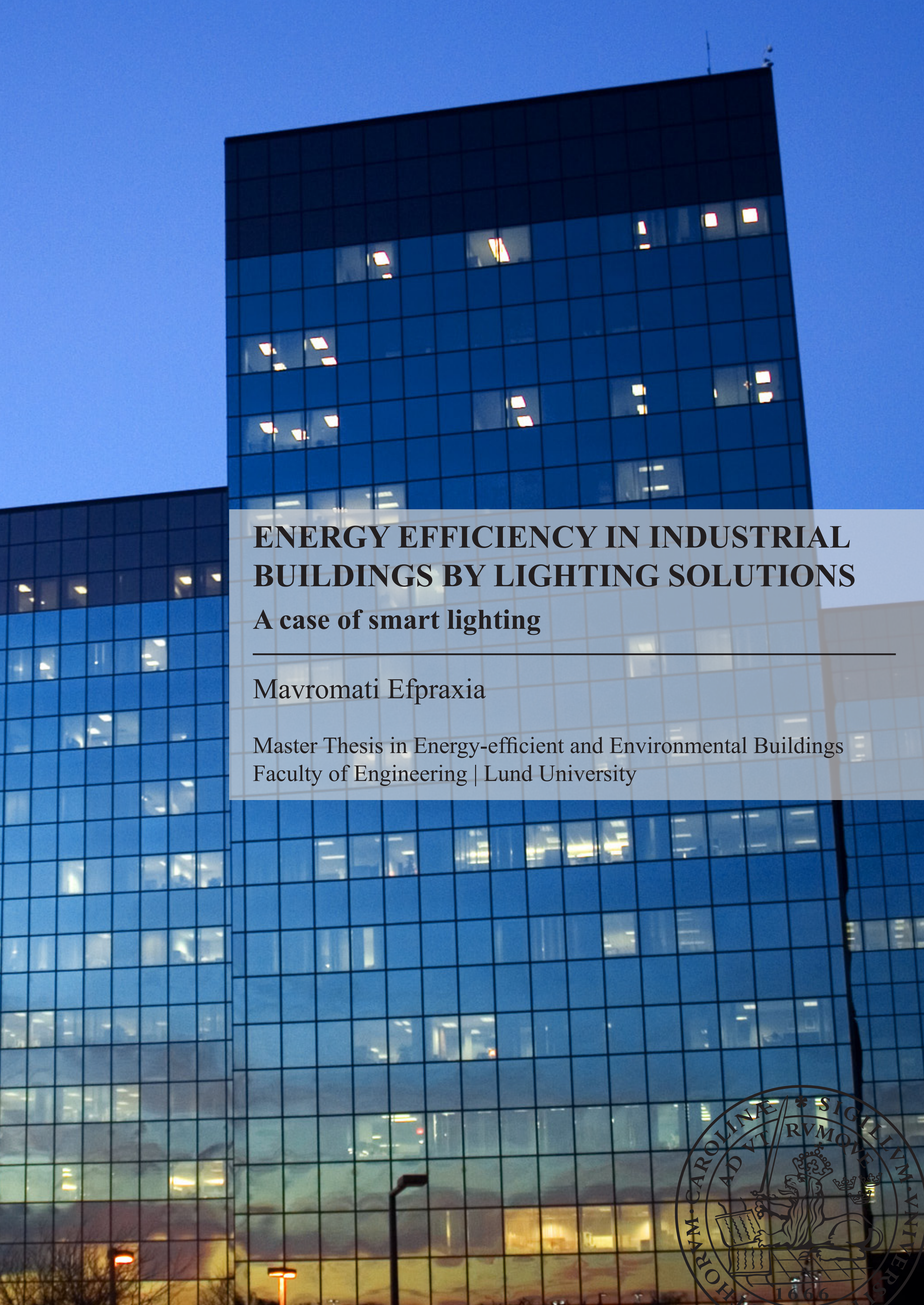

ENERGY EFFICIENCY IN INDUSTRIAL BUILDINGS BY LIGHTING SOLUTIONS

A case of smart lighting

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Master Thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Preface/Acknowledgements

This thesis has been shaped as part of the Master Programme in Energy-efficient and Environmental Building Design, held by Lund University of Sweden. This study is conducted as part of the internship at MEDESCO S.A. company in Athens, Greece.

Several people have helped me in completion of this thesis. Firstly, I would like to express my gratitude to Dennis Johansson and Kaisa Svennberg for providing me with the theoretical and practical background.

Furthermore, I feel thankful to my colleagues at MEDESCO S.A. that gave me the opportunity to work under their guidance and gain valuable knowledge on lighting design. I would, especially, like to thank G. Sanidas, for the chance to work at such an organized company and gain working experience.

Lastly, my family has been proved a noteworthy emotional and financial succor of this effort.

Mavromati Efpraxia

Athens, Greece

Wednesday, October 22, 2014

Abstract

"Architecture is the learned game, correct and magnificent, of forms assembled in the light."
Le Corbusier.

Nowadays, lighting covers a great portion of the total energy use of a building, almost 21%, while in most of the places, the quality of the existing lighting conditions is usually notably poor. In addition, lighting is responsible for 14% of all electricity demand in EU (CELMA, 2011) and 19% of the latter worldwide (CELMA, 2011).

At the same time, the European Union has set ambitious climate and energy targets for sustainable development, widely known as "20-20-20 Energy Efficiency Targets", with which all countries should comply. (European Commission, 2014).1 Europe has already developed a wide range of policy instruments in charge to stimulate the uptake of sustainable technologies, including lighting. (European Commission, 2011).

The objective of this study has been to examine the energy performance and the lighting conditions of an industrial building, poorly daylit and with electrical installation. The building is located in Greece, a place that offers great quantity of daylight and the possibility to achieve notable energy savings due to lighting and improved building envelope. Therefore, the main question of this thesis has been whether the introduction of smart lighting technology is more preferable than modern LED in terms of lighting, functionality, energy and cost savings. The thesis was conducted with the aid of computer programs, such as DesignBuilder and DIALux.

The study has shown that the investigated industrial area would have been underlit even though a huge amount of lights of great wattage would have been used, rendering the lighting installation completely inefficient. Daylight is not used at all rooms. The lighting conditions can significantly be improved if smart lighting technology is introduced, in combination with the optimum window size and technology in the spaces where daylight is beneficial, such as offices. If the aforementioned are applied, the energy savings and thus, the cost savings become remarkable. More specifically, replacing the lamp technology, reducing the amount of fixtures and using occupancy, motion and daylight harvesting sensors in combination with dimming control may lead to a reduction in energy use for lighting of around 90.3%. At the same time, light appears to be more evenly distributed in the room.

In conclusion, improvements towards more energy efficient lighting conditions within rooms are possible if daylight is more wisely used and electrical installation is carefully designed. Under these conditions, the energy need and the desired lighting levels are easily met reducing a building's footprint and contributing to a better environment.

Keywords: Passive strategies, daylight, electrical lighting, simulation, smart lighting technology, LEDs, energy efficiency, profitability.

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[1] Three key objectives for 2020:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

Table of content

Terminology / Notation

Terminology[2]

Illuminance:	The light falling on a surface.
Luminance:	The measurable brightness of a surface or the sky.
Luminous flux:	The flow of light, the total output from a source.
Luminous intensity:	The quantity of light flowing in a particular direction from a lamp or a small patch of sky.
Daylight factor:	The ratio of daylight illuminance in a room to the simultaneous illuminance from the sky on an unobstructed horizontal surface.
Daylight Autonomy:	Percentage of the year where illuminance levels may be satisfied by daylight alone.
Luminaire/Fixture:	A light fitting, the enclosure that protects a lamp and controls the direction distribution of light.
Lamp:	The actual source of light within a luminaire.

[2] Terminology retrieved from the book “Daylighting. Architecture and lighting design”, P. Tregenza and M. Wilson.

Mathematical notation

E	Illuminance (lux)
L	Luminance (cd/m^2)
I	Luminous intensity (cd)
φ	Luminous flux (lm)
r	Reflectance (%)
DF	Daylight factor (%)
LPD	Lighting Power Density (W/m^2)
RH	Relative Humidity (%)
RF	Rainfall content (mm)
λ	Heat conductivity (W/mK)
U	Thermal conductance (W/m^{2}K)
LCC	Life Cycle Cost
NPV	Net Present Value (€)
TCO	Total Cost of Ownership (€)
ROI	Return On Investment (years)

1 Introduction

1.1 Background

The building of study is an industrial building located in Serres, Greece. Due to Greece's geopolitical situation, industry has been widely developed in close connection to the society during the last years. As a result, nowadays, Greece has many good examples of both modern and historical industrial buildings to demonstrate. (Marina Karavasili, 2010).

