can burn them, and as a result, the users start to notice the brown leaves, and consequently, complain about the appearance of the plants.

Sometimes plants adapt to inadequate lighting conditions and are able to survive, and this is always a big surprise.

5. Artificial light: which parameters do you use for evaluating the quality of a lighting fixture. Do you take into account the visual appearance of the plants? (comfort for end user)

Normally the client doesn't request any test on the visual appearance of the plants under artificial light.

We refer to the spectra of assimilation curve, and provide a optimum lux level to be reached. We explain that if they use LEDs, this part of the spectrum has to be covered.

In some cases, Architects use different Temperature of light sources one close to the other. This produce a non-regular effect on the leaves and as result, the visual appearance is not optimal. It would be better to have a sin-

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gle LEDs lighting source, with all the spectrum that the plants necessitate.

Other important notes from the interview

- *Plants need dark, as they have an internal clock (Photosynthesis "Dark" and "light-dependent"-Reaction), and as humans, that is good to prevent illness and parasites.*
- *When there is more light, usually they need more water.*
- *Usually less light less water.*

1.1.4 Today's issues related to ILGW

From the analysis of the process to build the ILGW and from the interview presented above, it's possible to summarize an overview of the issues related to the living wall, with a focus on the lighting aspect:

- The decision of having the ILGW inside a building, sometimes happens too late in the architectural project phase, and this could have a negative impact on the maintenance of the plants.
- The lighting sources for the living wall existing on the market, are nowadays poor, and doesn't help the visual comfort for the end users, which is a parameter not considered most of the time by the client.
- Plants are very difficult to maintain, and the collaboration of all the stakeholders could make the difference for the living organism.

Fig.14 Google's Australian HQ (Pyrmont, NSW) by Portfolio InDesign © by greenroofaustralasia.com

Fig.14 Aveda Milan © by Grace Min. Pinterest.com

1.1.5 Light For plants

1.1.5.1 Biological effect of artificial light and daylight on plants

Plants require light for photosynthesis and to control many hormonal and morphological variations in the cellular structure; to do so effectively, certain colours of light offer improved outcomes for photosynthesis. The ultimate source of light on planet earth, is no doubt the sun. The sun is a broad-spectrum source of light, which emits photons of all wavelengths constantly, with no strong emission lines. From a human point of view, sunlight it is perceived as 'white light'. A prism can display white light, which is the combination of violet (400–450 nm), blue (450–520 nm), green (520–560 nm), yellow (560–600 nm), orange (600–625 nm), and red (625–700 nm. [9]
The light used for photosynthesis by plants is largely the same as the light used in the visible spectrum, ranging from 400 to 700 nm. However, the leaf of a plant reflects a much higher share of green than any other colour of photons, resulting in the green colour we usually associate with leaves[10].

Photosynthesis

During photosynthesis, when carbon dioxide and water are converted by chlorophyll into carbohydrates by plants, light is the source of energy which enables this process. Plants use these carbohydrates as humans use food, and they ultimately form the substrate for proteins, fats and vitamins, which are required in all living organisms. During this process in plants, oxygen is also formed, which remains the primary source of atmospheric oxygen on planet earth. Furthermore, light is instrumental in the creation chlorophyll, xanthophylls, carotenoids, anthocyanins, and phytochrome, as well as determining the biological clocks of plants. As light changes, so to can the size, colour, shape, movement, flower productions and fruit yield of the plant [11].

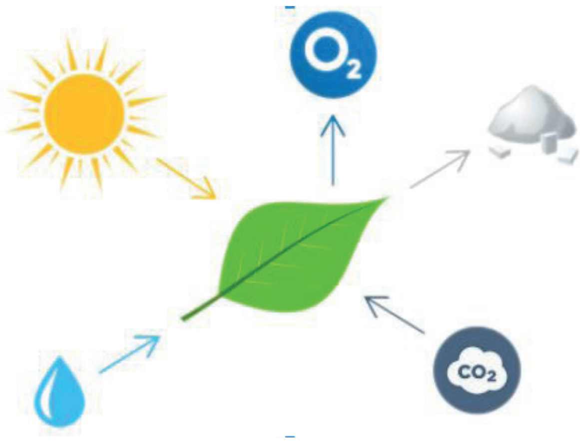

Fig.15 Author's sketch - Photosynthesis process

Respiration

The diametrically opposed process to photosynthesis is respiration, which allows carbohydrates to be oxidised and transform to dioxide, water and energy. While this process does not require light and chlorophyll, it necessitates food, oxygen and enzymes in order to take place. While the former process only occurs in the presence of light, the latter is constant. Given a normal level of irradiance, photosynthesis in plat forms is greater than respiration, resulting in a net production of oxygen from leaves. Still, where irradiance decreases to the point where carbohydrate production levels are the same as the amount carbohydrates needed for respiration, photosynthesis cannot occur; this is called the compensation point. When irradiance levels are low, and light levels are at the compensation point, plants are not able to survive, as carbohydrates become depleted and are insufficient for respiration during the night[12].

Other Photoresponses

Photomorphogenesis is a light-controlled differentiation of a plant due to responses caused by photoreceptor and by phytochrome in the short wavelength part of the spectrum. These photoreceptors could differ according to the species of plants. Phytochrome Pr and Pfr have an impact on the molecular structure of the plant. The photomorphogenic responses are the following:

- flowering
- seed germination
- stem elongation
- pigment formation

The movements of the plants caused by the light, is called phototropism. Phototropism is the mechanism that moves the plant towards the light source. Photonasty is the motion that flowers have at day when they open up, or during night time when they close[13].

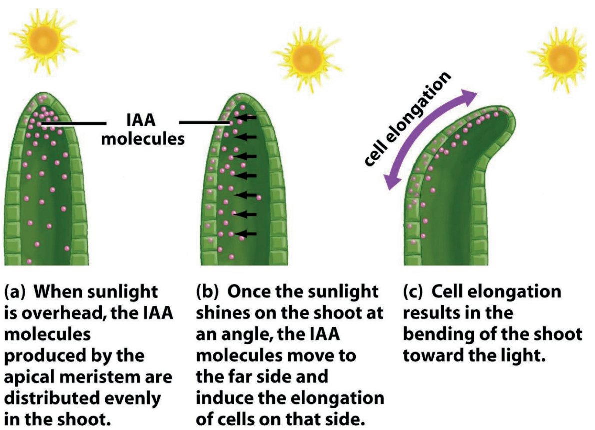

Fig.16 Phototropism process - Figure 30-22 A Brief Guide to Biology, 1/e © 2007 Pearson Prentice Hall, Inc.

Radiant-Energy Measurement

When compared to the human eye, plants respond differently to radiant energy. With this in mind, it is incorrect to measure plant irradiance based on illuminance. This is of particular importance when measuring the effect of lamps with different spectral power distributions on plants. Photosynthetically Active Radiation (PAR) is measured by evaluating number of moles of photons between 400

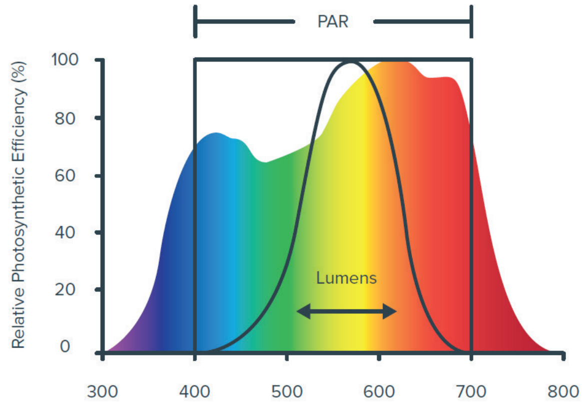

Fig.17 Photosynthetically Active Radiation (PAR) and McCree Action Spectrum ©by growersnetwork.org

and 700 nm[14]. The Photosynthetic Photon Flux Density (PPFD), or the photon irradiance, is expressed in $molm^{-2}s^{-1}$ .For most light sources, the conversion from illuminance to PPFD is in the range between 0.01 to 0.02 $\mu mols^{-1}m^{-2}$ per lux

Common Plants and Illuminances

Professionals that are designing an internal space using plants usually use acclimatised plants. These plants are accustomed or conditioned to lower levels of humidity and illuminance, as well as a lower frequency of watering. The acclimatisation process helps ensure that the plants remain healthy once exposed to an internal space. There are recommended illuminances for trees, floor plants, tables and desk plants that are commonly used in office and internal spaces, that commonly receive around 14 hours of light per day.

Artificial light for plants

The terms plant lighting refers to the use of light sources for the effective growth, flowering and maintenance of plants, but in what ways can we examine the effect of light on plants? First, by looking at the light quantity, which determines the levels of photosynthesis in the plant. Second, the light quality, which is defined by the spectral composition of the light, and determines the growth, shape, development and flowing of the plant. Last, the light duration, which is sometimes referred to as the photoperiod, are impacts the flowering of plants[15].

As stated in the introduction, it is necessary to dive into horticultural lighting to understand the scientific knowledge available today.

Spectral composition of LEDs lighting source and plant response has been object of several studies among the past twenty years.

In a recent study, Burattini et Al.[16] demonstrated that white LEDs that have different CCT and different percentages of blue and red wavelength in the spectrum, affect the growth and the morphology in spinach plants.

Lydie Huché-Thélier et Al.[17] argue that the use of monochromatic LEDs could support a more accurate spectrum for plant development and morphology, and that the light response is species-dependent. In a greenhouse setting, for instance, supplemental light with 80% red and 20% blue reduced the stem elongation in Euphorbia pulcherrima specie by 34%, in comparison to HPS lamp lighting.

Today the horticultural lighting manufacturer are producing LED chips that cover most of the PAR needed for plant growth. In the Fig.18, there are represented in dotted lines the curves of the spectrum related to peak of Chlorophyll a, Chlorophyll b and Phytochromes responses (nm) to light stimuli, and with the continuous lines, are represented the LED chips spectral distribution within the Deep blue, Hyper Red and Far Red wavelengths

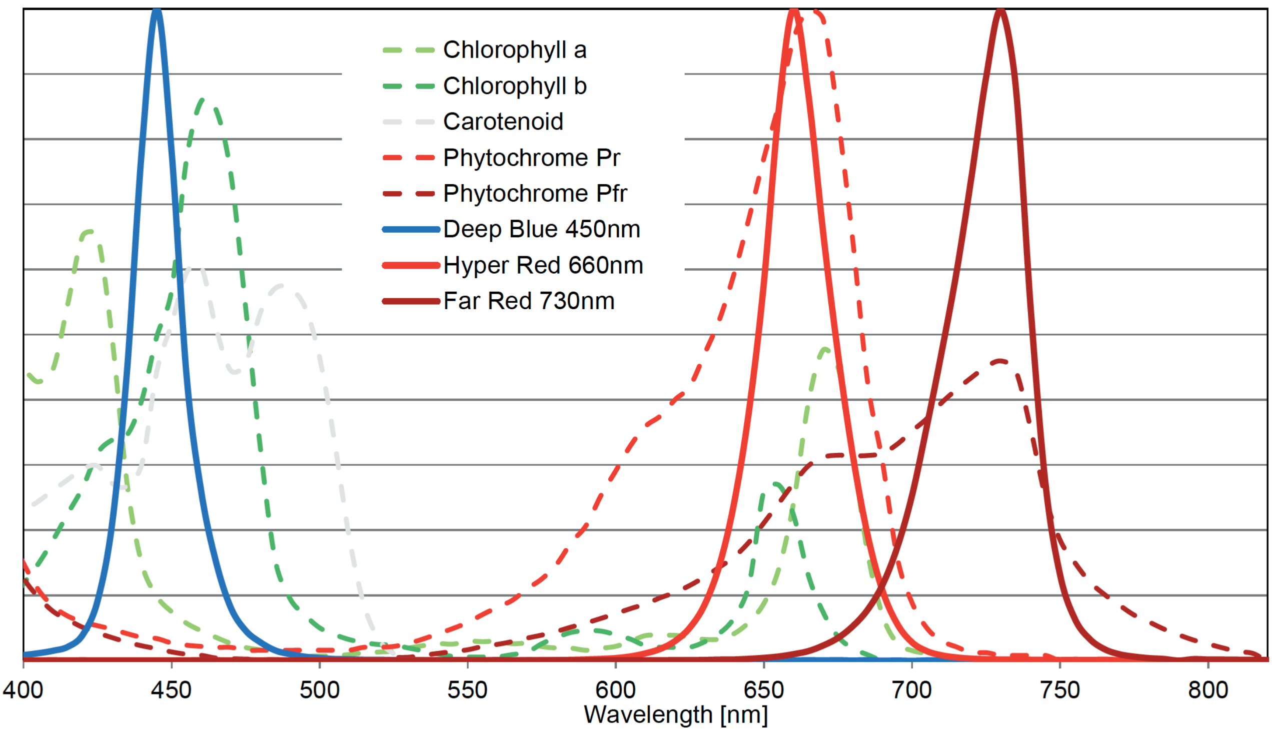

Fig.18 All three important wavelength available in the same LED package in OSRAM LEDs. © by Horticulture Lighting with LEDs | OS SSL | NR AW CH - OSRAM Opto Semiconductors| November 2016

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1.1.5.2 Impact of natural light cycle (day and night) on plants

Plant is an organism that responds to time and seasons. When spring arrive, the plant awakes from a long sleep, and producenew bugs. This is part of the seasonal biological clock.

The daily internal clock is defined as "Circadian rhythm". The term comes from Latin: Circa diem which literally means "around the day". There is a molecular biological clock that responds to the stimuli coming from the environment, as light and dark cycle, nutrients among other [18].. The knowledge on this topic is in a development process, and the molecular mechanism that stimulates the reaction in plant, are still largely unknown.

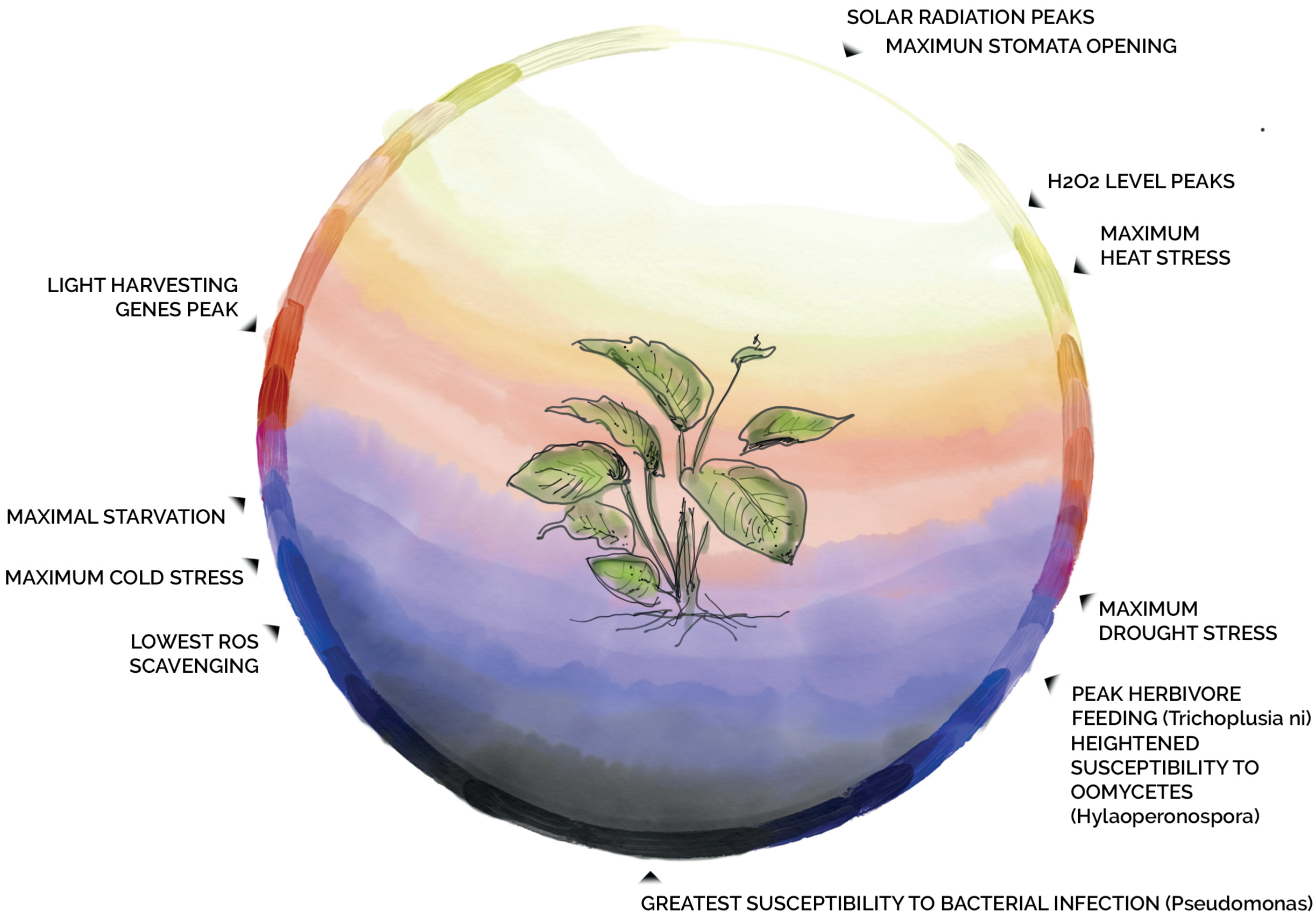

Fig.19 The clock of doom[19] - Plants are continually subjected to biotic and abiotic stress. Incidence of many of these stresses fluctuates over the 24-h cycle. This figure plots approximate peaks of these time-of-day dependent stress factors around the clock from dawn (ZT0) to dusk (ZT12), and back to dawn.

1.2 END USER IN OFFICE ENVIRONMENT

1.2.1 Biological and psychological human needs

Having plants as decoration in indoor spaces could have a positive impact on the mood of the people that use the space.
In fact, human perception is a complex mechanism that involves the eye and the brain on a conscious and unconscious level[20], and among many needs, humans have a biological and psychological need to be in contact with nature, through the visual information provided from the space, especially in the critical situation of indoor environment.
ILGW adds an aesthetic value to the space, and the atmosphere that brings into it, it's stimulating a multi sensorial experience for the users. Visual information arrives into the brain through the light that reflects on the surfaces around us..
The organic surface of the leaves of the ILGW is lit by daylight and/or artificial light, and in order to appear vivid and pleasant, necessitates an appropriate quality/quantity of light. This light changes over the day, and provides information about time and environment, also important for the human biological needs.

The psychological need of humans of being in touch with nature, has been objects of several studies. The psychologist Heerwagen, focused his exploration into the effect that footprints of nature have on people [21]. He carried out several test, to see the response in different subjects sitting on a desk to perform memory and problem-solving tests. The results revealed that a significant number of testers, performing on the desk decorated with acacia tree images, had a higher score in the tasks.

This was confirming his theory that humans assemble the icon of the acacia tree to the feeling of being secure, protected and nourished.

Fig.20 Moodboard - Light and time - Different appearance of a Ficus potted, under different lighting set up: 1 Daylight (Overcast sky); 2 Daylight (Clear sky); 3 Artificial light (Diffuse); 4 Artificial

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Fig.21 Acacia tree at sunset - Masaai Mara, Kenia ©by Julia Hartmann

Another essential element for relaxation of visual comfort and mood at the same time, are the fractals in nature. Fractals are defined as "A curve or geometrical figure, each part of which has the same statistical character as the whole. They are useful in modelling structures (such as snowflakes) in which similar patterns recur at progressively smaller scales, and in describing partly random or chaotic phenomena such as crystal growth and galaxy formation" (Oxford Dictionary). The density of fractals is the ratio between the parts of the figure and the empty part inside a defined area.

People have a stress-reducing experience with density around 1.4 [22].
These theories and knowledge, confirm the importance of creating a natural light distribution on the ILGW, following the sample that nature provides. The more natural (irregular) light distribution, the better.

Fig.22 Author's Photo - Walk in the park, Zurich - Im Viadukt

1.2.2 Physical components of the space

The modern office space is based on the idea of being smart and comfortable, and the principle of ergonomy for the users is one of the significant foundation. The office is the place where people spend most of their time, and for this reason, it's in the company's interest to provide a pleasant and functional space for them, in order to boost their productivity.
The installation of an ILGW in the working place as mentioned above, could add not only aesthetics, but also improve the well-being of the users.
During the design of the ILGW, the interior design style must be taken into consideration. For example, one must reflect and decide upon the choice of species of plants and the shades of green that best suit the material finishes (background and surrounding ILGW), as well as considering the lighting design concept, in particular whether artificial light is needed to support the plant life.
Regarding the colors of the plants, if the office space has low ceiling height, it is preferred to use light shades of green, to let the space appea bigger. The dark colors better suit a bigger or complex space, where the interplay of light and dark plants, can add emphasis and characteristic to the room.
Adding luminaires big in size to light the ILGW, could be not in harmony with the surrounding. For this reason the suggestion is to hide the luminaire when possible, or study a product design that is in line with the furniture and the materials of the interior design.

The first step is anyway the evaluation of daylight intake of the room, the position and size of the glazed openings, and the construction details of ceiling-walls-floor.

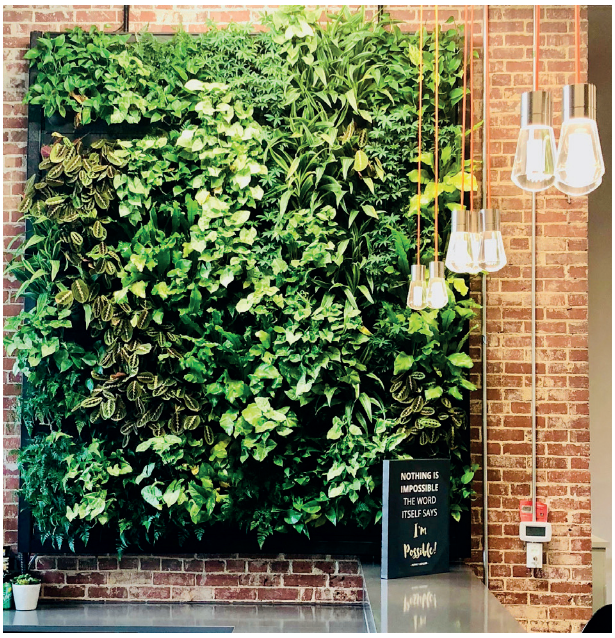

Fig.23 Co-wotking space- Industrial style: Interior design that allows to install pendant luminaires and track system lighting, without bothering the overall indoor environment. Charlotte coworking space © by thelaunchfactory.com

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1.2.3 Light for user

1.2.3.1 Visual Comfort

Biological effect of artificial light on eye tissues.

In the office environment, the users are exposed to artificial light constantly for hours with average period of 8 or more hours per day.
The Standard EN 62471 categorizes the photo-biological hazard due to artificial light exposure, in different classes[23]:

- Actinic UV-hazard for eye and skin
- UVA-hazard for the eye
- Blue-light hazard for the retina
- Thermal retina hazard
- IR-hazard for the eye

The hazards depend on many different factors, such as the eye health condition, age and time of exposure to light.

The UV band is sub-divided in three wavelength regions (CIE 2006/62471):
- UVA from 400–315 nm
- UVB from 315–280 nm
- UVC from 280–100 nm

As stated in the Health Effects of Artificial Light[24] report:

"*Exposure of the cornea to UVA and UVB usually induces reversible lesions of the corneal epithelium. UVC can induce lesions of the corneal stroma and the Bowman membrane leading to corneal opacity and potentially to corneal neovascularization. IR usually only causes irritation but may, at high energy levels (>3 mJ/cm2), also cause deep stromal lesions and even perforations. Protection from IR and UV components of the sunlight is therefore recommended in certain instances (Sliney 2001).*"

"The absorption spectrum of the lens changes with age. In young children, more than 80% of blue light is transmitted to the retina. At around 25 years of age, only 20% of the light between 300 and 400 nm and 50% of wavelengths between 400 and 500 nm is transmitted"

According to the information above, the strategy to support the visual comfort in office environment, cannot exclude the understanding of the harmful side of the lighting source utilized.

Glare.

When the light direction and intensity is miscontrolled, there are phenomena of glare. The glare is depending both on the luminance but also on the area where the light falls on. Comparing two identical light level sources, falling on two surfaces differing from each other on the size, the bigger one could generate a sense of discomfort for the user[25].
In the lighting design for the vertical greenery, it's indeed necessary to prevent glare phenomena, installing luminaires that avoid the critical angle that affects the users visual comfort. Shielding system , recessed luminaire sources, or other preventive action, have to be used in the office environment.

Fig.24 Luminaires without shielding. Glary effect from certain angles. Göteborg Energi, Gothenburg, Sweden © by Greenfortune.com

Fig.25 Pantone Green - Natural and artificial texture - © by greylessinseattle.com

Contrast and hierarchy.
The human eye is captured by bright areas of a space. This happens when the other areas have a low light level shining on their surfaces. This contrast of light and dark draws the eye's attention, and defines a hierarchy of the lit elements in the space.
The perception of depth, it is also connected to the prominence of a certain elements, due to its luminance. By boosting the contrast of different parts, it is possible to create some visual illusions that help in the definition of a hierarchy, improving the perception of the architectural space and giving clues about places of importance [26].

In a relaxation room for the employees, the ILGW could serve as the "picture" to glaze at, with the scope of relaxing the eyes and the thoughts. In this case, the living wall should create a little contrast with the surrounding space, in order to guide the focus on itself.
When the ILGW is used close to the working station, instead should have less accent on it, in order to not disturb the attention and focus of the people during tasks performance.

Color response.
Colors make the planet a better place. The response to colors by the human, it has been object of several studies, and the results until now, show that physiological and psychological color response is something subjective, but in some cases, researchers have found a common tendency. Birren [27] found out that the red color could raise blood pressure, and that that the opposite effect could be stimulated by the blue, as in nature the fire has a red color, and is burning and generating energy, while the blue sky is static and suggesting calmness.
Other studies underline that people looking at shades of natural green, have a boosting effect on their creativity and motivation. The human eye has the capacity of distinguish around 10 millions of different shades of colors.
The importance to have a light on the leaves, that reveals a true appearance of the plants, in the ILGW is thus a relevant factor. The human brain is connected to the vision and there is an unconscious connection between eye-brain, that verify and recognize a real natural element, from an artificial one.

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Fig.26 Leaf colors and structures © by Patrick Blanc

1.2.3.2 Impact of natural light cycle (day/night) on humans

„Biological clocks are an organism's innate timing device. They're composed of specific molecules (proteins) that interact in cells throughout the body. Biological clocks are found in nearly every tissue and organ. Researchers have identified similar genes in people, fruit flies, mice, fungi, and several other organisms that are responsible for making the clock's components.„[28]

As described above for the plants, these cycles of about twenty-four hours allows the organism to perform its biological functions, during the dynamism and the change of the environment (light and dark, nutrition, seasonal change).
The physiological responses during thetwenty-four hours, are described in the following diagram.

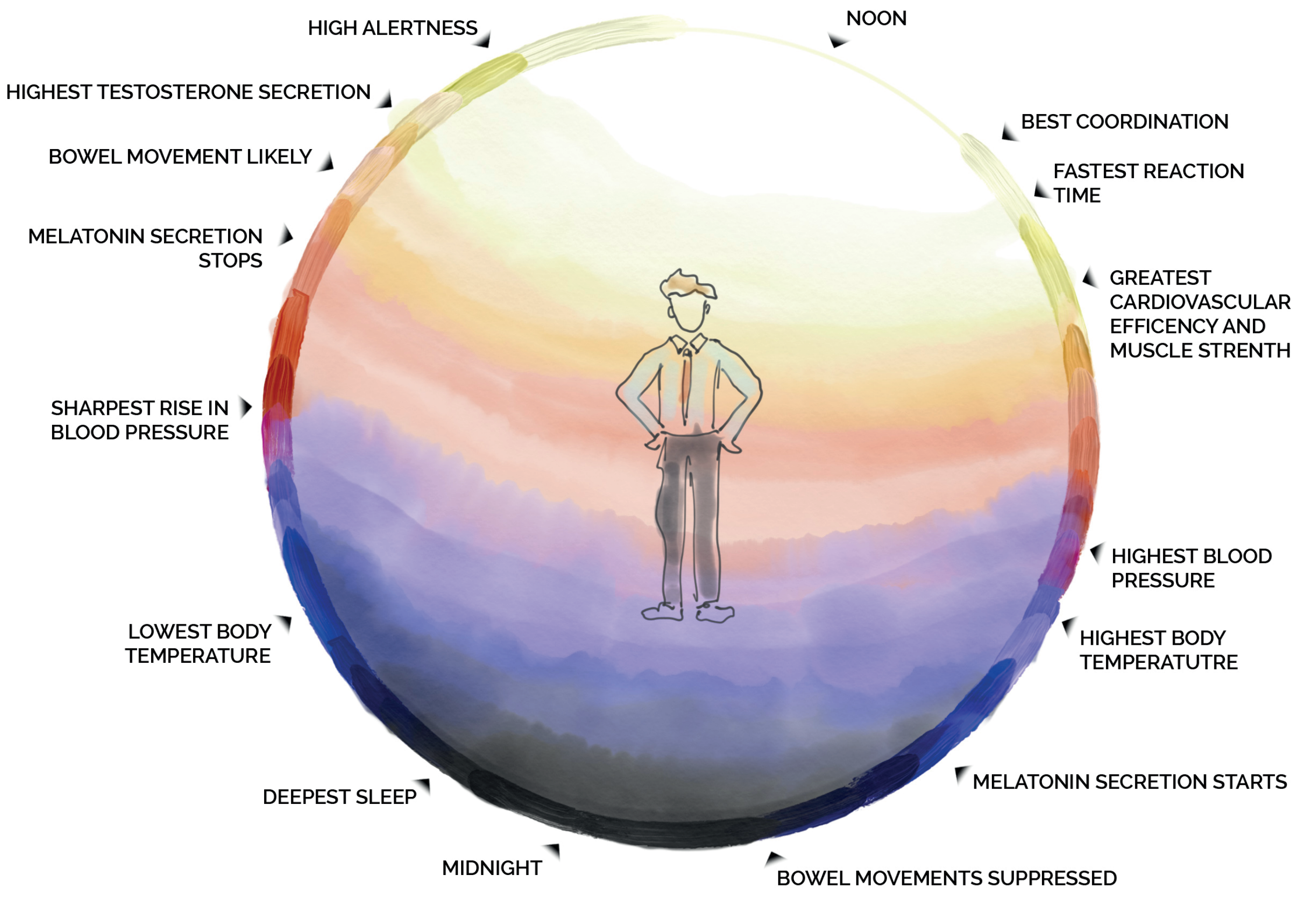


Fig.27 Human Biological clock

2. CASE STUDY:
Givaudan Innovation Center, Zurich,

2.1 About

The case study analysed in the report for my internship experience at Lightsphere GmbH, was the project for the new Givaudan Innovation Center located in Kemptthal, Switzerland.