This building is a newly-built dairy factory, situated at the outskirts of Serres, a medium-sized city of northern Greece. It was chosen due to easy access, its particular use and the combination of daylight and electrical light utilization.

It has been noted that the average energy use of lighting in office buildings ranges between 15 and 25 kWh/m^{2}y (Santamouris, Argiriou, Dascalaki, Balaras, & Gaglia, 1994), indicating that this number might be higher in industrial ones. Thus, there is huge potential of energy savings due to lighting in the industrial sector as lighting appears to be the most cost effective to reduce the energy use and the CO_2 emissions. (CELMA, 2011).

1.2 Overall aim

Having the correct light in buildings and particularly in work places is of paramount importance. Studies have revealed the significance of applying the right quantity and color of light according to the use of a room, and its impact on psychological mood in working places. (Küller, Ballal, Laike, Mikellides, & Tonello, 2006). According to this study, people experience their working environment in a more positive way when the latter is not perceived as too dark or too bright.

The aim of this study is to comprehensively design the lighting in a newly-built industrial building and to fulfill lighting and energy related criteria with main focus on the optimization of the energy performance of the building.

Requirements that need to be fulfilled are:

- Architectural quality and adaptation to the characteristics of industrial buildings.
- Daylight harvesting.
- Energy efficient electrical lighting installation.
- Thermal comfort and energy requirements stemming from the usage of the building.
- Energy efficient building with passive and active solutions for:
    - Building envelope.

    - Heating/cooling.
    - Lighting.
    - Moisture safety.
- Adaptation to regulations:
    - Greek energy regulation.
    - Daylighting requirement for BREEAM exemplary level for the offices.
    - ASHRAE Energy Standard for buildings except low-rise residential buildings.
- Cost analysis of the lighting installation.

The energy demand and the thermal comfort of the existing building and the extension will be evaluated and compared with the Passive House criteria (FEBY document). (Sveriges Centrum för Nollenergihus, 2012). In addition, the Greek regulation concerning energy in buildings (National Press, 2010) and the ASHRAE Energy Standard (ANSI/ASHRAE/IESNA, 2004) will be applied.

Finally, the cost analysis of the suggested improvements will indicate the payback period of the system and will unveil which lighting and energy system is cost-effective and worth applying.

1.3 Scope and limitations

All the proposed changes, that aim to improve the energy performance of the building, such as the structure of the building, are based on past experience and academic research, and are for academic purposes only, contrary to the lighting solution suggested here that reflects the client's brief for an energy saving and contemporary lighting system. As a result, the application of a case study limits the theoretical generalization.

Moreover, the use of simulation programs implies assumptions and uncertainties in the final result concerning the energy demand, especially since it is a new construction and there are no data available concerning energy use.

For this reason, three scenarios corresponded to different lighting designs are simulated:

- Simple lighting technology (fluorescent and metal halide lamp technology).
- LED technology (fixture and lamp technology of high luminous efficacy, so that the simulation corresponds to energy efficient lighting design).
- Smart lighting technology.

To analyze the building as a system, two scenarios concerning energy demand of the whole building, also taking into consideration the least and the most energy efficient lighting installation, are simulated:

- Existing conditions.
- Improvements.

Conditions that describe a low-cost building solution, such as conventional lighting technology and adequately insulated wall, no care for moisture safety and the building's footprint expressed as CO_2 production, are regarded as “existing conditions” since these refer to the way the facility has been designed, according to the client’s brief.

“Improvements” include all changes that contribute to more energy efficient building design, such as well insulated structure (walls, roof, and ground floor), infiltration rate, ventilation, smart lighting technology, moisture safety and reduction in CO_2 emissions.

2 Smart Lighting Principles

LED lighting is continuously gaining ground because of its notably low power consumption and its high efficacy at the same time. The extensive use of LED technology implies great potential of energy and consequently, cost savings of around 50-70%. If all lighting would be replaced by LED technology, the total electricity demand would be minimized to 4%. (CELMA, 2011).

Nowadays, the term “Smart Lighting” is widely used and refers to lighting technology with increased level of functionality and responsiveness to various stimuli. However, the term “smart” causes vagueness due to its strong dependence to history. (NanoMarkets, 2012).

In definition, Smart Lighting is a heterogeneous lighting technology area, integrating among others sensor and control technology, as well as information & communication technology, which leads to higher efficiencies and a lower CO_2 footprint in the use of electrical energy, in combination with enhanced functionalities and interfaces of lighting in the ambient, commercial and public domain. (Photonics21 Strategic Research Agenda, 2014).

Smart Lighting systems contribute to additional energy savings compared to conventional LED technology of around 80% since they include fixtures of high efficiency which are automatically controlled and adjust accordingly to occupancy and/or daylight availability, motion, etc. In general, the advantages of Smart Lighting systems are summarized below:

- Fully independent fixtures.
- Maintenance-free.
- High efficacy of around 94-100 lm/W.
- Long lifetime of lamp technology of over 20 years.
- Durability of fixture technology.
- Incorporated temperature, motion, occupancy and daylight harvesting sensors into each fixture.
- Dimming control for both active and inactive dimming level from 0 to 100% with regulated delay.
- Wirelessly connected via WiFi.
- Remotely monitored via Internet.
- Regulated light intensity to assure consistent light quality throughout the space.

A Smart Lighting system is based on a hierarchical structure that contains four distinct levels. The hierarchy is depicted in Figure 1:

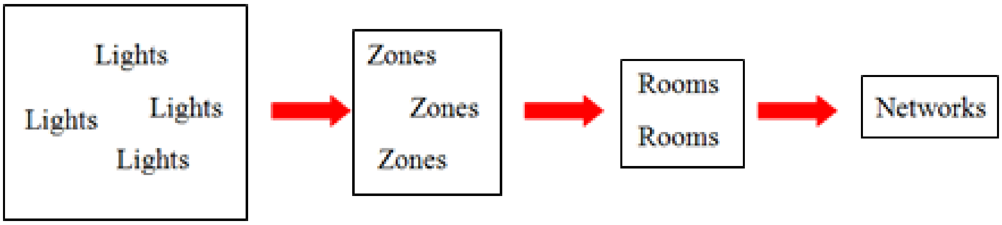


Figure 1: Hierarchy of Smart Lighting system.

More precisely, fixtures with common functional characteristics, such as dimming or operating hours, can be grouped (zoned) together forming the rooms. It is feasible that each room contains more than just one zone of fixtures, if necessary. All rooms are connected wirelessly to the facility network through gateways which collect all the data. The whole system can be remotely monitored and controlled via Internet with the aid of a computer software, as illustrated in Figure 2:

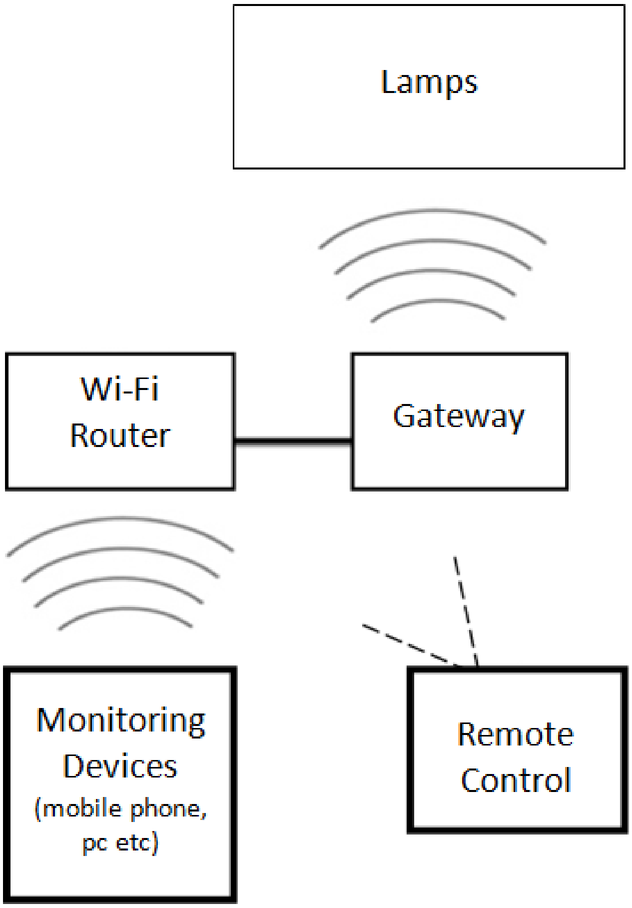


Figure 2: Connectivity of Smart Lighting system.

The sensors found incorporated into each smart fixture aim for a long lasting and more energy and cost-effective system. Their characteristics are listed and briefly analyzed below:

- **Temperature sensor**
  It is widely known that the output of LED lights is largely affected by the ambient temperature. The rule that governs this relationship is that as the ambient temperature increases, the light output decreases. (Wikpedia, 2014). Hence, the existence of the temperature sensor is of high importance since it measures the fixture's temperature, controls its function and protects it from overheating. In case of overheating, it dims or switches off completely the overheated fixture and prevents the deterioration of both the fixture's and the LED's lifespan.

- **Motion sensor**
  As an integrated element of a smart fixture, the motion sensor detects the motion of an object and particularly, of people in a room, and controls the fixture's function accordingly. (Wikipedia, 2014). The condition that governs its function is that once motion is detected in a room, the fixture is switched on. If no motion is detected, the fixture is set off or dimmed to its preconfigured minimum light output.

- **Occupancy sensor**
  The occupancy sensor detects the occupancy of a room by people and controls the fixture accordingly. (Wikipedia, 2014). Its function is similar to the motion sensor's one; once occupancy is detected, the fixture is switched on. If no occupancy is detected, the fixture is set off or dimmed to its preconfigured minimum light output.

  Yet, the occupancy sensor differs from the motion sensor as it allows the fixture to function in an occupied room even if no motion is detected, whereas the motion sensor switches the fixture off if no motion is detected in the room even if the latter is still occupied. Therefore, the occupancy sensor functions additionally to the motion sensor when the latter can no longer control the light installation and thus, the illuminance levels of a room.

- **Daylight harvesting sensor**
  Sun is usually the largest source of light. Daylight is highly appreciated by people and it is usually preferred to artificial lights. Daylight harvesting sensor can lead to additional energy savings since daylight is introduced in a room and better exploited by an installation.

  The condition that governs its function when integrated in a fixture is that it measures the illuminance levels over a surface and controls the fixture by continuously adjusting its light output, so that the measured illuminance levels due to the combination of natural and artificial lighting are always kept above the room's minimum light requirements. In case the target illuminance levels are satisfied solely by daylight, the fixture is switched off or dimmed to its preconfigured minimum light output. In case daylight alone is not enough, artificial lighting switches on dimmed to the amount needed to meet the target illuminance level. Finally, in case there is no daylight, the fixture is set on being the only light source responsible to meet the requirements.

The centralized control that Smart Lighting systems with incorporated independent sensors have, allows the implementation of temperature, occupancy and motion control, daylight harvesting, scheduling and reporting. The user is able to have a detailed insight of the lighting conditions in each room of the building, an ability that has the following advantages:

- Access to multiple facilities via a single interface.
- Benchmark one facility versus another or more facilities.
- Deeper operational visibility.
- Possibility to develop together with specialists what is more important to each company, facility, etc.

The vast possibilities that Smart Lighting systems offer are summarized and analyzed below:

- **Control**
  Control over the configuration of the light installation is feasible in a smart lighting system. The users are able to control, set and modify light levels, create schedule profiles, group fixtures, adjust sensor delay, etc, by using the software or by switching to manual control (keypad).

- **Insight**
  A smart lighting system provides the possibility to its users to have insight of the facility via an interactive map found in the software. The users are able to understand where the activity is concentrated and visualize in charts the energy use and cost, the daylight harvesting and the occupancy of the facility at any time of the day, month or year.

- **Reporting**
  Integrated sensors into smart fixtures collect data that allow the creation of reports concerning energy use and cost, daylight harvesting and occupancy data. Reports are presented in charts and on an hourly, daily, monthly or even yearly basis.

- **Ease of use**
  Software for smart lighting systems is usually easy to handle with a simple web-based interface that allows quick familiarization of the users.

- **Security**
  Secure access to the software of the smart lighting system is usually protected by entering username and password data. Username and password are solely known amongst the users of the system and hence, access is limited to a certain group of people.

- **Scheduling**
  In a smart lighting system, it is possible to control and schedule the light installation. The user can create different profiles that correspond to the facility's needs and operation, such as shifts, holidays, etc, in order to optimize the energy and cost savings achieved.

- **Maximum energy-efficiency**
  The maximum energy-efficiency of a smart lighting system is preserved by the excellent combination of LEDs and sensors incorporated into each fixture, as well as by allowing to the users to have insight and continuous overview of the energy and cost savings of the facility.

- **Adaptability to different needs**
  Smart lighting systems are adaptable to different needs and their users are able to control and adjust the lighting installation accordingly to different facilities' or rooms' operation, etc by applying the different lighting profiles and scheduling systems.

In conclusion, Smart Lighting systems are a prosperous technology. The flexibility a Smart Lighting system presents leads in remarkable energy efficient and cost effective lighting solutions as well as in the mitigation of CO_2 emissions.

2.1 Smart lighting and energy balance

All light sources emit both light and heat in the form of convection, conduction and radiation. Yet, the portion of light and heat emitted varies depending on the type of the lamp technology. As a result, each type has a different thermal footprint, see Figure 3. (LED Academy, 2012).

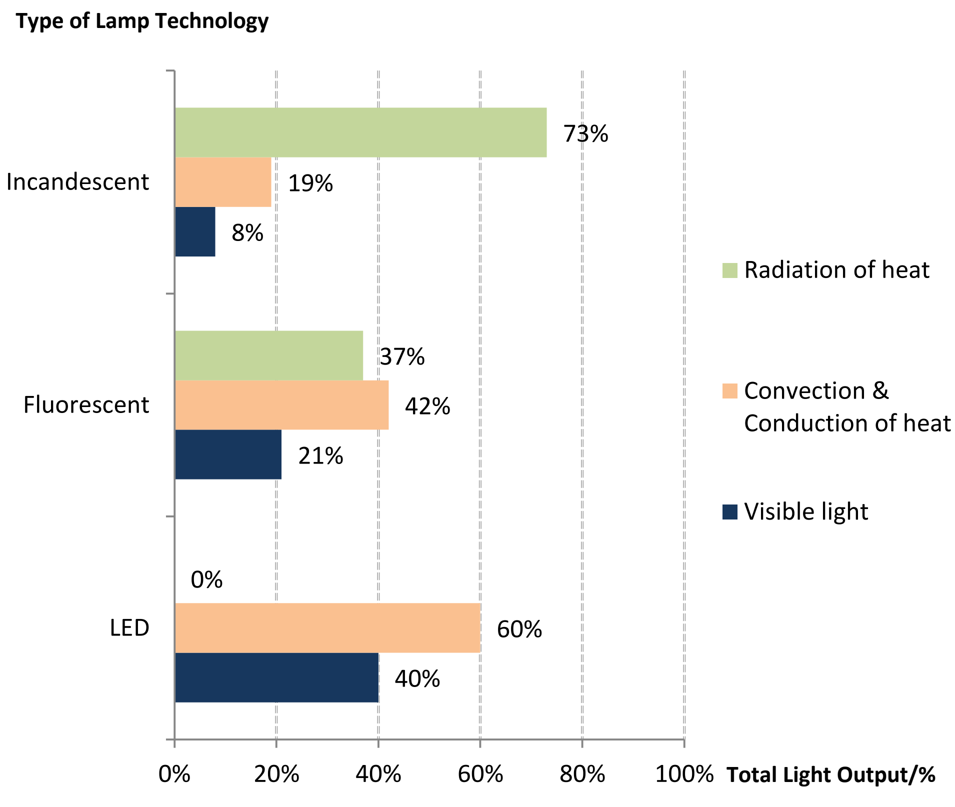


Figure 3: Light and heat portions produced by light sources.