Givaudan is a company that produces fragrances for different kinds of goods, such as food and perfumes, among other applications. The building will host offices and laboratories from the research departement.
The atrium of this building is the core element of the architecture as a means for representing the company's philosophy and heritage. Seven columns of vertical garden will stand in the middle of this atrium, providing a decorative and prestigious touch to the space, and symbolising the importance of nature for givaudan and its seven divisions. This is precisely the reason why the client asked for a deep study on the light conditions that the plants will be exposed to, in order to find the best solution to provide a good environment for the plants to grow by creating a symbol for Givaudans innovative capacity.
The project for the new Givaudan Innovation center is done by Bauart Architekten und Planer AG. It's an extension of an existing building in Kemptthal, located in the canton of Zurich, Switzerland. To enhance the space of the atrium, a space 12 meters high, with above 3 semi rounded skylights, the landscaper has designed seven green columns of vertical garden, standing in the middle of the atrium. The meaning behind the columns is to create an interaction of the work givaudan does with its exploration on new fragrances from plants and fruits all over the world. Bringing the diversity and natural aspect into the innovation

Fig.1 Rendering Atrium Givaudan Innovation Center © by Bauart Architekten

center to create space to meet, interact, relax and get inspired. The process of all the steps taken during the lighting design for the Givaudan living columns, and presented in the internship report, are:

- Daylight impact analysis
- Test of appropriate LEDs module with growing process of plants (selected for the columns),
- Concept research: position of luminaires
- Conclusion of defined solutions for this project: pros and cons

2.2 Criticism during the design process

As a fundamental process of understanding light impact into the atrium, a daylight simulation has been done during the internship report. By using the lighting simulation tool RELUX the atrium was built in 3D to better understand the architectural shape and daylight impact related to the circulation of the sun. By better understanding the daylight situation and the lack of light in some crucial areas helped to implement the concept for the artificial light. The daylight impact result, underlined a not ideal daylight distribution and intensity, to support plant's growing requirement.

The nature of this deficiency was due to two main factor:

-The geometrical factor of the living columns. The radial shape of the living wall, during the year, defines always a cast shadow on the plants hanging, on all the columns, on the side facing North.

-The architectural shape of the atrium. The architectural levels intersection, blocks the light flow coming from the skylights. This means that the upper part of the columns receives most of the daylight, and the low part of the columns receives a drastically decreased daylight level.

Since the project was already under construc-

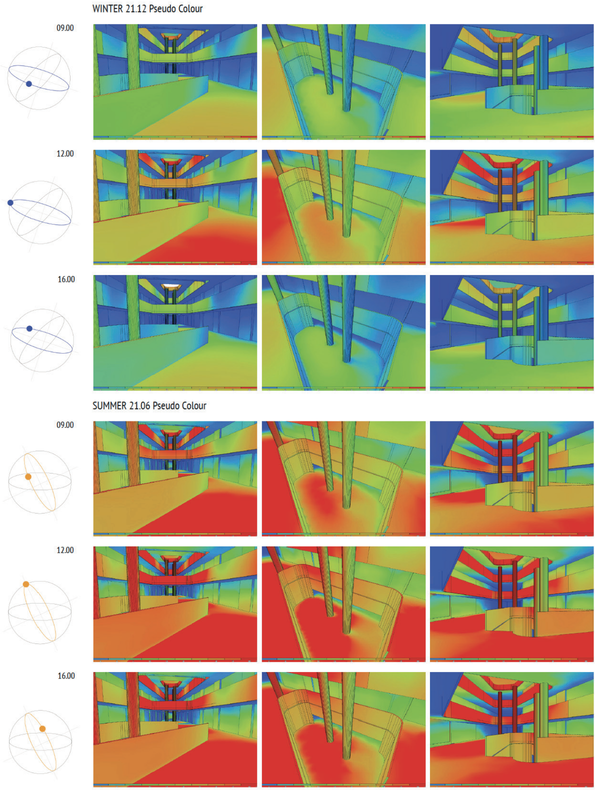


Fig.2 Daylight simulation. Relux. 3D model. Results show Winter and Summer daylight impact into the building

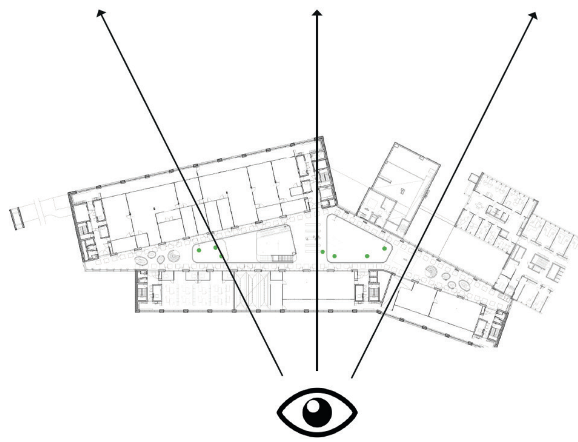
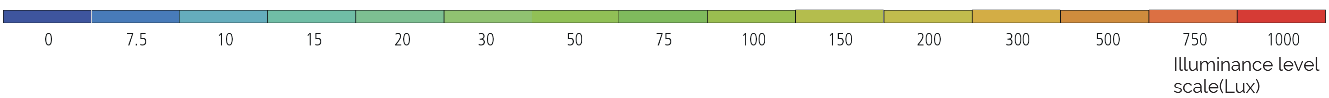


Fig.3 Architectural plan - How to read simulation's results



CASE STUDY

tion, the only strategy to support plant's life, was to add artificial light to light up the columns.
After this first step, the design process has been bouncing between conceptual ideas, testing (mockups -virtual simulations) and reshaped designs, to define an artificial lighting design concept in line both with the client and architect's vision and the needs of the plants itself.

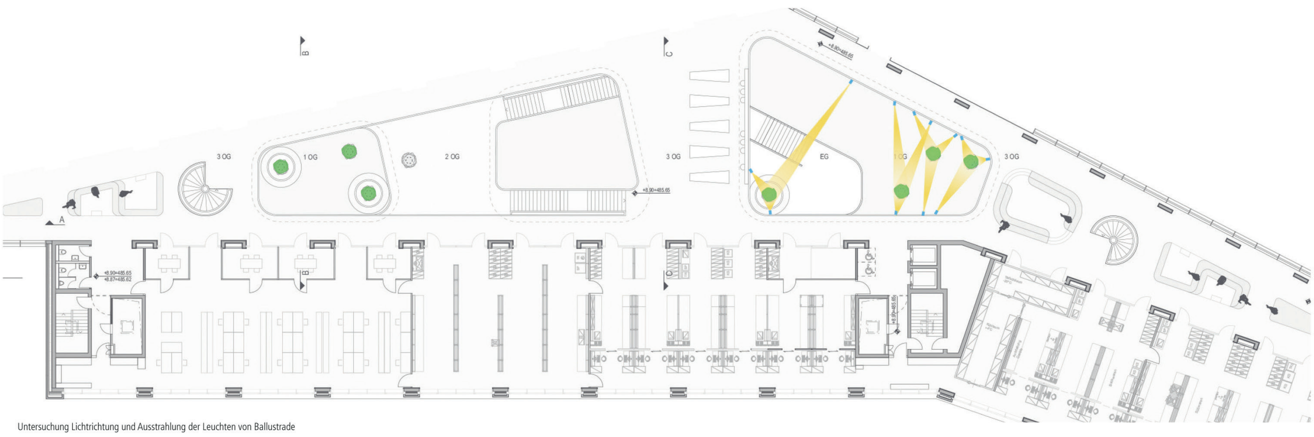
The mockups were made to evaluate:

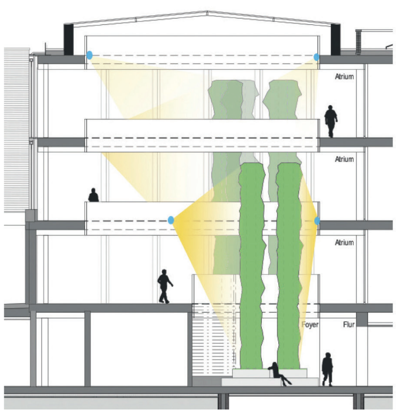
1. An appropriate LEDs module to support requirements for plant species selected by the landscaper
2. Position of luminaire in the atrium, without bothering the aesthetics of the architectural and interior design style

The two solutions presented at the end of this testing phase, to the client, were:

Balaustrade
The option n°1 is to place projectors on the white balaustrade that surrounds the void in each floor. Finding the right product to illuminate the cylindrical surface of the columns in a uniform way with distances up to 20m an beyond and still avoid glare, was a challenge in its own. A research among several lighting manufacturers has been done. With a geometric approach, from the plan view, and in section view, it is possible to estimate the minimum number of luminaires necessary to cover the entire surface of each columns with light. But to understand the light in space only a 1:1 Mok-up provides the answers in detail.

Hanging Luminaires
The option n°2 is a hanging modular luminaire, inspired by an organic shape and attached to the column surface, that it will be part of the column structure and camuoflages within the





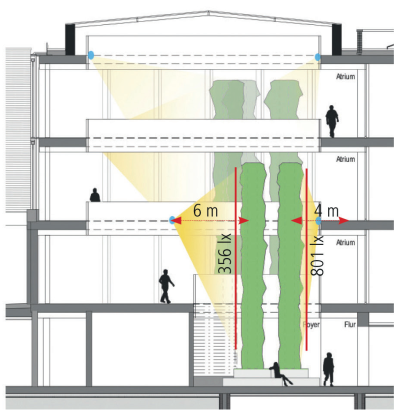


Fig.4 Plan - Sections - Render visualization of study option 1: Balaustrade © by Lightsphere GmbH

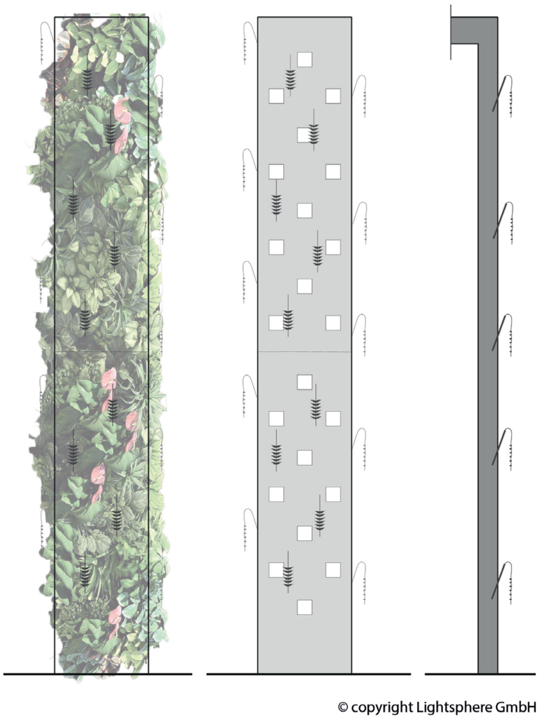


Fig.5 Illustration option 2 - Hanging luminaires - Section/front view
© by Lightsphere GmbH

surface of plants. The luminaire will be composed by small round-shaped plates with honeycomb louvers, connected to a linear stick fixed directly into the column structure. The design of the plates is thought to be orientable for the best flexibility spreading the light equally to the surface of the plants.

The results of the simulations and other observations, showed that there are pros and cons in both cases. Following, a list of what the results suggest:

Option 1 Balaustrade

- The mutual distance between each column and the closest possible point to fix the luminaire to the balaustrade, is in some cases too far to provide enough light on the column surface.
- There are some "no go areas", where it is not possible to fix any fixture, due to the glare issues for the users passing by the columns.Furthermore, there are issues related to the space necessary for the maintenance vehicle to drive freely around the columns.
- The total amount of fixture mounted on the balaustrade is high. this could interfere with the aesthetic harmony of the atrium.
- Singular LED for each luminaire: no flexibility for spectrum of light.
- Good uniformity of light distribution on the columns.
- a lot of shilding accessoiries necessary to prevent glare.
- the size of the fixtures itself.

Option 2 Hanging luminaires

- The light distribution on the column is more dense where the luminaire module is fixed. That means that a "spotty" effect could appear especially during the darkest winter day, when the overall amount of light in the atrium is less, and the contrast would be perceived more.
- Possibility of placing different LED chips in each module: provides a great opportunity creating the right light spectrum within the fixture.

2.2 Knowledge gained

The key point gained during this experience for the lighting design process for plants in an indoor architectural context, is that it is crucial to undertake a daylight study prevision, at an early stage of the building design process.
The possibility of taking advantage of the natural source of daylight does not only gain an economic advantage, but could also improve the overall atmosphere and aesthetics of the space, keeping the interior design free from any imposed additional object or system that could be visible and incompatible with the architect and client's idea for the final appearance of the building.

3. VISION

3.1 Initial research question

„Is it possible to enhance the quality of artificial illumination to fulfill growing requirements of natural plants and at the same time achieve visual comfort for the end user, creating aesthetically pleasing office environments?"

In the modern workplace, light supports different functions:

- guiding
- communicating
- focussing
- decorating
- relaxing
- inspiring

If we combine the role of the ILGW inside an office, with the categories above, we can highlight the function that relates to the ILGW: decoration, relaxation and inspiration for the employee's vision.
Looking at the strategy to achieve a good result of the lighting for ILGW, we should consider indeed different parameters.

- *Visual Hierarchy of room elements*
  - Ratio contrast VS uniform brightness (background/surrounding)
  - Visual focus (accent light)
  - Applied colour finishes (wall/furniture)
- *Correct Perception (quality and quantity)*
  - Luminance
  - CCT
- *Correct Location/Angle (position of light source)*
  - Glare free
- *Luminaire components (Light source, control gear)*
  - No flickering

Parameters connected to type of plants: leaves shape-leave size-glossiness leaves-shades of green

Parameters connected to architecture: to be planned accordingly to design of space and furniture

3.2 From the Initial research question to the Final research question

After having explored the different topics connected to the Initial research question, it is possible to define the Final research question.

„If the artificial light for ILGW supports the plant's growth, optimising intensity, direction and CCT, is it possible to achieve a pleasant effect for the user's visual comfort?"

The parameters depend on the following factors:

INTENSITY
-species of plants
-distance between the light source and the plants
-available daylight

DIRECTION
-interior design style
-architectural structure of the building

CCT
-light source spectrum
-shades of green of the leaves plant

4. CRITERIA

4.1 Criterion 1: Support Plant needs

The spectrum of the light that stimulates the plants needs, as we saw above, is the PAR region.
Light has different effects on the plant growth and biology. For a good maintenance, it is important to have a relatively slow growth rate of the leaves. Despite the slow growth rate, there will be a reinforcement of the roots, that will keep the plant stably fixed to the wall.
The intensity of the light needs to reach some quantities of μmol/m²s, that varies from plant to plant. Daily Light Integral (DLI) value depends on the family of the plant.
For this reason it is suggested to place the plants in a specific position, as far from the artificial lighting source as the plant value requires.

4.2 Criterion 2: Support user's visual comfort.

The visual comfort of the users depends on the biological effect of artificial light, as reviewed in the chapter 1.2.3.1 (Biological effect of artificial light on eye tissues). It's thus requested to avoid the eye's exposition to UV light.
The artificial light for the ILGW needs to be positioned in a way to avoid the direct angle with the users glaze, to prevent glare.
The contrast between the luminance on the plants and the surrounding vertical components of the space, have to be calibrated and balanced. Depending also on the function that the ILGW has, it is important to take into consideration the lighting effect to achieve.
The biological needs of the user, in particular the desire to be in contact with nature, must also be considered.