Judging from Figure 3, LED lamps generate more light and less heat compared to other types of lamp technology, such as incandescent and fluorescent lamps, rendering them more energy efficient. LEDs' luminous output appears to be around five times higher when compared to incandescent lamps and around two times when compared to fluorescent ones. On the other side, radiation, convection and conduction cover around 92% of the total energy use for lighting in incandescent lamps, 63% in fluorescent lamps and only 40% in LEDs.

Smart lighting systems make use of the prosperous LED lamp technology and therefore, take advantage of the constantly developing LED's contribution to the energy balance.

2.2 Smart Lighting and LCC

Smart Lighting systems are newly introduced to the market. This fact results in higher initial cost, also known as cost of investment, when compared to conventional and inefficient lighting. Despite the higher initial cost, the notably lower power need for the system to operate leads to lower energy cost on an annual basis. Moreover, the maintenance cost is negligible because of their prolonged guarantee. Note that the work cost to replace broken fixtures or lamps is excluded from the LCC calculation in this study.

Taking the aforementioned into consideration and bearing also in mind the interest rate for the electricity, the payback period of a Smart Lighting system usually accelerates the Return on Investment (ROI) to typically less than 5 years. (Michael Feinstein, 2013).

3 Methodology

MEDESCO S.A. is one of the leading ESCOs in the Greek market that provides energy efficiency improvement or energy services with specialization on energy savings due to lighting and electrical use in general.

By definition, an ESCO, acronym for Energy Service Company or Energy Savings Company, is a commercial business that provides a wide range of energy solutions of main concern the energy savings. (ESCO, 2014). It takes makes use of the concept of performance-based contracting, which means that ESCO's financial incomes are directly linked to the amount of energy saved. (Diana Ürge-Vorsatz, 2007).

A basic plan is strictly followed throughout this study in order to deliver results on time and on budget but most importantly, according to the client's will. It is the same plan that MEDESCO S.A. has developed and it has been used for all projects.

This plan is structured into the following steps:

- **Deep understanding and identification of the project.**
  The first stage includes the client's brief, collection of all the necessary information and technical equipment before the audit.
- **Audit.**
  The possibility audits offer is the documentation of the existing conditions, the desired ones as well as the collection of all data that eventually will contribute to the completion of the project.
- **Concept idea.**
  The concept idea is developed along with the information provided by the client, data gathered during the audit and with compliance to national and international regulations.
- **Technical documentation.**
  The concept idea is written down to a report that is handed over to the client. This report documents in detail all the information on how the concept idea is formed, the technical characteristics of its components that the receiver of the report needs to know and how the project is feasible to be easily performed.
- **Application of concept idea.**
  The concept idea is performed in reality once both the consulting team and the client come to an agreement.

3.1 Model and surrounding conditions

The building of study is located at the outskirts of Serres, a medium-sized city of northern Greece. It is perfectly aligned to the North-South axis with the cold rooms, like refrigerators, placed in North to avoid unnecessary heating loads. Being close to the city, the factory is easily accessed by car, as seen in Figure 4.

Figure 4: Map of Serres.

The building is of around 9,550 m^2 and of metal construction. Its plan is shown in Figure 5. It has various net room heights (2.9, 5.0, 6.3 and 7.0 m) and it includes three main categories:

- Production and storage
- Cold spaces, offices and corridors
- Parking lots for clarkes.

The target illuminance levels for each category are 300 lx, 150 lx and 100 lx respectively, according to regulations. The electricity cost is assumed to be 0.11 €/kWh and the operation hours to approximately 16 hours/day, 365 days/year.

Finally, the desired temperature indoors differs from space to space in order to meet the needs for the production line of a dairy factory; 4° C, for the cold rooms and the refrigerators, whereas 25° C, for the rest of the rooms.

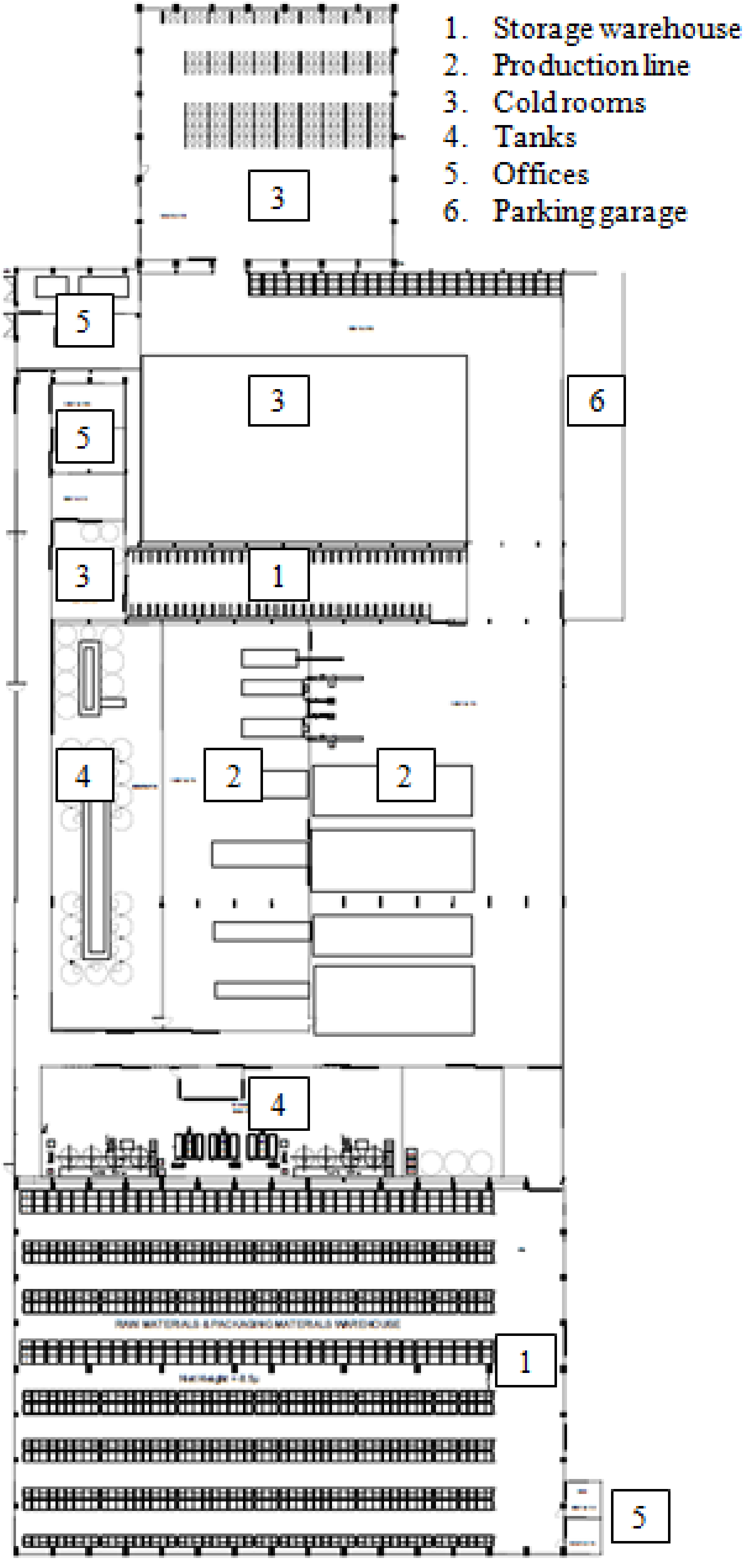


Figure 5: Plan of the building in study.

The light construction of the building follows the same pattern at the whole facility and it is coated with a layer of polyurethane panel insulation. Yet, the insulation's thickness depends on the usage of the space for the specific needs to be met; 120mm of polyurethane panels are preferred for the cold rooms and 80mm for the rest of the facility.

The structure of the construction elements in a cold room is depicted in Figure 6:

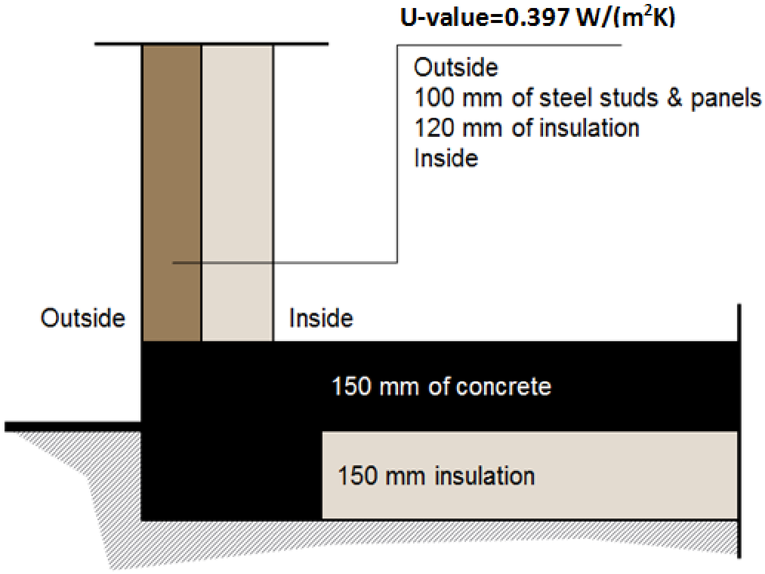


Figure 6: The structure of the building.

3.2 Software used

3.2.1 Autodesk® Ecotect® Analysis 2011

Autodesk® Ecotect® Analysis 2011 is a computer software dedicated to building analysis which allows the application of energy efficient and sustainable design's principles. It is common among architects and designers within the building sector with specialization in sustainable building design. (Autodesk Ecotect Analysis, 2014).

The software is able to analyze, simulate and render complex building structures and shapes taking into consideration the climatic data for different locations with its main focus to measure and improve the performance of a building.

Autodesk® Ecotect® Analysis 2011 is used in the thesis to generate the climatic analysis upon which the energy simulations take place.

3.2.2 DIALux

DIALux is a computer software dedicated to powerful and professional lighting design for indoor and outdoor scenes, in constant connection to world's leading manufacturers. It always uses updated luminaire data with full photometric data sheets and it calculates the energy need due to lighting. Thus, the compliance of lighting design systems with existing national and international guidelines is feasible to be tested and full documentation is possible. (DIALux, 2014).

DIALux is used in the thesis to assess the lighting design of the studied building. The output is used for energy simulations in Design Builder.

3.2.3 WUFI® Pro 5

WUFI® Pro 5 is a computer software dedicated to realistic calculation of the coupled heat and moisture transfer in building components which are exposed to natural climate conditions. In other words, it calculates the hygrothermal behavior of multi-layer building structures. (WUFI® Pro 5, 2013).

WUFI® Pro 5 is used in the thesis to evaluate the building structures in direct connection with the environmental conditions. The output is used for the energy simulations in Design Builder.

3.2.4 Design Builder

Design Builder is a state-of-the-art computer software dedicated to accurate and detailed energy calculations for complex building models in regards to energy, carbon, lighting and comfort performance. It aims to help architects and designers to design and simulate environmentally friendly buildings. (Design Builder, 2014).

Design Builder is used in this thesis to assess energy calculations in combination to the aforementioned simulation programs. (WUFI® Pro 5, DIALux).

3.3 Climate analysis

Since Thessaloniki is close to Serres, its climatic conditions were used for the simulations in Ecotect Analysis instead. Thessaloniki's climate is viewed as moderate with climatic conditions that vary throughout the year.

More specifically, the temperature rarely drops below 0° C during winter and it usually rises to +40° C during summer, see Figure 7. The relative humidity (RH) fluctuates between 40-80% annually and the prevailing winds blow from North-East and South. The solar radiation and the rainfall content (RF) are rather constant throughout the year, however, there is no data provided for daylight, see Figure 8.

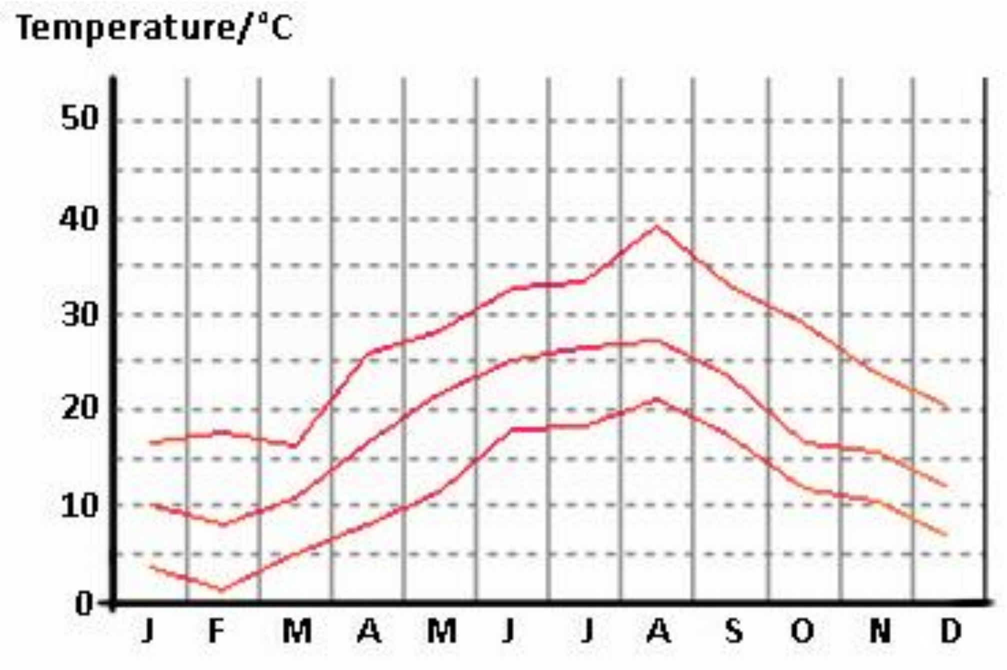


Figure 7: Annual fluctuation of ambient temperature.

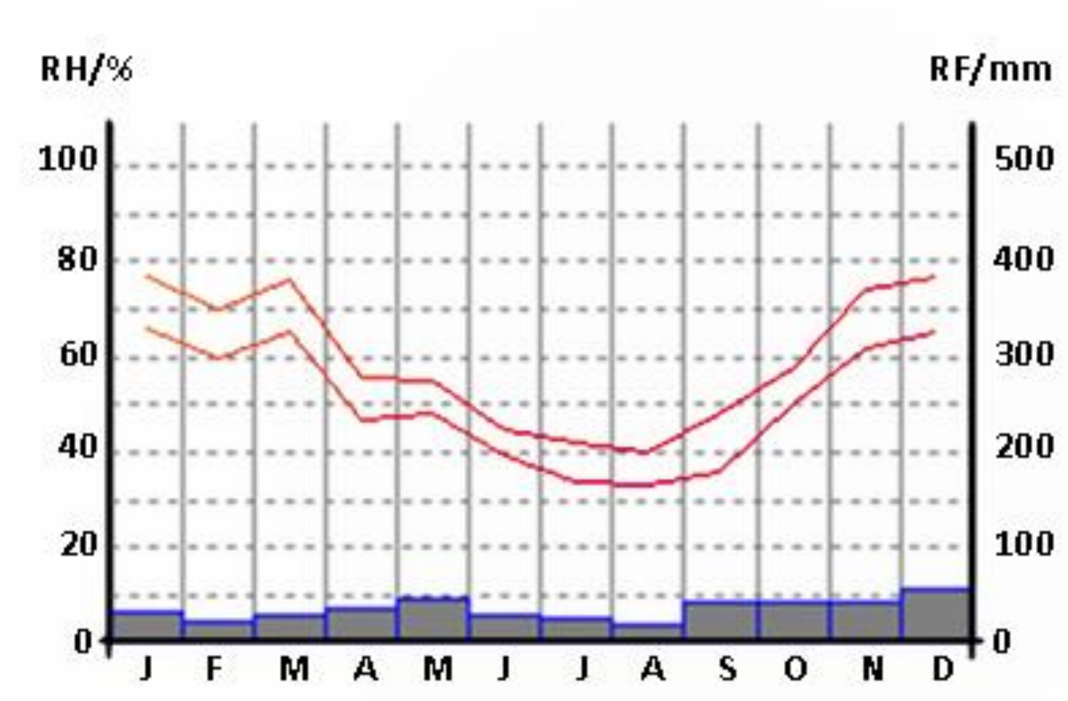


Figure 8: Annual relative humidity (RH) and rainfall content (RF).

The cooling season lasts from March till the middle of November with the degree hours for cooling peaking in August. On the contrary, the heating season starts from September and ends in late May, with its peak in February, as illustrated in Figure 9.