4.3 Criterion 3: Aesthetics

The beauty of the atmosphere that plants bring into a space.
Beauty connected to the visual appearance of the plant through light.

4.4 From the Criteria to the Parameters

4.4.1 Intensity

INTENSITY> TYPE OF PLANTS/POSITION OF ILGW IN THE ROOM

- Family of plants suggested by expert of ILGW (Interview)
- Interaction daylight - plants

4.4.2 Direction

DIRECTION> BEAUTY IN NATURE VS ROOM'S ATMOSPHERE

- Patterns and shadows (possible lighting strategies)

4.4.3 Spectral distribution and CCT

SPECTRAL DISTRIBUTION AND CCT> LEAVES APPEARANCE UNDER ARTIFICIAL LIGHT

- interaction different spectra of light with the shades of green (test)

5. EVALUATION PARAMETERS

5.1 INTENSITY: Type of plants and position of ILGW in the room

The intensity of the artificial light depends on the family of plants. As the expert suggested in the interview (see above in chapter 1.1.3.2), the producer of the ILGW usually has a list of families of plants, that out of their experience, defines which type is suitable for the indoor purpose. there is also a body of research and studies[1] made on several plants, that provides an optimal DLI value to reach for each one.
The position of the ILGW in the space, depends on the Daylight availability.
If the daylight condition is enough for the plants, the position of the ILGW shouldn't be positioned too close to the glazing openings, in order to prevent burnt leaves phenomena, especially during the hot season (Fig.1).

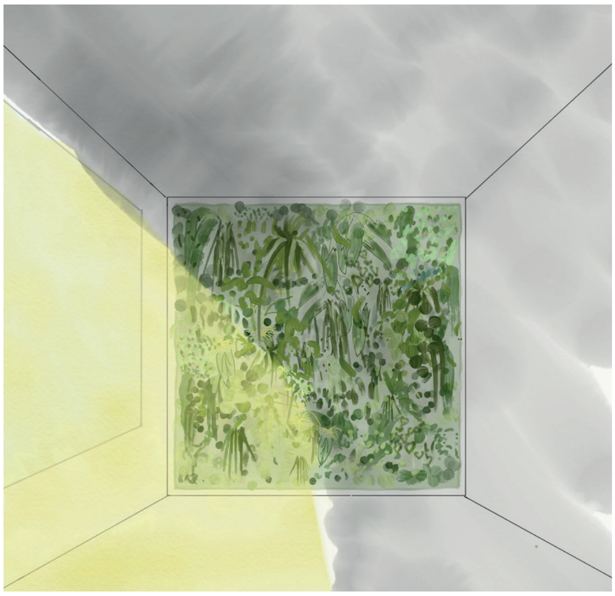


Fig.1 Direct sunlight on ILGW - Avoid to prevent burnt leaves.

For the daylighting prevision, it is possible to use software such as VELUX Daylight Visualizer, which allows us to simulate the direct light intake a room, for a specific site, during the entire year. In this way is possible to measure the minimum distance from the glazed opening, and create a "suitable" area for the position of the ILGW.

EVALUATION PARAMETERS

In case of shading system, it's important to have an overview on the usage of it, during the week. The better practices suggest that artificial lighting be installed even in good daylight conditions, to prevent long period of darkness caused by shutters left down during the weekend by the employees, or in general for standard process of the building management (e.g. security).

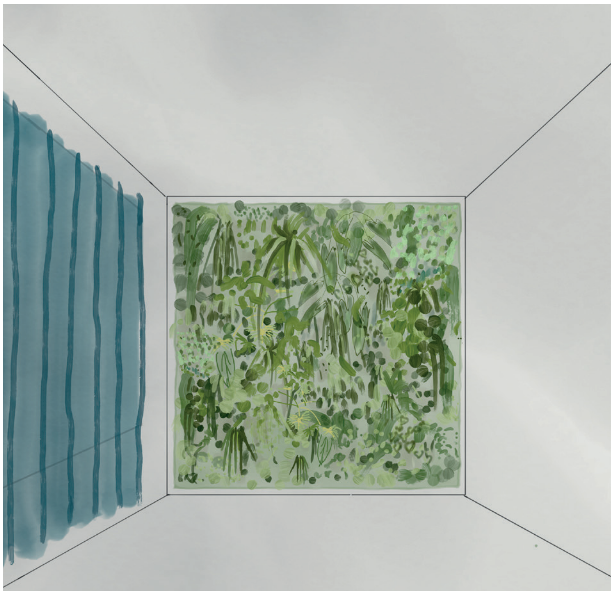


Fig 2 Shading system producing darkness for long periods.

EVALUATION PARAMETERS

A possible approach for the light intensity study, could be summarized with these two cases:

- Daylight+ General ambient light condition **optimal** for plant growth: selection of species of plants; positioning accordingly to the light measurement map

The first step is the site analysis. The light level* is measured in different points of the ILGW area, and out of this data, it is possible to map the area as shown in Fig. 3

*different light levels during day/year
*evaluation of best/worst condition

The second step is the selection of species of plants that request an amount of light that is possible to reach in the map.

The third step is to position the plants in the ILGW, comparing the light level available to the light level needed from the single specie (Fig.4).

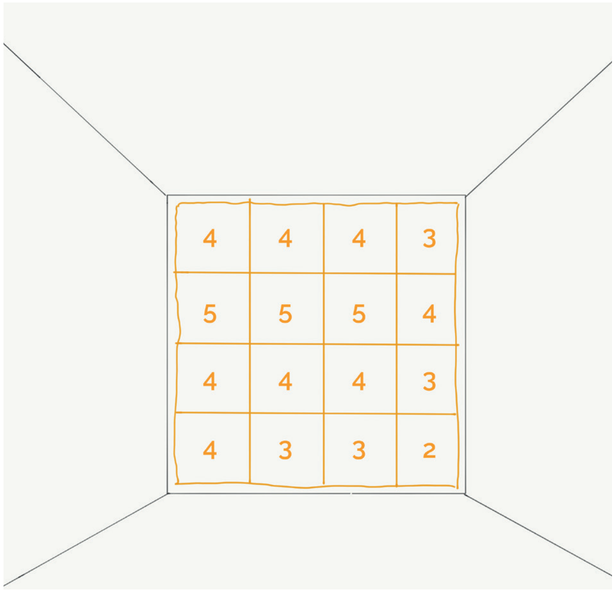


Fig.3 Measurement Map of daylight-ambient light availability

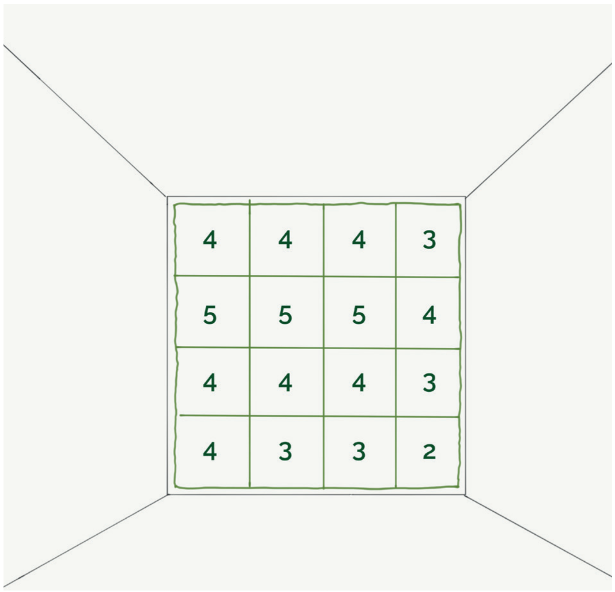


Fig.4 Position of several plants, following the Measurement Map of daylight-ambient light availability

The numbers indicate a value that has no unit. The single number want to represent the matching between the light level on the map, and the light level that supports plant growth.

EVALUATION PARAMETERS

The other approach is shown below:

- Daylight+ General ambient light condition **not sufficient** to support plant's growth: Artificial lighting design concept considering the interior design style and the construction details; mapping the ILGW area with light levels; choosing the species of plants; more flexible positioning of the plants in the ILGW (more flexibility for the artistic composition of the shades of green)

The first step is the site analysis. The light level is measured in different points of the ILGW area, and out of this data, it is possible to map the area as shown in Fig. 5

The second step is the artificial lighting design, that should consider the interior design style (surfaces and materials) and the construction details, to better assess the possibility to integrate the lighting fixture into the ceiling/floor (Fig. 6-7-8)

The third step is the selection of species of plants that request an amount of light that is possible to reach in the map (Fig. 9-10-11)

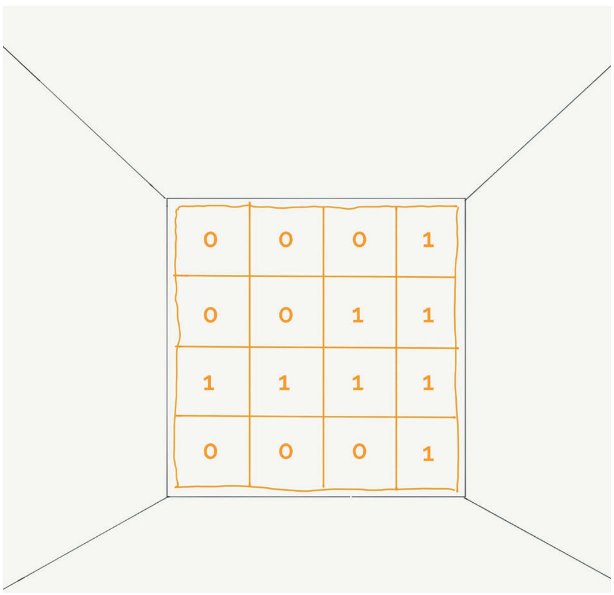


Fig.5 Measurement Map of daylight-ambient light availability

EVALUATION PARAMETERS

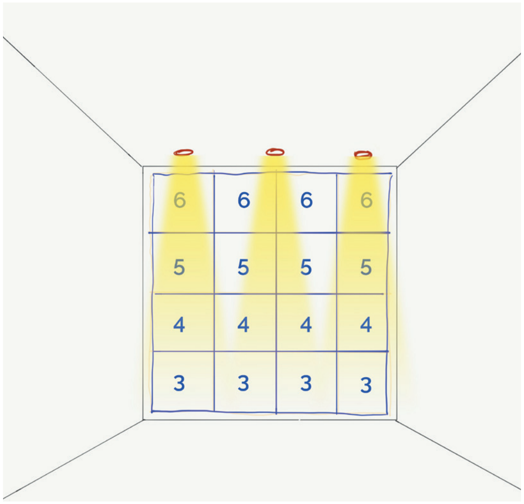


Fig.6 OPTION 1. Artificial lighting design concept; map of the ILGW area with light levels

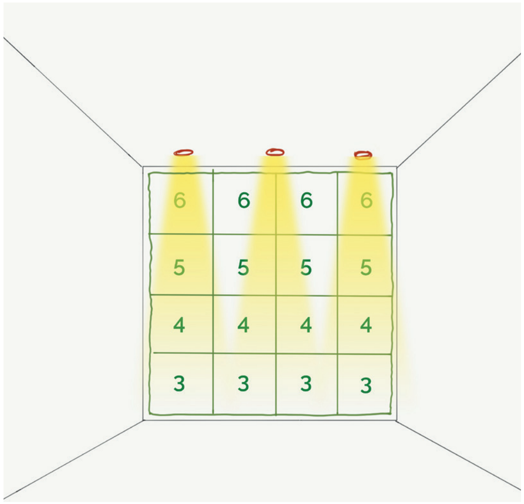


Fig.9 OPTION 1. Position of several plants, following the Measurement Map of the artificial lighting design

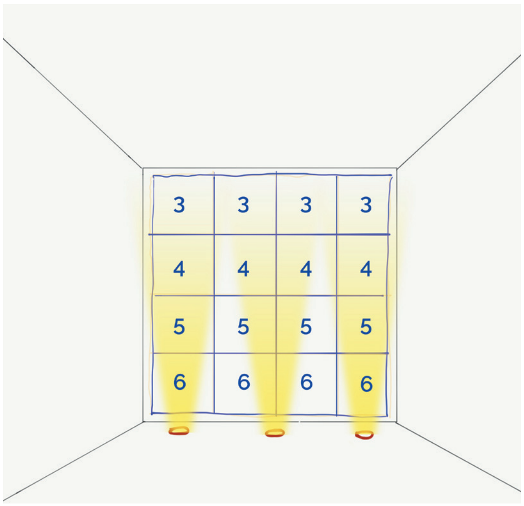


Fig.7 OPTION 2. Artificial lighting design concept; map of the ILGW area with light levels

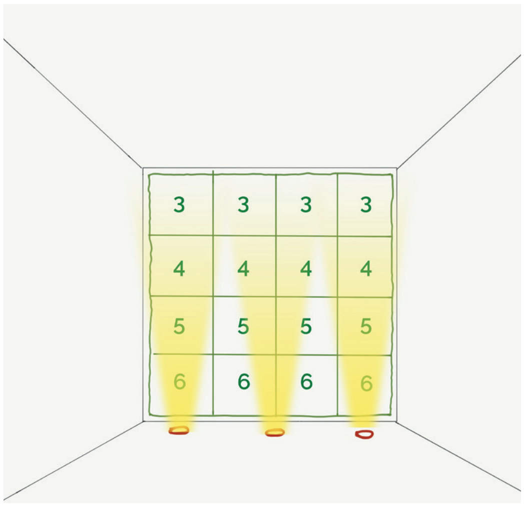


Fig.10 OPTION 2. Position of several plants, following the Measurement Map of the artificial lighting design

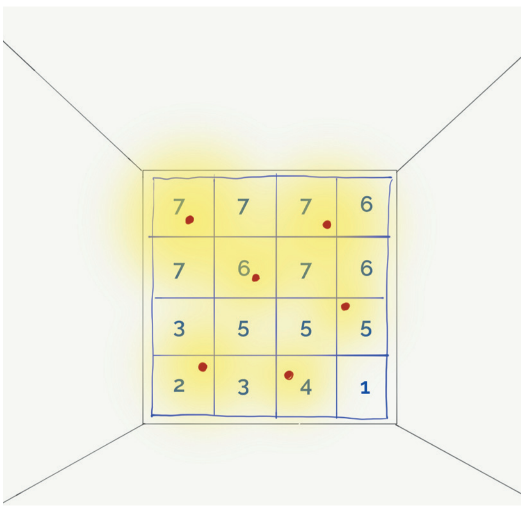


Fig.8 OPTION 3. Artificial lighting design concept; map of the ILGW area with light levels

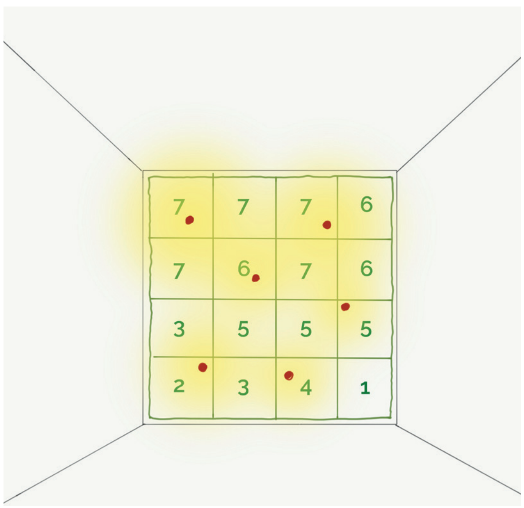


Fig.11 OPTION 3. Position of several plants, following the Measurement Map of the artificial lighting design

EVALUATION PARAMETERS

5.2 DIRECTION: Beauty in nature vs room's atmosphere (patterns and shadows)

Depending on the position of the lighting source and on the light distribution, the living wall will appear more or less "natural".
The position of the lighting source is dependent on the interior design style and on the construction details of the architecture itself.
To support the user's biological needs, it is relevant to achieve an artificial light that aims to reconnect the users with nature. A strategy could be to recreate a pattern within light and shadows, that reminds us of a natural environment (Fig.13).