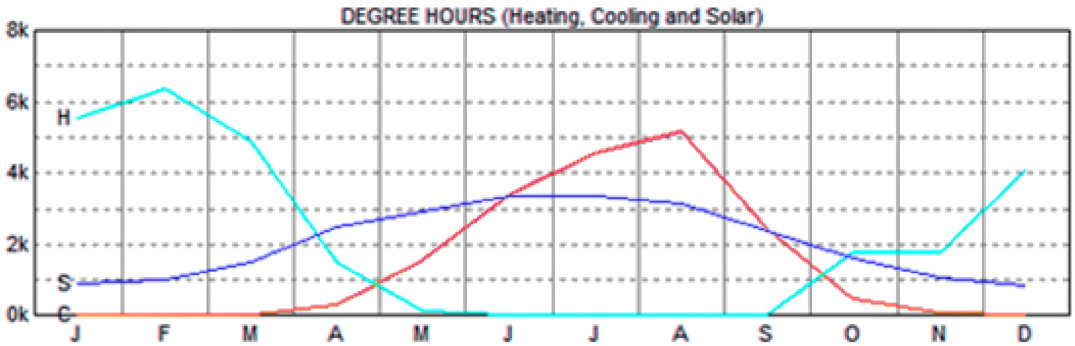
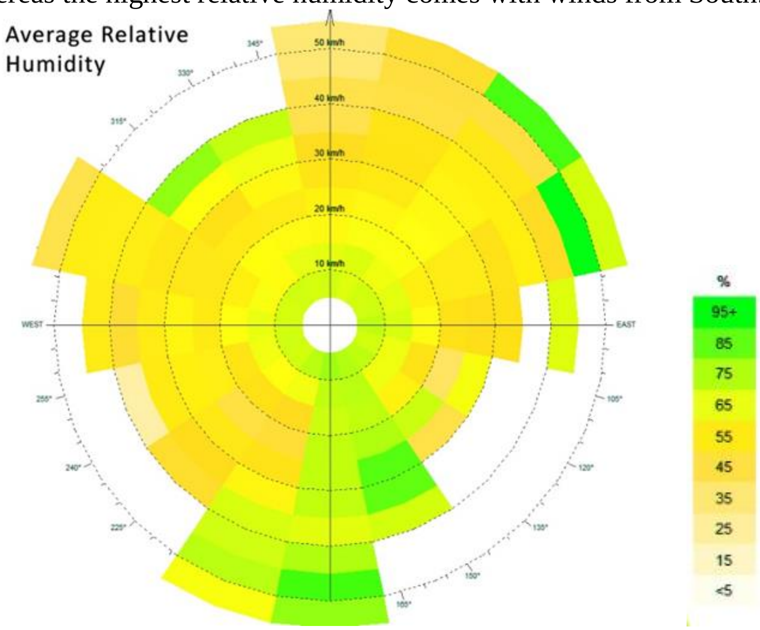


Figure 9: Annual degree hours for heating (H), cooling (C) and solar radiation (S).

Generally, the degree hours stand for the number of degrees Celsius by which the average indoor temperature on an hourly basis is above (cooling degree hours) or below (heating degree hours) a certain temperature that assures thermal comfort indoors. Therefore, degree hours, as a measurement to determine the energy demand of a building in heating and cooling, are strictly linked with the climatic data of the geographical location of the building as well as the structure of the latter. (Wikipedia, 2014). In Figure 9, the cyan line gives the heating degree hours based on a reference temperature of 18°C on a monthly basis. The red line gives the cooling degree hours based on a reference temperature of 26°C. The dark blue line indicates solar excess degree days of additional heating due to incident solar radiation on the external envelope of the building. (Autodesk Ecotect Analysis, 2014).

According to Figure 10, the prevailing winds and the warmest ones come from North-East and South, whereas the highest relative humidity comes with winds from South.



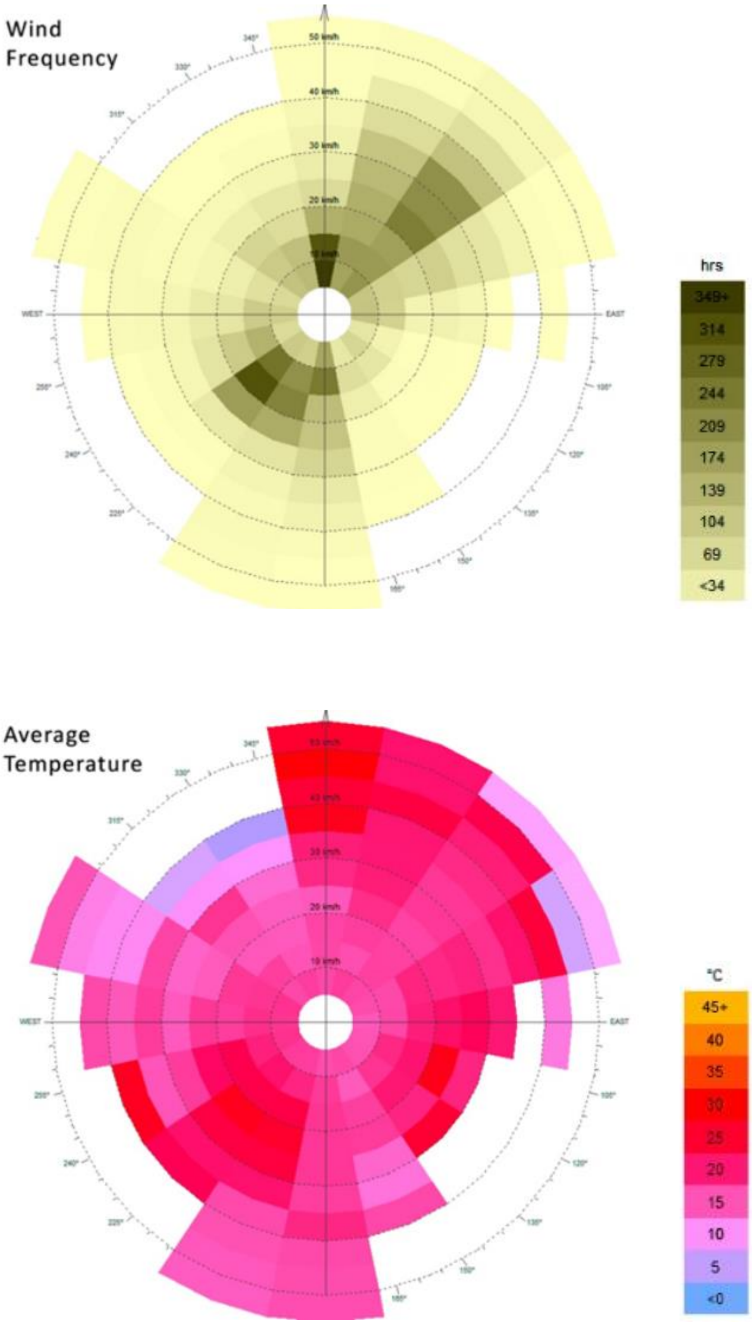


Figure 10: Prevailing winds in Thessaloniki and their characteristics.

Finally, Figure 12 to Figure 14 present the aforementioned climatic analysis on a weekly basis for one year in graphs.

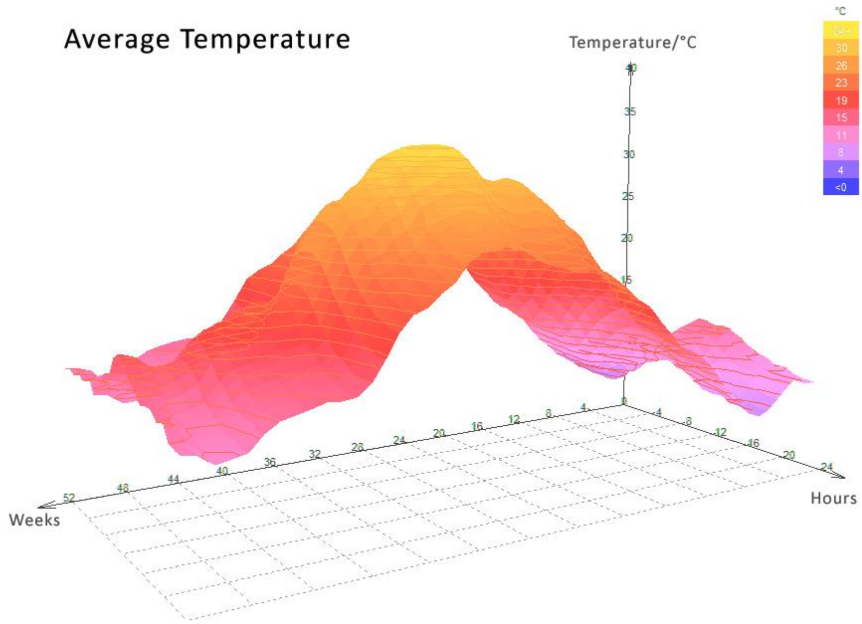


Figure 11: Weekly average ambient temperature of Thessaloniki.