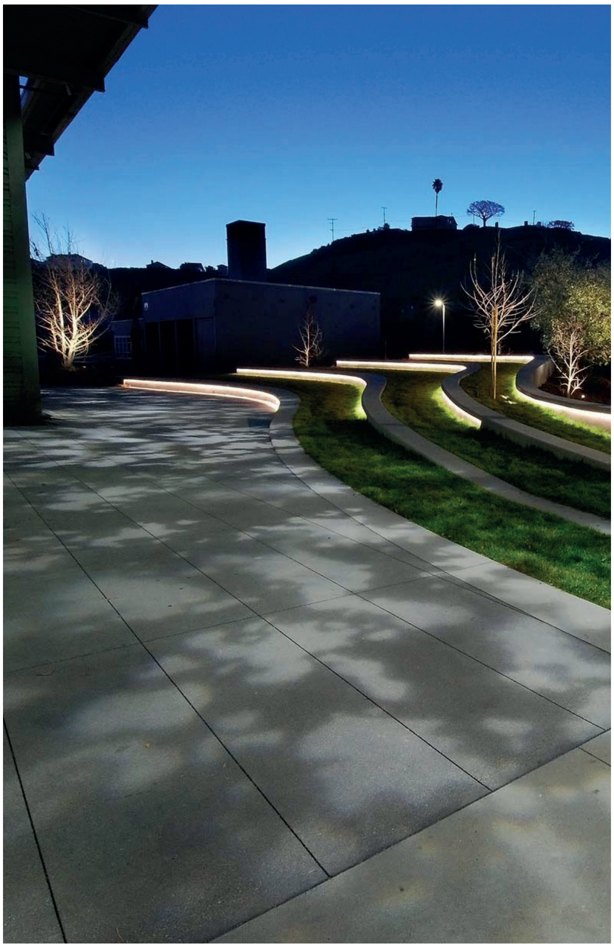


Fig.13 Gobo projection with natural pattern. Designing a "Moonlit Theater" for YouTube | © by Oculus Light Studio

Fig.14 Walk in the park - Zurich - Im Viadukt

The walk in the park or in the forest (Fig.14), has a relaxing effect on people. This calming effect is due to the fractal shadows on the walkway: a repetitive irregular shape, that repeats itself many times in smaller size.

Considering these psychological benefits, the light distribution for the ILGW should be something that avoids uniformity, and that enhances the beauty of the plants, as in a natural environment.
In the following sketches, we will lay out a possible approach to this new lighting strategy.

EVALUATION PARAMETERS

This sketch aims to represent the ILGW under a gobo projection lighting.
The light distribution recreates a typical Tropical forest imaginary, where the plants are hidden in shadows and sparkling under the shafts of sunrays that fall on the leaves.

Fig.17 Lastolite Gobo Set © by Nature | Kayell Australia

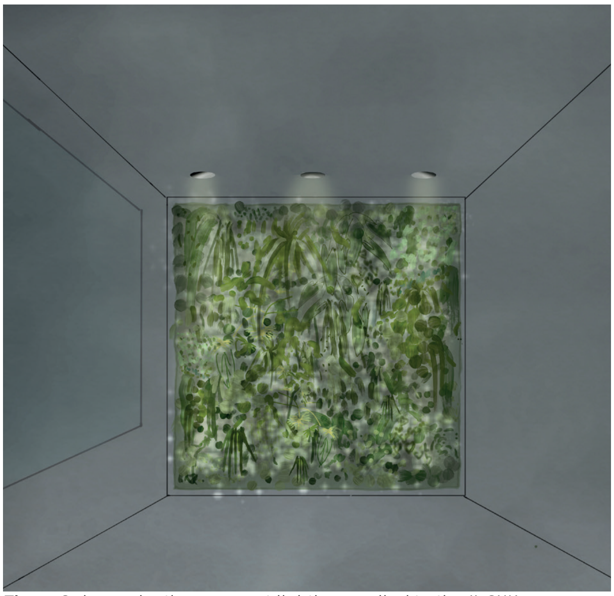


Fig.15 Gobo projection concept lighting applied to the ILGW

Fig.16 Tropical forest- Mossman George- Queensland- Australia

EVALUATION PARAMETERS

Another strategy to avoid uniformity, is shown in the next figure (Fig.18). The biophilic design concept, could be applied also to the shape and color of the luminaire, The light distribution is not even, and could also be customised and dimmable for the specific families of plants. The light is close to the wall, and does not produce glare for users.
The lighting installation is hanging by a tiny steel wire, and it is repeated repeated as many times as needed .
Furthermore, the luminaire camouflage itself, without disturbing the harmony of the ILGW.

Fig.18 Nature- mimic luminaires shape

5.3 SPECTRAL DISTRIBUTION AND CCT(K) (Leaves appearance under artificial LED light)

To evaluate these parameters, a lighting test experiment has been done. We will look into it in the next chapter (6. LIGHTING TEST EXPERIMENT)

Fig.19 Sting of pearls-Pinterest

References

[1] James E. Faust. *FIRST Research Report Light Management in Greenhouses I. Daily Light Integral: A useful tool for the U.S. Floriculture industry*. https://www.specmeters.com/assets/1/7/A051.pdf (Accessed on the 05-03-2018)

6. LIGHTING TEST EXPERIMENT

SPECTRAL DISTRIBUTION AND CCT(K)
(Leaves appearance under artificial LED light)

6.1 Introduction

The lighting test experiment aims to evaluate the visual effect, on an array of ornamental plants, under light emitted from monochromatic LEDs, by changing the spectral composition and CCT using a dmx control, in order to study the interaction between the leaves appearance and the blue/red amount of the wavelengths, relevant to the growth of the plants.

The lighting test will comprise of different phases in order to achieve a suitable spectrum for each case of four ornamental plants. The phases are explained later on in the chapter.

The photographic comparison method used to evaluate the results, should help in an analysis of the imagery, a comparison of individual features, an evaluation of the significance of the comparison, and a verification of the comparison.

6.2 Technical equipment used during the lighting test - an overview

- Spectrometer device Asensetek Lighting Passport ™ - model no. ALP-01- DC 5V-500mA
- Spectrum Genius Mobile (SGM): iPhone App SGM Asensetek Version 3.3.2
- Spectrum Genius Agricultural Lighting (SGAL): iPhone App SGAL Asensetek Version 2.2.0
- Luminaire: SE B50x60-P32-RVUW_Full spectrum luminaire (61cm - 2,8 kg/m)
- DMX control: Cameo Control6 DMX Pult, 230 V
- Camera reflex Model CANON EOS D750 - DC 18-55 Manual settings (Aperture f/4.5, Shutter Speed 1/50s, ISO 125)

Fig.1 Spectrometer device by Asensetek Lighting Passport
https://lumicrest.com

Fig.2 Position of the camera CANON EOS D750 in relation to plants and the LED luminaire

Fig.3 Position of the Spectrometer in relation to plants and the LED luminaire

LIGHTING TEST EXPERIMENT

6.3 Ornamental plants used during the lighting test - an overview

The following species of plants were selected for the lighting experiment, out of the species selected by the landscape designer, in the design for the ILGW reported in the case study (Chapter 2.Case Study):

- Cyrtomium falcatum
- Epipremnum aureum
- Chlorophytum comosum
- Billbergia nutans

The plants discriminate in shape, colour and glossiness of the leaves, to better analyse the visual effect.

Group of ornamental plants used for the lighting test. Picture Fig.4 has been taken in the indoor office environment, in the afternoon with daylight/sunlight exposure via glass windows. This image has been chosen as a benchmark for the appearance of colour and glossiness of the leaves, as the daylight provides the best visual appearance of any object.

The proposed families of plants are often applied in ILGW due to the low level of light requirements for the photosynthesis process.

Fig.4 The proposed families of plants are often applied in ILGW due to the low level of light requirements for the photosynthesis process.

Fig.5 Cyrtomium falcatum

Fig.6 Epipremnum aureum

Fig.7 Chlorophytum comosum

Fig.8 Billbergia nutans

6.4 Physical set-up

It was important to define a physical set-up as a dark room that allows precise lighting measurements. In the Figure 9, the room is shown with the general light on, to recognize the silhouettes of the technical parts. The test was carried out in the office of Lightspehere GmbH in Zurich/CH, during the night hours from 10pm-3am. All windows of the room were closed with the electric blinds, so that there was no light trespass from the adjacent street. As an additional precaution, to prevent any light bounced from the floor, a professional black opaque fabric was placed on the floor. There was no other light in the room switched except the LED luminaire.
The camera was positioned on a tripod, and the pictures were taken using a remote control, to prevent any movement of the camera.
The spectrometer device, was positioned on top of a black box, to reach the same height of an imaginary plane were the leaves were falling, inside the camera's captured frame.
The luminaire was suspended from a wooden structure, perpendicular to the floor, at a distance from the leaves and sensor of 200 mm, as depicted in the sketch (Fig.10).
All lighting scenes were arranged by using the DMX control, in the dark, and were static until the end of each phase.
The luminaire was set for 100% intensity during all the phases.

Fig.9 Experimental lighting test set-up. All the light sources in the test room were switched off, not to interfere with the test results. A black matt fabric was on positioned

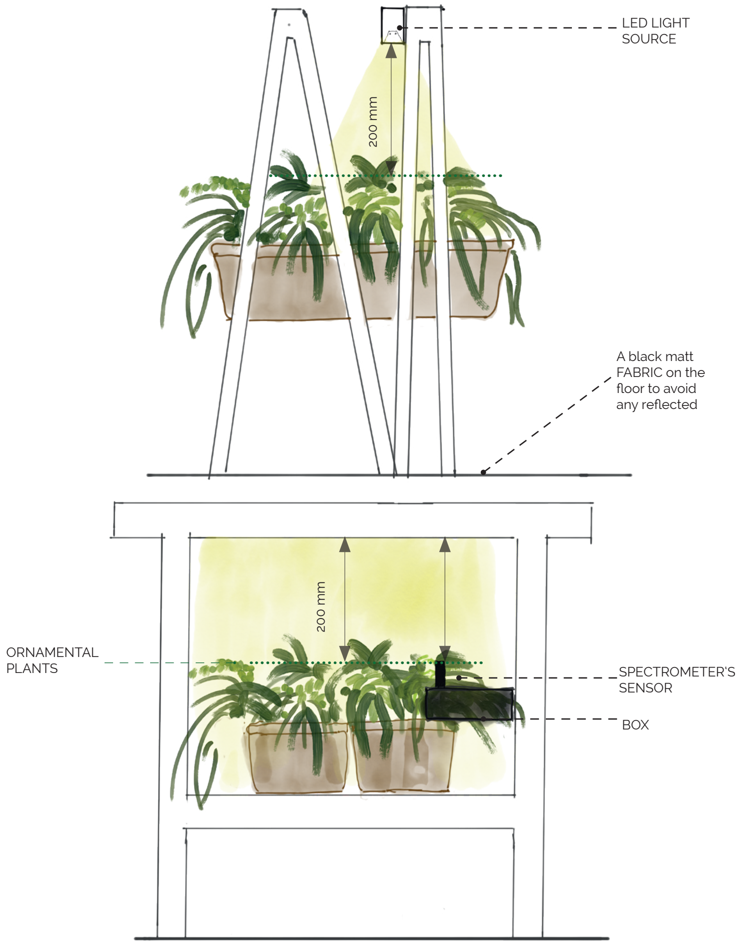


Fig.10 The image defines the distance between the light source and the spectrometer's sensor. It was based on the average distance between the light source and the leaves considered for the test.

LIGHTING TEST EXPERIMENT

6.5 Methods - Phases

The experiment consists of two main steps:

STEP1: PRETEST, to defined:
-Luminaire output
-Spectrum required to fulfill the plants growth
-Spectrum required to visually support he user in office environment.
STEP 2: TEST
-Spectrum obtained by merging the spectra plants/user (Curve inside the subtraction of definite integrals of spectrum1 and spectrum 2 functions).
-Visual comfort spectrum (plants appearance similar to sunny afternoon condition)
-Experimentig with Red/Blue ratio (R/B=2, R/B=1 R/B=0.5)

PRETEST (PT):
Phase 0 (PT_0):
Measurements of the LED lighting source output, with and without the opaque filter and the prismatic filter.

- Single monochromatic chips NO FILTERS (PT_0_Red, PT_0_Green, PT_0_Blue, PT_0_White)
- All on monochromatic chips NO FILTERS (PT_0_RGBW)

- Single monochromatic chips PRISMATIC FILTER (pf) (PT_0_pf_Red, PT_0_pf_Green, PT_0_pf_Blue, PT_0_pf_White)
- All on monochromatic chips PRISMATIC FILTER (pf) (PT_0_pf_RGBW)

- Single monochromatic chips OPAQUE FILTER (of) (PT_0_of_Red, PT_0_of_Green, PT_0_of_Blue, PT_0_of_White)
- All on monochromatic chips OPAQUE FIL-TER (of) (PT_0_of_RGBW)

- Single monochromatic chips ALL FILTERS (af) (PT_0_af_Red, PT_0_af_Green, PT_0_af_Blue, PT_0_af_White)
- All on monochromatic chips ALL FILTERS (af) (PT_0_af_RGBW)

The measurements of the monochromatic LEDs were taken in a vertical alignment with the single LED chip, horizontally centered with it, at a distance of 100 mm (Fig.11).
Due to copyright reason, it is not possible to show the arrangement of the LEDs chips in the luminaire.

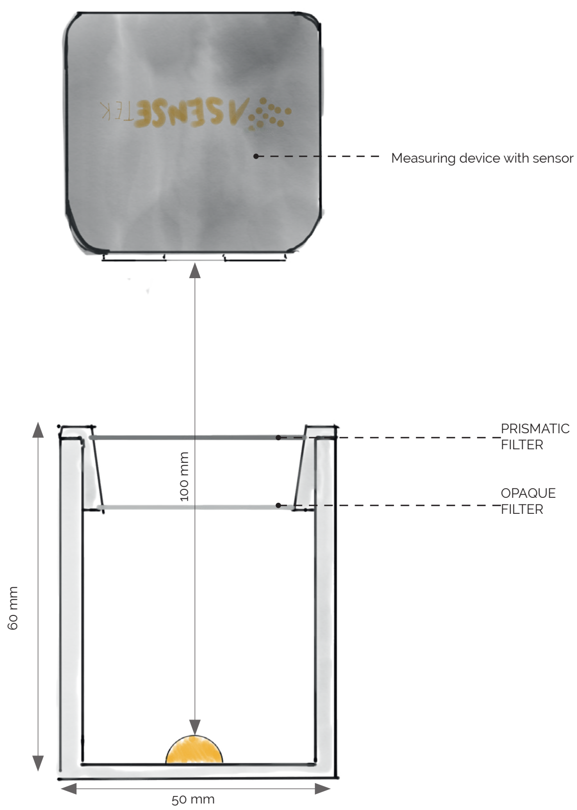


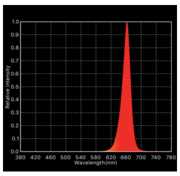
Fig.11 Section through the LED luminaire indicating distance between LED chip and sensor of the measuring device

PRETEST_Phase 0

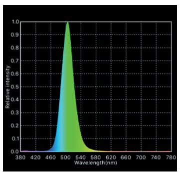
LED's lighting source output

	Values obtained from the luminaire manufacturer's datasheet in nanometer (nm) or	No filters applied	Prismatic filter (pf)	Opaque filter (of)	Prismatic + Opaque filters (af)
Hyper-Red LED chip	660 nm	659 nm	657 nm	663 nm	663 nm
Green LED chip	505 nm	502 nm	504 nm	505 nm	505 nm
UltraViolet LED chip	367nm and 395 nm	395 nm	395 nm	394 nm	395 nm
White	4000 K	4852 K	3901 K	3979 K	3888 K
RGBW		4360 K	4438 K	4518 K	4470 K

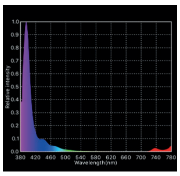
Spectra with Prismatic+Opaque filters



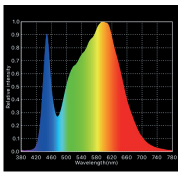
Hyper-Red



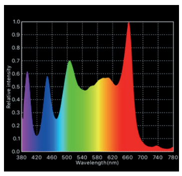
Green



UltraViolet



White



RGBW

*Every single monochromatic chip was measured at 100% of its intensity

Fig.12 Pretest_Phase 0_Data collected

LIGHTING TEST EXPERIMENT

PRETEST (PT)

Phase 1 (PT_1) Setting the spectral distribution of the LED lighting source that supports CRITERION n.1 [4.1] Support plant needs.

Kevin R. Cope and Bruce Bugbee[1] examined the effect of absolute and relative amounts of blue light on plants growth and development. The conclusion of the study was that the plant's growth and morphology depends on several aspects, as for example the age and the species of plant. Overall, a higher amount of absolute blue light, directed the growth toward a compact shape.

In the maintenance of the ornamental plants, the expert's advice (interview with Mr. Bulgarelli) states that it's preferred to have steam not too long and a relatively slow growing process, in order to avoid empty areas between the vegetation that show the soil behind on one hand, and on the other hand, to keep the maintenance process sustainable.
According to the ornamental plants needs, the setup of the above "ideal" spectrum for plants growth (SPECTRUM1) built for the test, was established, It refers to the percentage of total PPF values within the Neutral Led type from Kevin R. Cope and Bruce Bugbee[2] experiment, where there is balance between the leaves area and the steam elongation response (Fig.13)
The percentage of total PPF in the neutral Led type are 19.1% (Blue), 47.9 % (Green) and 33% (Red).

Furthermore, another parameter important for the plants is the Daily Light Integral (DLI).
Studies[3] have demonstrated that each specie of plant develops better under specific DLI values. Considering the families of plants utilized in the test, the value to reach will be in the range of DLI= 4-6 ($\mu mol \cdot m^{-2}$)

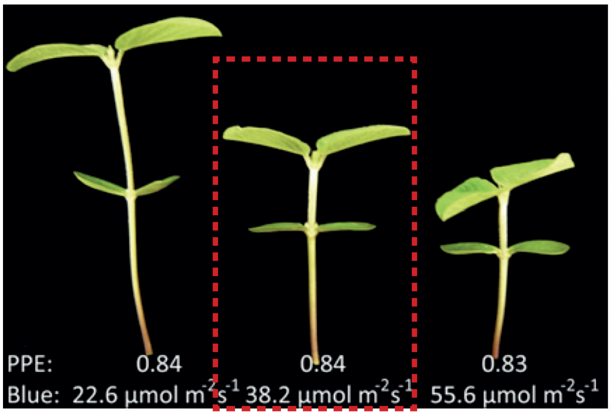


Fig.13 The effect of absolute blue light (mmol·m−2·s−1 of blue photons) on soybean stem length at 9 DAE in the low light treatment (200 mmol·m−2·s−1). Stem elongation decreased with increasing blue light although phytochrome photoequilibria (PPE) was nearly constant across [a]

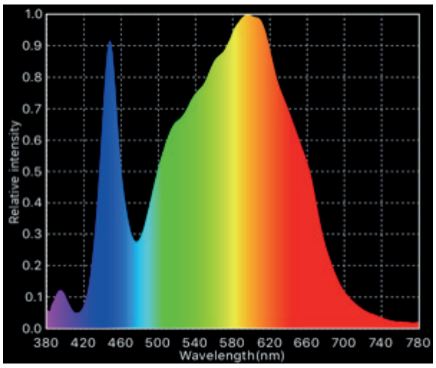
Overview of the measurements and data recorded, for the spectrum for plants growth (SPECTRUM1)

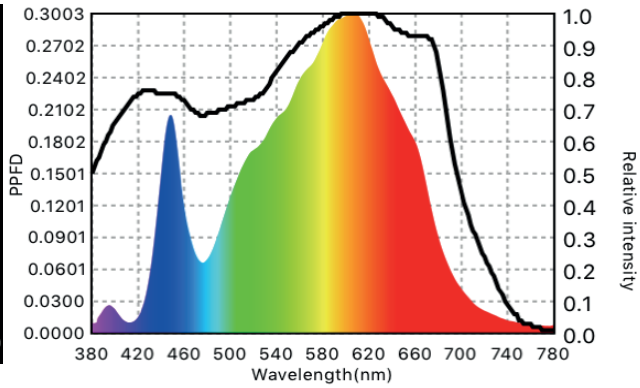
- measurement with Spectrum Genius Mobile (SGM) : (PT_1_SPECTRUM1_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (PT_1_SPECTRUM1_SGAL)
- Picture of the plants (PT_1_SPECTRUM1_Image)

LIGHTING TEST EXPERIMENT

PRETEST_Phase 1

SPECTRUM1 (plants)





SPECTRUM1_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
3693	3867	85	595

SPECTRUM1_SGAL

DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
4.2646	49.359	18.803	21.975	8.5789

*Color tint could appear different in case of special screen set-up/printer set-up.
One have to make sure to have a standard color and saturation set-up.

Fig.14 Pretest_Phase 1_Data collected

LIGHTING TEST EXPERIMENT

PRETEST (PT)

Phase 2 (PT_2) Setting the spectral distribution of the LED lighting source that supports CRITERION n.2 [4.2] Support user's visual comfort.

In the office environment, the users are exposed to artificial light constantly for a long hours with average period of 8 or more hours per day. The Standard EN 62471 categorizes the photo-biological hazard due to artificial light exposure, in different classes[4]:

1. Actinic UV-hazard for eye and skin
2. UVA-hazard for the eye
3. Blue-light hazard for the retina
4. Thermal retina hazard
5. IR-hazard for the eye

The hazards depend on many different factors, such as the eye health condition, age and time of exposure to light.

The UV band is sub-divided in three wavelength regions (CIE 2006/62471):
- UVA from 400–315 nm
- UVB from 315–280 nm
- UVC from 280–100 nm

As stated in the Health Effects of Artificial Light[5] report:

"Exposure of the cornea to UVA and UVB usually induces reversible lesions of the corneal epithelium. UVC can induce lesions of the corneal stroma and the Bowman membrane leading to corneal opacity and potentially to corneal neovascularization. IR usually only causes irritation but may, at high energy levels (>3 mJ/cm2), also cause deep stromal lesions and even perforations. Protection from IR and UV components of the sunlight is therefore recommended in certain instances (Sliney 2001)." [6]

"The absorption spectrum of the lens changes with age. In young children, more than 80% of blue light is transmitted to the retina. At around 25 years of age, only 20% of the light between 300 and 400 nm and 50% of wavelengths between 400 and 500 nm is transmitted" [7]

Tissue/ molecule	Wavelength (nm)	Mechanism	Consequence
Cornea	<300 and >800	Heat dissipation	Keratitis, droplet keratopathy
Iris	Melanin: 380-700	Heat dissipation	
Lens	Peak at 365 at 8 years Peak at 450 at 65 years	Heat dissipation	Cataract (nuclear and/or cortical)
Retina	400-700 Rhodopsin: 507 SWS: 450 MWS: 530 LWS: 580	Photochemical damage type I: max at 507 nm type II: max at shorter wavelengths Toxicity potential	Solar retinitis Maculopathy Aggravation of retinopathy
RPE	Melanin: 380-700	Heat dissipation	Potentiation of lipofuscin toxicity (melanolipofuscin)
Lipofuscin	355-450 A2E: peak at 430-440	Photodynamic effect Retinal toxicity	Solar retinitis Age-related maculopathy (probable) Aggravation of retinopathy
Xantophylle pigments	Lutein: 446 Xanthine 455 Zeaxanthine 480	Heat dissipation	Reduced blue light toxicity Protects against AMD

Fig.15 Interaction of light with eye tissues and chromophores. Health Effects of Artificial Light, Scientific Committee on Emerging and Newly Identified Health Risks

According to what explained above, the strategy to support the visual comfort in office environment, cannot exclude the understanding of the harmful side of the lighting source utilized.
The other parameters, such as contrast, glare and color response, will be evaluated in a successive step of the test.
The setup of the "ideal" spectrum for human in office environment (SPECTRUM2) built for the test, indeed will take into account the hazards (UV-band related), with a limitation in the spectrum of the intensity of UV-A/B/C.

Overview of the measurements and data recorded, for the spectrum for human in office environment (SPECTRUM2):

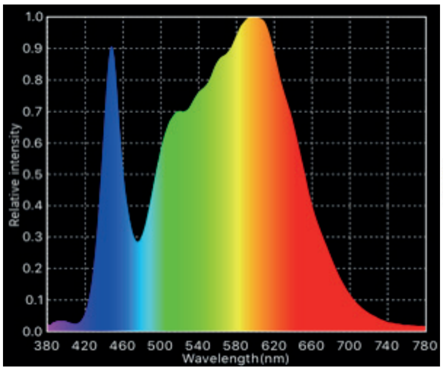
- measurement with Spectrum Genius Mobile (SGM) : (PT_2_SPECTRUM2_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (PT_2_SPECTRUM2_SGAL)
- Picture of the plants (PT_2_SPECTRUM2_Image)

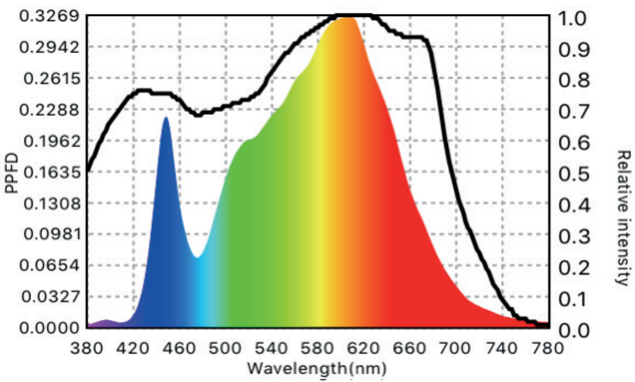
Notes: during the experiment, due to the luminaire technology, it was not possible to utilize the White channel only (at maximum power intensity), for setting up the spectrum of the user (as supposed during the strategy of the experiment's preparation). The increase of intensity of the White channel, was producing side effects, as double lux level, and consequent glare on the leaves.
To keep the lux level similar in each phase, the general luminaire intensity was kept 100% and the White also static at 60%. In this way was possible to create the condition for the post comparison evaluation, losing flexibility in the customization of the spectra.

LIGHTING TEST EXPERIMENT

PRETEST_Phase 2

SPECTRUM2 (users)





SPECTRUM2_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
3815	3992	85	598

SPECTRUM2_SGAL

DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
4.5344	52.481	18.87	24.32	9.27

Fig.16 Pretest_Phase 2_Data collected

LIGHTING TEST EXPERIMENT

TEST (T)

Phase 1 (T_1) Combine SPECTRUM1 with SPECTRUM2

In this phase, the aim was to obtain a spectrum that was a combination of both the spectra for plants and user.

Overview of the measurements and data recorded, for the mixed spectrum (SPECTRUM1-2):

- measurement with Spectrum Genius Mobile (SGM) : (T_1_SPECTRUM1-2_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (T_1_SPECTRUM1-2_SGAL)
- Picture of the plants (T_1_SPECTRUM1-2_Image)

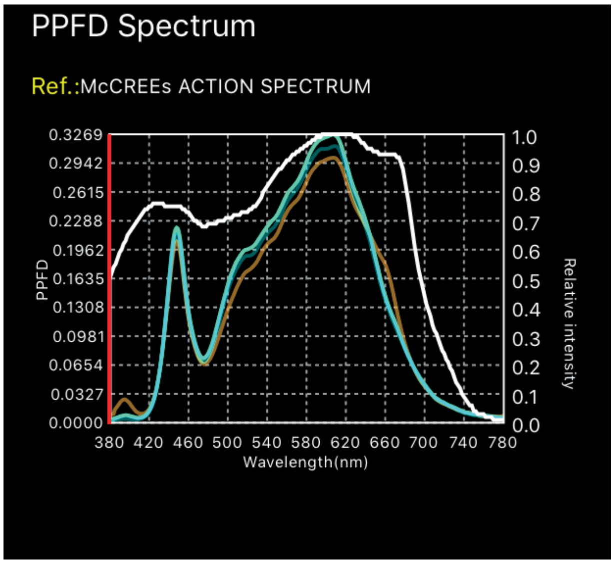
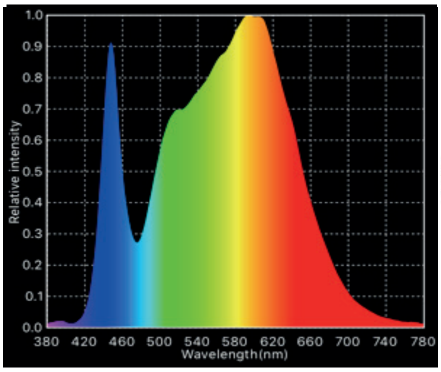


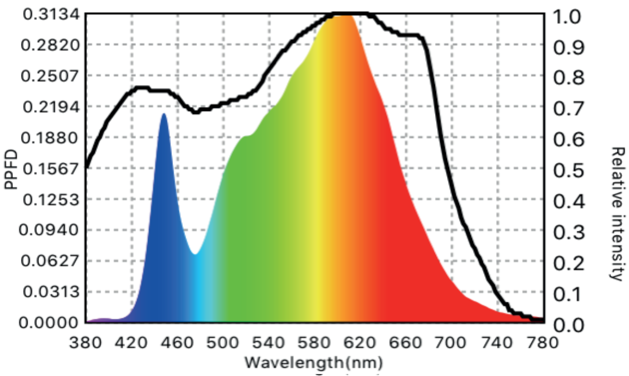
Fig.17
- Spectrum 1
- Spectrum 2
- Spectrum 1-2 (mixed)

LIGHTING TEST EXPERIMENT

TEST_Phase 1

SPECTRUM1-2 (mixed spectra)





SPECTRUM2_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
3381	3967	85	595

SPECTRUM2_SGAL

DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
4.5344	50.556	18.263	23.448	8.8418

Fig.18 Test_Phase 1_Data collected

LIGHTING TEST EXPERIMENT

TEST (T)

Phase 2 (T_2) Adjustments of the spectrum to achieve a pleasant appearance of the plants.