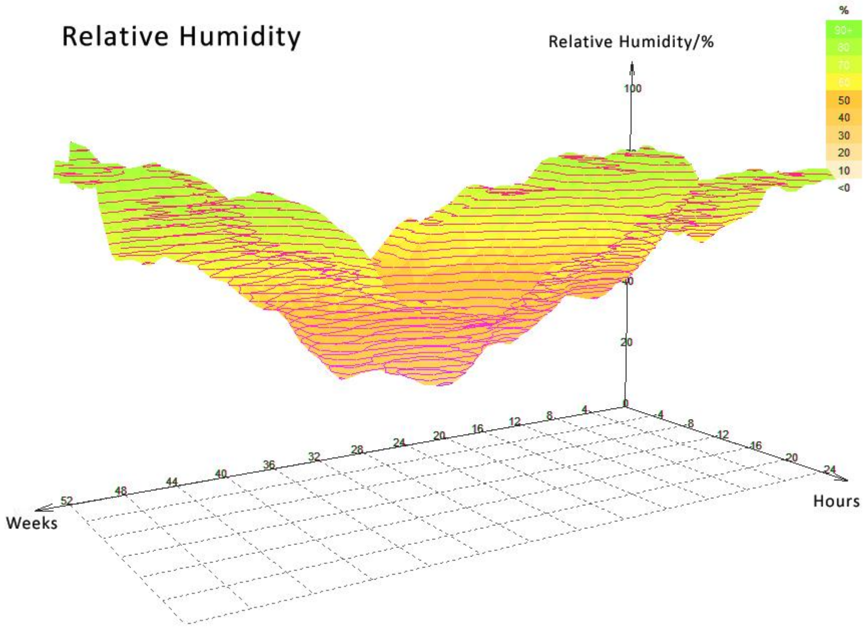


Figure 12: Weekly relative humidity of Thessaloniki.

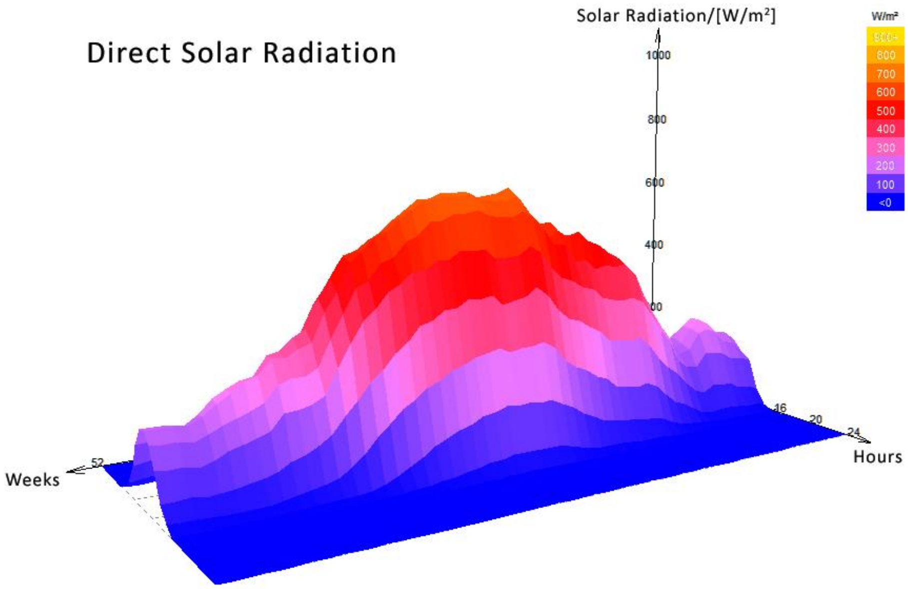


Figure 13: Weekly direct solar radiation of Thessaloniki.

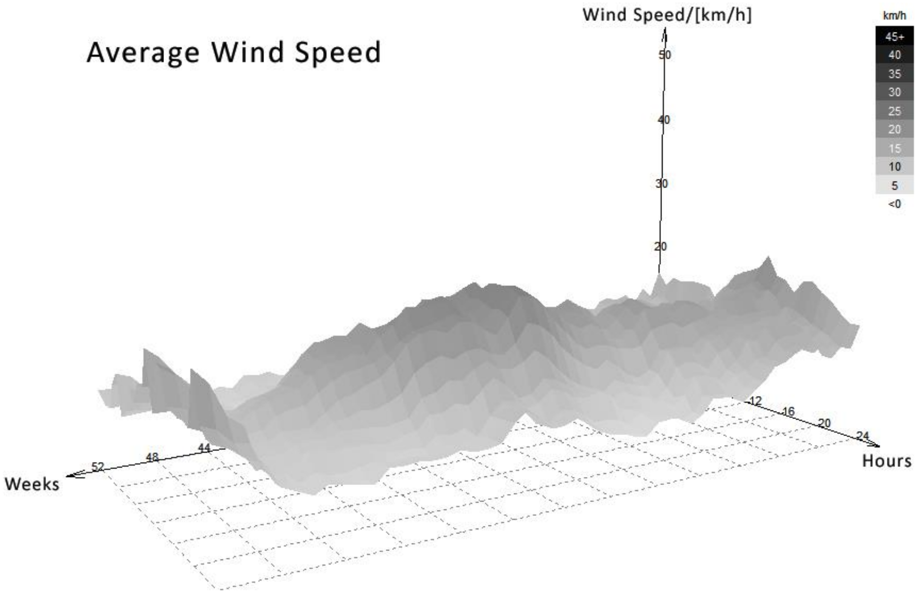


Figure 14: Weekly average wind speed of Thessaloniki.

3.4 Measurements with lux-meters

Since it is a newly built factory, it was impossible to measure the existing illuminance levels. However, the photometric files of the fixtures used in the project were tested to secure the accuracy of the final result with the aid of the digital lux-meter LX1010B of high accuracy, see Figure 15.

Figure 15: The lux-meter used for the measurements.

Two types of fixtures were used; the DLE-12 and DLE-18. The light source was placed perpendicularly, 10m. away from the wall and 1.10m. higher from the floor surface. The illuminance levels were measured upon a rectangular grid of 0.7*1.0m. and the reflectances of the surfaces are presented in Table 1:

Table 1: The reflectances of the surfaces on the basement.

Reflectances / %	
Ceiling	80
Floor	50
Walls	30

Lastly, two different simulations were run on DIALux for each fixture taking into consideration the actual size and reflectances of the space for the simulated model.

3.5 Simulations

Numerous simulations took place. Firstly, the climatic analysis was generated in Ecotect Analysis. Secondly, DIALux was used to simulate the lighting conditions in the rooms and lastly, the energy simulations were performed in Design Builder. The lighting simulations in DIALux were based on the “EN 12464:2002 Lighting of workplaces” standard.

Provided that there are no data concerning lighting and energy use available, both “existing” conditions and the proposed solution were simulated in design software and then, the outputs were compared to each other with the use of Microsoft Excel.

3.6 Standards and regulations

According to the Greek energy regulation, the country is divided into four climatic zones that affect the design limitations, with Serres belonging to Zone C. Table 2 summarizes the levels defined by the criteria that should not be exceeded, for climatic zone C:

Table 2: The criteria concerning lighting and energy use set by the Greek regulation.