Overview of the measurements and data recorded, for the spectrum supporting visual comfort (SPECTRUMVC):

measurement with Spectrum Genius Mobile (SGM) : (T_2_SPECTRUMVC_SGM)
measurement with Spectrum Genius Agricultural Lighting (SGAL): (T_2_SPECTRUMVC_SGAL)
Picture of the plants (T_2_SPECTRUMVC_Image)

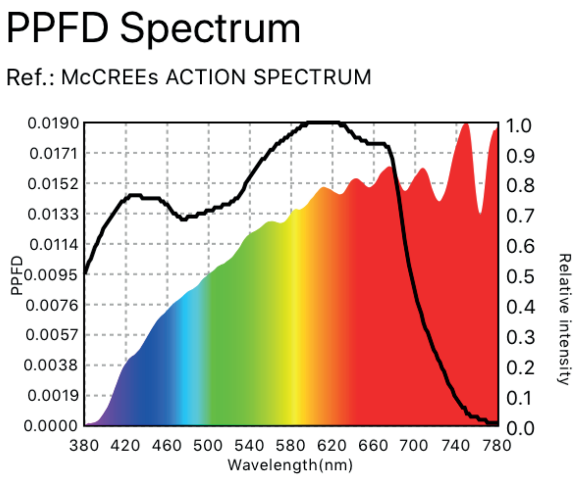


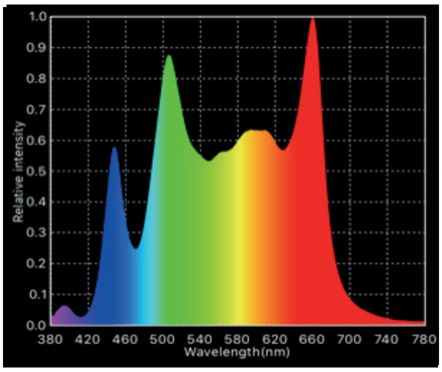
Fig.19
Results of the measured light spectrum on the tested plants in the indoor environment, 6.0m away from the glazed opening, during a sunny day at 4.30 pm.

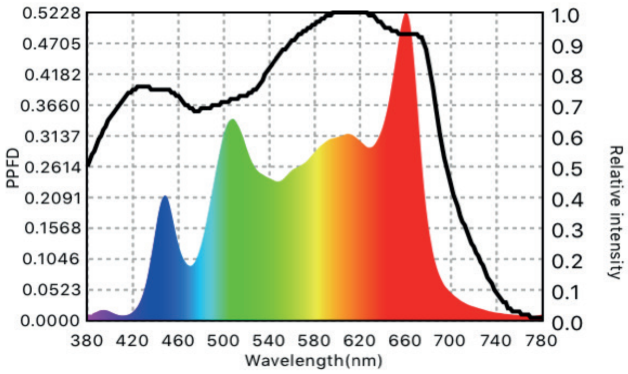
Fig.20
Image of the tested plants in the indoor environment, 6.0m away from the glazed opening, during a sunny day at 4.30 pm.

LIGHTING TEST EXPERIMENT

TEST_Phase 2

SPECTRUMVC (visual comfort)





SPECTRUMVC_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
4576	4443	95	660

SPECTRUMVC_SGAL

DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
5.9945	69.381	29.833	27.91	11.631

Fig.21 Test_Phase 2_Data collected

LIGHTING TEST EXPERIMENT

TEST (T)

Phase 3 (T_3) Adjustments of the mixed visual comfort SPECTRUMVC, testing with amounts of Red and Blue light ratio (R/B ratio) to test the visual appearance response.

"The optimal light spectrum for plant growth and development likely changes with plant age at plant communities."[2]

With the hypothesis of having a dynamic interplay of R/B ratio during the growing period (to optimize the growing process) would be interesting to evaluate the visual appearance of plants under several conditions.

Overview of the measurements and data recorded, for the spectrum supporting visual comfort with changed R/B Ratio:

1. R/B ratio 2:1 (SPECTRUM-RB1)
2. R/B ratio 1:1 (SPECTRUM-RB2)
3. R/B ratio 1:2 (SPECTRUM-RB3)

- measurement with Spectrum Genius Mobile (SGM) : (T_3_SPECTRUM-RB1_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (T_3_SPECTRUM-RB1_SGAL)
- Picture of the plants (T_3_SPECTRUM-RB1_Image)

- measurement with Spectrum Genius Mobile (SGM) : (T_3_SPECTRUM-RB2_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (T_3_SPECTRUM-RB2_SGAL)
- Picture of the plants (T_3_SPECTRUM-RB2_Image)

- measurement with Spectrum Genius Mobile (SGM) : (T_3_SPECTRUM-RB3_SGM)
- measurement with Spectrum Genius Agricultural Lighting (SGAL): (T_3_SPECTRUM-RB3_SGAL)
- Picture of the plants (T_3_SPECTRUM-RB3_Image)

TPhase3(1)_SPECTRUMRB1

Illuminance (lux)	CCT (K)	CRI (Ra)	λp (nm)	DLI (mol/m²)	PPFD PAR (μmol/m²s)	PPFD R (μmol/m²s)	PPFD G (μmol/m²s)	PPFD B (μmol/m²s)	λP FR (nm)	λP UV (nm)
4298	4414	91	508	4.8876	56.569	20.187	26.051	10.327	700	395
		TM-30-15 Rf	**TM-30-15 Rg**		**PPFD FR (μmol/m²s)**	**PPFD UV (μmol/m2s)**	**R/B**	**R/FR**		
		91	95		1.2941	0.0454	1.95	15.6		

TPhase3(2)_SPECTRUMRB2

Illuminance (lux)	CCT (K)	CRI (Ra)	λp (nm)	DLI (mol/m²)	PPFD PAR (μmol/m²s)	PPFD R (μmol/m²s)	PPFD G (μmol/m²s)	PPFD B (μmol/m²s)	λP FR (nm)	λP UV (nm)
3907	5379	93	395	6.2018	71.78	20.26	30.277	21.238	700	395
		TM-30-15 Rf	**TM-30-15 Rg**		**PPFD FR (μmol/m²s)**	**PPFD UV (μmol/m2s)**	**R/B**	**R/FR**		
		90	99		3.2835	9.6748	0.95	6.17		

TPhase3(3)_SPECTRUMRB3

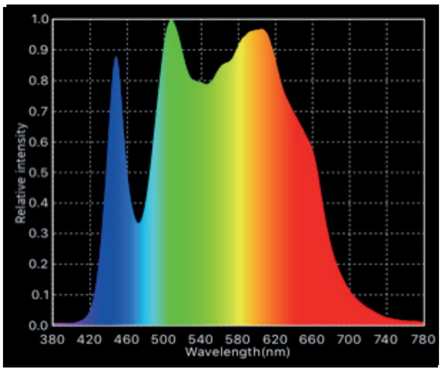
Illuminance (lux)	CCT (K)	CRI (Ra)	λp (nm)	DLI (mol/m²)	PPFD PAR (μmol/m²s)	PPFD R (μmol/m²s)	PPFD G (μmol/m²s)	PPFD B (μmol/m²s)	λP FR (nm)	λP UV (nm)
3763	7027	84	395	5.2457	60.714	12.213	27.403	21.085	700	395
		TM-30-15 Rf	**TM-30-15 Rg**		**PPFD FR (μmol/m²s)**	**PPFD UV (μmol/m2s)**	**R/B**	**R/FR**		
		80	91		2.5748	9.8455	0.58	4.74		

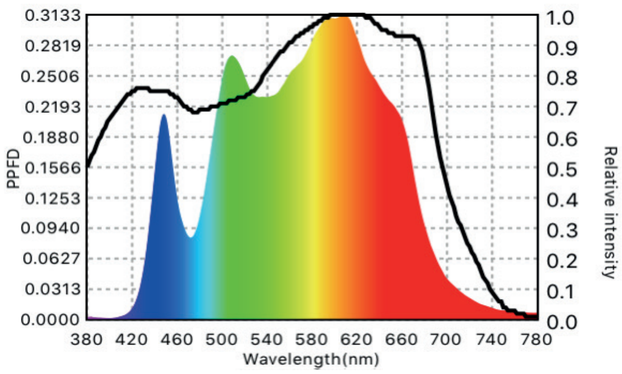
Fig.22
Measurements data of the T_3 Phases

LIGHTING TEST EXPERIMENT

TEST_Phase 3

SPECTRUMRB1 (R/B =2)





SPECTRUMRB1_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
4298	4414	91	508

SPECTRUMRB1_SGAL

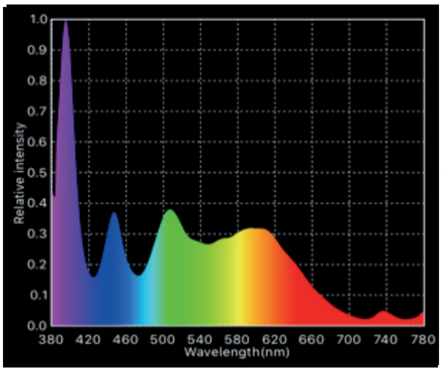
DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
4.8876	56.569	20.187	26.051	10.327

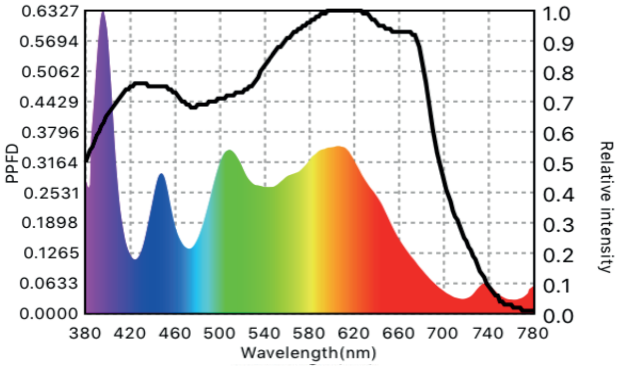
Fig.23 Test_Phase 3_1_Data collected

LIGHTING TEST EXPERIMENT

TEST_Phase 3

SPECTRUMRB2 (R/B =1)





SPECTRUMRB2_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
3907	5379	93	395

SPECTRUMRB2_SGAL

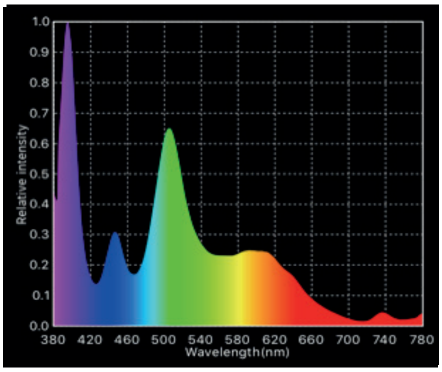
DLI (mol/m²)	**PPFD PAR** (μmol/m²s)	**PPFD R** (μmol/m²s)	**PPFD G** (μmol/m²s)	**PPFD B** (μmol/m²s)
6.2018	71.78	20.26	30.277	21.238

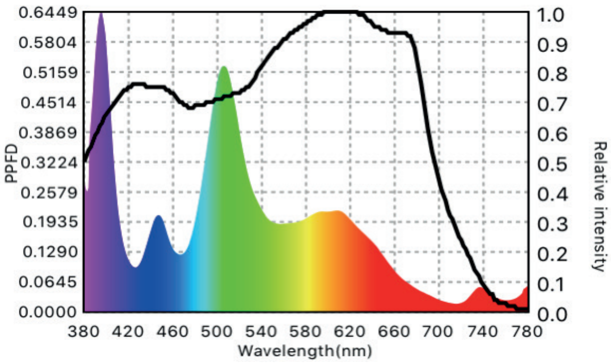
Fig.24 Test_Phase 3_2_Data collected

LIGHTING TEST EXPERIMENT

TEST_Phase 3

SPECTRUMRB3 (R/B =0.5)





SPECTRUMRB3_SGM

Illuminance (lux)	**CCT** (K)	**CRI** (Ra)	**λp** (nm)
3763	7027	84	395

SPECTRUMRB3_SGAL

DLI (mol/㎡)	**PPFD PAR** (μmol/㎡s)	**PPFD R** (μmol/㎡s)	**PPFD G** (μmol/㎡s)	**PPFD B** (μmol/㎡s)
5.2457	60.714	12.213	27.403	21.085

Fig.25 Test_Phase 3_3_Data collected

LIGHTING TEST EXPERIMENT

References

[1] Kevin R. Cope and Bruce Bugbee. *Spectral Effects of Three Types of White Light-emitting Diodes on Plant Growth and Development: Absolute versus Relative Amounts of Blue Light*, 2013

[2] Ibid.

[3] Torres & Lopez. Measuring Daily Light Integral in a Greenhouse. Department of Horticulture and Landscape Architecture, Purdue University. 2016

[4] Scientific Committee on Emerging and Newly Identified Health Risks. Health Effects of Artificial Light. European Commision. 2012

[5] Ibid.

[6] Ibid.

[7] Ibid.

7. RESULTS OF ANALYSIS

Two differents methods were used to analyse the data collected.

- Firstly, a photographic comparison method was introduced, to evaluate the relations between the photographic appearance and the relative spectrum of all the phases in comparison with the daylight scene.
- Secondly the author rated the natural appearance of the leaves in all the different lighting scenes, in order to compare the rates with the relative percentage of RGB wavelengths in the spectra.

7.1 Comparison method

- Visual comfort spectral distribution similar to daylight condition (Fig. 1/2). The visual comfort spectrum results to have the higher CRI(Ra) value.
- High level of ultraviolet and low level red light, makes organic texture similar to artificial plants (Fig.3)
- High presence of yellow-red part (Fig.4), makes organic texture appear dull (not healthy appearance).
- In the intermediate cases, a colder CCT improves slightly the appearance of leaves (Fig.5).

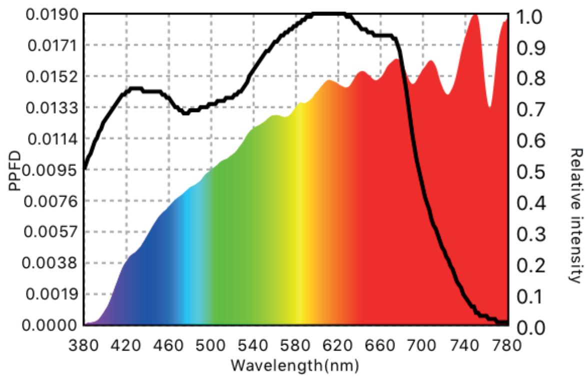


Fig.1 Daylight spectrum

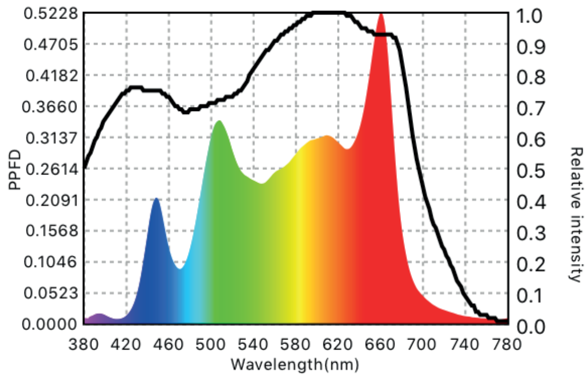


Fig.2 SPECTRUMVC Visual comfort

Fig.3 SPECTRUMT33- High level UV, low level Red

Fig.4 SPECTRUMT1-2- High Yellow-Red part

RESULTS OF ANALYSIS

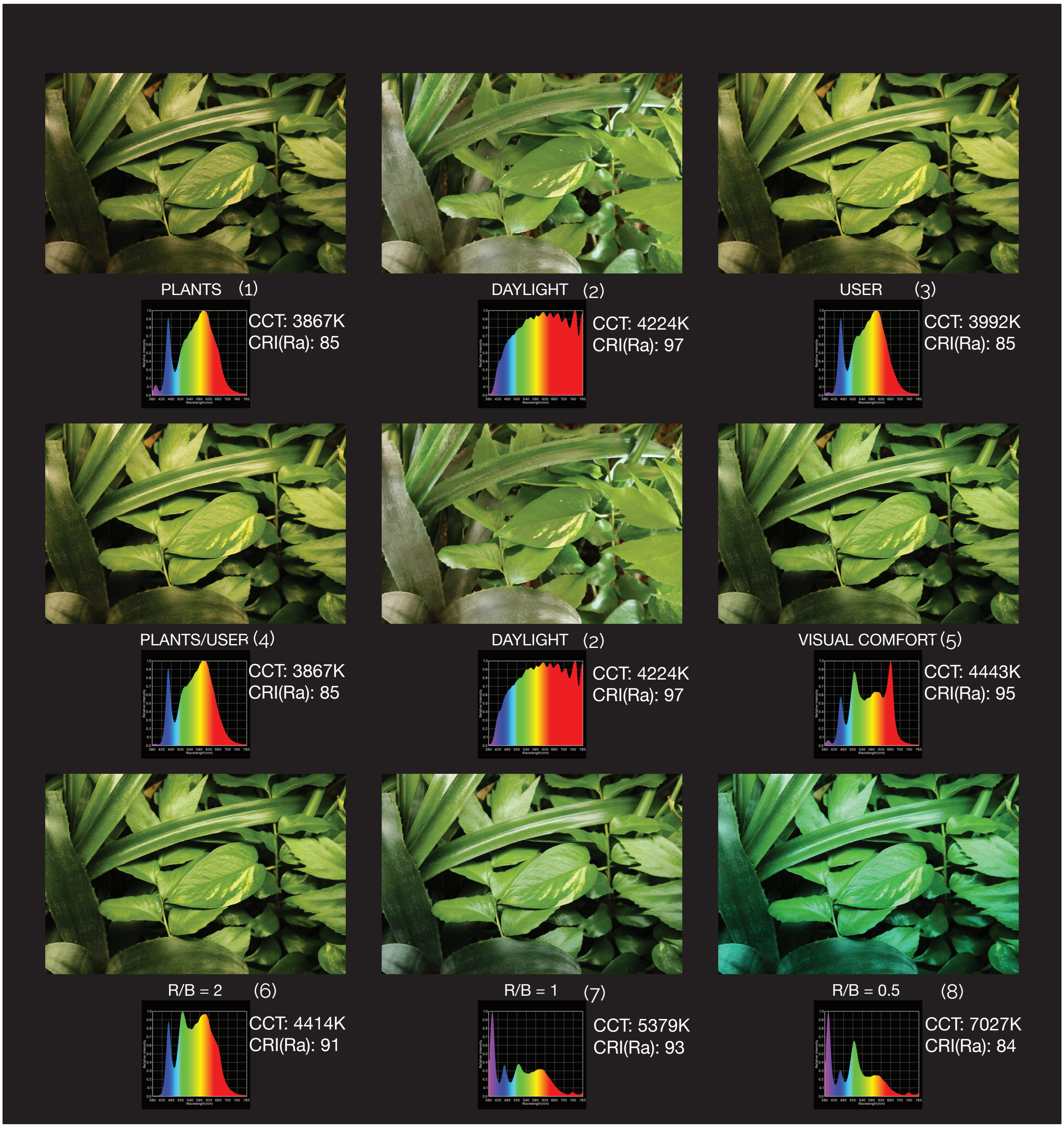


Fig.5 Photographic comparison method representing: plant spectrum requirement (1), Daylight spectrum(2) User spectrum requirement(3), Plant and user spectrum requirement combined(4), Visual comfort spectrum that achieves a pleasant appearance of the plants(5), Spectrum R/B ratio 2:1(6), Spectrum R/B ratio 1:1(7), Spectrum R/B ratio 1:2(8).

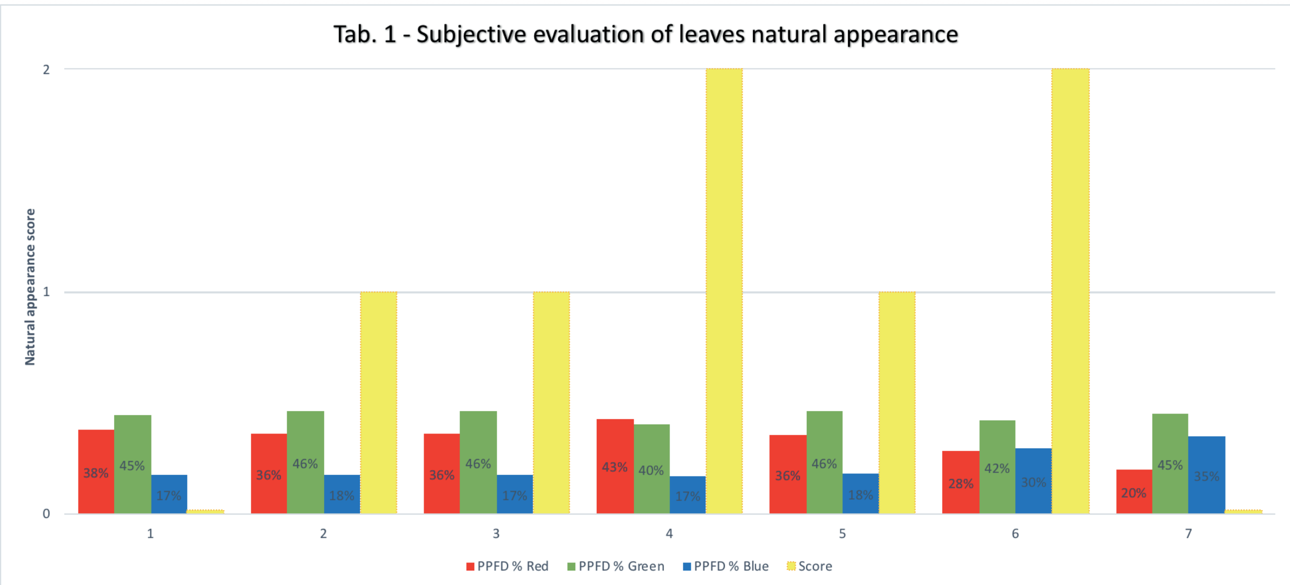
7.2 Subjective quality assessment

The partecipant of the subjective quality assessment was the author.

Gender: Famale.
Age: 31.
The partecipant has no limitation in the visual behavior and in the recognition and differentiation of colors

For the subjective quality assessment, the double and multiple stimulus method was used.
It consisted in comparing two or more picture, and rating the subjective perception of the leaves appearance. The comparison was made using the daylight condition, as the best rating score reference. The parameters taken into account were the natural appearance of the organic texture and color.
The score 0 was referring to a "bad appearance" (not pleasant/unnatural). The number 1 represented "not ideal appearance" and the score 2 "good appearance"(similar to daylight condition).

Firstly, a photographic comparison was made, between the photographic appearance and the daylight scene.
Secondly the partecipant rated the natural appearance of the leaves in all the different lighting scenes, in order to compare the rates with the relative percentage of RGB wavelengths in the spectra.
The results in the Tab.1 show the percentage of spectral composition in comparison to the subjective quality assessment of the leaves appearance.
The partecipant scored 2 (maximum rate) the spectrum T_2 Visual comfort, and the spectrum T_32 R/B:1.
The score 0 was rated for the spectrum PT_1 Plants and T_33 R/B: 0.5.
The rest was evaluated as "not ideal appearance".



Tab. 1 Legend 1: PT_1 Plants, 2: PT_2 User, 3: T_1 Mixed Plants/User, 4: T_2 Visual Comfort, 5: T_3 R/B=2, 6: T_3 R/B=1, 7: T_3 R/B=0.5

RESULTS OF ANALYSIS

Fig.6 Double stimulus method

Fig.7 Double stimulus method

Fig.8 Multiple stimulus method

7.3 Conclusion

Some broad conclusions can be drawn from the experiment:

1. As anticipated, the lighting scene T_2 with the spectrum created to achieve the visual comfort, has the most similar spectral distribution to the daylight reference one and it also covers the plant's requirements.

- To achieve higher values of the yellow part of the spectrum, whenever the green part of the spectrum is too low, the outcome of the visual appearance of the plant looks not ideal, rather dull/boring.
- When UV and higher values of the Green part of the spectrum are combined the appearance of the plants looks very unnatural and flat.
- Both the Visual Comfort (VC) spectrum and the T_32 (R/B=1) spectrum seems to better reflect a correct and pleasant appearance of the organic texture of the plants. In the VC spectrum, the Red part is higher, and this will affect a faster and bigger growth for some species of plants. The scene T_32 has a very high value of UV light, but it still gives an interesting result in terms of visual appearance. It would be valuable for the research outcome to be able to manipulate the UV values, keeping the rest of the spectrum exactly as it was. This outcome will give additional information, but unfortunately due to the technical aspects it was not doable.

In real life scenario its important to consider that there will be additional general office lighting in the room, often with colour temperature of 4000K. This would influence the spectral composition of lighting for the ILGW, especially in the green/yellow part of the spectrum. In the future further lighting experiments could be considered in a more realistic office physical set up to be provided to better address the subjective quality assessments, by inviting substantial number of participants to adequately evaluate the visual appearance.

Fig.9 Best possible score on visual appearance of plants

8. PARAMETERS EVALUATION: OVERVIEW

In order to find an answer to the Research question, the thesis work went through the related literature review, to examine the body of knowledge in the field and build up a new strategy to design artificial lighting for ILGW.

The parameters evaluation, has been assessed, in the practical field, through an interview with an expert designer of ILGW, a case study of a real project, and a lighting test experiment based on a qualitative evaluation method.

To summarize the insights gained, we can draw the following conclusions:

- The flexibility of the position of the plants, depends on the light intensity. As shown in the chapter 5.1, planning the lighting sources position in advance, allows us to choose the species and the artistic composition of the shades of green. This also has benefits on the aesthetics of the ILGW design.
- It is necessary to know the usage of the room in the routine week, to avoid the mistake of leaving the plants in the darkness for long periods.
- A uniform artificial light distribution, on one hand helps the uniformity of the plants morphology, on the other hand the effect on the ILGW could result dull and unnatural. For this reason, it would be interesting and insightful to study and prototype new luminaires, that are able to spread the light in a programmatic random way, supported by a logic positioning of the species of plants accordingly to the light level reached in each area of the ILGW.
- The visual appearance of the plants depends on the spectral composition and color temperature of the light source. The lighting test experiment shows that, the best appearance of the organic texture, was under the visual comfort spectrum, which had the most similar spectral distribution to the daylight reference spectrum. The CCT of this lighting set up, was 4443 K .

9. DISCUSSION

The vision of this thesis is to support the plant's growth and the visual comfort in modern office spaces through lighting design by re-thinking the excisting standard protocols used for the design of lighting essential for living walls to thrive.
The lighting technology development, allows the diffusion of many possibilities for the designing of light for ILGW. Today we are able to draw the necessary elements from the toolbox of technology and design development. We can pick the best solution, easily test it, and quickly go back and forward in the moving test experiment, where each step is providing new improvement, confirming/discarding past assumptions and experiences.

The horticultural lighting technology, is growing fast, giving us the possibility to choose between a wide range of LED chips recipes. The research work, showed the correlation between the spectral composition of a LEDs lighting source, and the appearance of the plants; thus this could be a helpful in the ILGW design process, to decide the kind of spectral distribution that better suits the species of plants selected, having a sort of preview of the visual appearance of the leaves under the artificial light selected.

The advanced 3D modeling softwares and printers, are instantaneous tools for product designers, to draw, realize and test new luminaire shapes and functionalities.
The strategies put forward represent a clear move towards biophilic design , taking inspiration from natural effects and organic shapes, in the design of light distribution and luminaire design for the living wall.

The quality and aesthetics related to luminaires and light technology, could make a shift from the standards light for indoor greenery, to a qualitative improvement that supports user's visual comfort, enhancing the atmosphere of the space.

Furthermore, as underlined throughout the thesis, the communication between the stakeholders involved, it is is a fundamental part in the design process for ILGW..
Architect, Interior designer, lighting designer, botanist and client, should cooperate together, to create a successful workflow in the complex design process of a living wall.

Further analysis, mock-ups and quantitative tests would examine in depth the feasibility of the new suggested strategy.

10. CONCLUSION

Having examined the current state of the ILGW field thoroughly, both from theoretical and practical points of view, it is clear that there is a need for improving the lighting for indoor greenery. To make a fundamental move forward, however, there needs to be a change in strategic perspective by professionals specialised in the area, looking beyond the plant's growth requirements, and focusing increasingly on the final users. The lighting designer job needs to have a interdisciplinary approach, embracing fields such as botany, biology, psychology, among other field, drawing on different disciplines and approaches to find creative solutions for the design and realisation of ILGW.

An inappropriate or inaccurate artificial light concept, for example, can easily result in the ILGW losing its aesthetic potential, thus compromising the entire space. The trend of having greenery inside workplace, seems to have become a must for modern companies, that increasingly place focus on their employees' well-being. As lighting designers to collaborate with lighting manufacturers creating customized luminaires of this biophilic design typology, could offer a unique solution and experience for the users.

Nature is finding her way to grow on the concrete, both outside and inside modern buildings. The ILGW will potentially become an indispensable tool for improving human well-being in working places, as well as innumerable other contexts. To move forward in this direction, this thesis has endeavoured to create a strategy that lighting designers, architects and interior designers can use to design and enhance the beauty of the atmosphere that an Indoor Living Green Wall can add to the office environment, supporting the plants growing requirements and a visual comfort of the people.

11. FUTURE WORK

In the future, further lighting experiments could be considered in a more realistic office physical set up to better address the subjective quality assessments, by inviting a substantial number of participants to adequately evaluate the visual appearance. Certainly, further studies are necessary to test the biological effect that, for example, the Visual Comfort spectrum proposed in the lighting test, would have on growth and morphology of different species of plants.

Furthermore, the research underlines the importance of the daylight prevision, so an interesting elaboration could be done on how to optimize the daylight intake in different architectural typologies, to meet the needs of the ILGW. By working with the double dynamic lighting concept, we could test where artificial light can boost the daylight during seasonal changes, across different geographical conditions.

Another area of great interest and need for research, would be to investigate how to meet the needs of plants and people in other functional settings, such as schools, hospitals, homes among other.

"Since, in the long run, every planetary civilization will be endangered by impacts from space, every surviving civilization is obliged to become spacefaring--not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive... If our long-term survival is at stake, we have a basic responsibility to our species to venture to other worlds." [1]

Taking inspiration from an incredibly thought-provoking article, *The importance of design in helping humanity become a multi-planetary species* [2], published in "The sustainable City XII" book [3], given the "futuristic" spirit this thesis research, a proposed next step of research is to apply this concept of a light for plants and people, in the design of new and innovative habitats, even beyond planets of our universe.

Fig.1 Sketch „Atlas interior" - Mohamad Al Chawa - ARC 592, Habitat - 2016 © by Mohamad Al Chawa

FUTURE WORK

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