Greek Energy Regulation		
Lighting		
Min. luminous efficacy / (lm/W)	0.55	
Min. uniformity ratio	0.40	
Max. power density / (W/m^2)	15	
	Corridors&Auxiliary rooms	Rooms of variable usage
Illuminance levels / lux	200	300
Power per area / (W/m^2)	6.4	9.6
Grid height / m	0.5	0.8
Thermal power per person / (W/person)	0	80
Thermal power per area / (W/m^2)	0	60
Mean presence coefficient	0	0.25
Suggested surface reflectances		
Ceiling	60% - 70%	
Walls	40% - 70%	
Floor	10% - 20%	
Desk & work surfaces	30% - 50%	
Thermal Comfort		
Serres: Zone C		
U_{roof} / [W/(m^{2}K)]	0.40	
U_{wall} / [W/(m^{2}K)]	0.45	
$U_{gr.floor}$ / [W/(m^{2}K)]	0.75	
$U_{openings}$ / [W/(m^{2}K)]	2.80	
U_{mean} / [W/(m^{2}K)]	1.05	

Moreover, the ASHRAE Energy Standard provides the recommended maximum lighting power density (LPD) in respect to the type of the room, see Table 3, that the installed lighting power should not exceed.

Table 3: Recommended LPD according to ASHRAE Energy Standard.

ASHRAE Energy Standard	
Recommended LPD / (W/m^2)	
Office (enclosed)	12
Low-bay manufacturing facility	13
Warehouse	10-15
Corridor for manufacturing facility	5
Parking garage	2

Harvesting daylight in offices will also be assessed. Consequently, the BREEAM criteria for Health and Wellbeing (BREEAM, 2009) presented in Table 4, need to be met:

Table 4: BREEAM criteria.

BREEAM criteria (for latitude ≤ 40°)	
Average DF	
First credit	1.5 %
Exemplary level	3 %
Minimum point DF	
First credit	0.6 %
Exemplary level	1.2 %
Minimum uniformity ratio	0.40

In more detail, compliance with BREEAM, which means achieving at least the first credit, requires that both of the following conditions are met:

a. At least 80% of net lettable floor area in occupied spaces is adequately daylit, having an average daylight factor of at least DF_{av}=1.5% at the working plane height of 0.7m under a uniform CIE overcast design sky.
b. A uniformity ratio of at least u_0=0.4 or a minimum point daylight factor of DF_{min}=0.6%.

The assessment of the daylighting conditions in a building aims to encourage and recognize designs that provide appropriate levels of daylight indoors for their users with the lowest possible use of electricity for lighting.

3.7 Parametric study: Lighting design

Firstly, a parametric study concerning the potential energy savings due to lighting was conducted with the aid of Excel and DIALux. This was achieved by analyzing three different scenarios of different lamp technologies and the integration of several techniques such as dimming, daylight control and absence/presence sensors. These scenarios are:

a. Simple lighting technology (fluorescent and metal halide lamp technology corresponding to the “existing lighting conditions”).
b. LED technology (fixture and lamp technology of high luminous efficacy, so that the simulation corresponds to energy efficient lighting design).
c. Smart lighting technology.

A second parametric study was conducted and concerned the lighting conditions in the office areas, so that the BREEAM criteria are met. The right of the users to view and connection with the outdoor world, direct and unobstructed access to daylight is of great importance and it is stipulated by the Swedish building regulation as a necessity in every building as long as the type of activity is not disturbed. (Helena Bülow-Hübe, 2001). Plus, studies have shown that the length and the geometry of an awning in general have the most significant effect on a building’s energy use. (Marie-Claude Dubois, 1998). Thus, the windows in the office areas were varied in number, placement and geometry until the optimum solution in terms of daylighting is achieved.

Secondly, the cost analysis of the lighting installation indicated the payback period of the system, the annual energy and cost savings and the total Net Present Value (NPV) over the period of ten years.

Finally, a third parametric study was conducted with the aid of Design Builder to investigate the potential energy savings of the building.

3.8 Cost analysis of the lighting system

When comparing different lighting installations, the payback period as well as the return of investment should be calculated as they are determinant indicators of how profitable the investment is.

The calculation of the payback period is possible by the following formulas [4] and [5], (Investopedia US, 2014) in an Excel sheet:

$$Payback\ Period\ (years) = \frac{Investment\ cost}{Annual\ savings}, \qquad [4]$$

$$Annual\ Savings = Annual\ energy\ \&\ maintenance\ cost{:}\ Case\ A - Case\ B, \qquad [5]$$

Lastly, the return of investment is also of great importance as it reveals the portion of the investment cost that will be covered each year and till the end of the payback period, after deploying the suggested lighting installation. It, also, yields the annual profit for the suggested solution.

The calculation of the payback period is possible by the formula [6], (Investopedia US, 2014):

$$Return\ of\ Investment\ (\%) = \frac{Annual\ cost\ savings}{Investment\ cost}. \qquad [6]$$

3.9 Moisture safety design

Both the old and a new structure of high performance for the wall, ground floor and roof will be evaluated in WUFI® Pro 5. Both structures will be used for energy simulations with the old structure corresponding to the “existing conditions”, whereas the new one will part of the suggested improvements.

3.10 Parametric study: Energy analysis

The energy analysis of the building will be performed with the aid of Design Builder. A short parametric study will take place to investigate the effect that each single improvement may bring on the energy savings. The four energy scenarios will be the following:

- Existing conditions, as defined previously.
- First improvement; changing the lighting system from conventional to LED lighting.
- Second improvement; changing the lighting system from conventional to Smart lighting.
- Improvements, as described previously.

The temperature indoors is 4° C, for the refrigeration areas and 25° C for the rest of the rooms. The infiltration rate is presumed to 0.05 ac/h, since in new constructions the amount of airtightness is high. The minimum ventilation rate is given by formula [7]:

$$q = 7\ l/(s \cdot person) + 0.35\ l/(s \cdot m^2) \qquad [7]$$

The insulating material chosen is the polyurethane panel with heat conductivity of λ=0.023W/(m·K).

3.11 Energy cost versus insulation cost

Changes on the structure of the wall, roof and ground floor also affect the total cost analysis of the building. Generally, as the insulation layer increases in thickness, the total energy demand for heating and cooling can be notably reduced. Yet, an irrational increase of the insulation layer may lead to excessive investment costs that may not be abridged by the expected reduction in the energy demand.

For this reason, it is worth-comparing the costs due to energy demand over a period of ten years against the initial cost and the different thicknesses of the insulation layer in order to determine how profitable these improvements may be.

More specifically, the energy cost is calculated by using formula [8]:

$$Cost\ for\ energy = Power\ (W)\ \times Operation\ hours \times Price\ of\ 1kWh \qquad [8]$$

Note that the current interest rate for electricity is also included in the calculation of the energy cost over the 10-year period.

For the calculation of the insulation cost, see formula [9]:

$$Cost\ for\ insulation = Area\ (m^2) \times Price\ of\ insulation\ of\ certain\ thickness \qquad [9]$$

The payback period and the return on investment are governed by the same rules described under subchapter 3.8 above.

3.12 Cost of the installation of the cooling machine

The initial cost for the cooling machine is added in this study to better describe potential savings. More specifically, it is assumed that no heat storage occurs during the night and thus, the total power is equal to the maximum power need for lighting for each lighting scenario in daytime, see formula [10]. (Dennis Johansson, 2005). The formula excludes VAT which is assumed to be 23% for products and services in the case of Greece.

$$Cost\ for\ cooling\ machine\ (SEK) = 100057 + 2.344 \times Power\ for\ lighting\ (W) \quad [10]$$

Finally, since formula [10] calculates the installation cost of a cooling machine in Swedish Krona (SEK), the result is converted in Euros to match the rest of the costs' currency unit. The currency conversion takes into account the latest rates for more up-to-date calculations and accuracy. (XE Currency Converter, 2014).

4 Results

4.1 Measurements with lux-meters

The output from the simulations was compared to the measurements in order to define the level of accuracy that the photometric files (*.ies) of the fixtures provide. In both cases, the illuminance was tested upon a grid with the dimensions of 4m width × 1.4m height. The results are presented in Figure 16:

W=4m

H=1.4m

91/94	95/97	97/98	95/97	96/98
93/94	97/99	98/100	97/99	92/95
92/92	96/98	98/100	96/98	92/93

Average/lux	95/97
Min/Avg	0.96/0.95
Min/Max	0.93/0.92

139/140	146/146	149/150	146/148	140/143
141/142	149/150	151/153	149/152	142/146
141/141	148/150	151/153	148/152	142/145

Average/lux	146/147
Min/Avg	0.94/0.95
Min/Max	0.92/0.91

Figure 16: Illuminance levels on the grid. Testing two different smart fixtures.

The values from the simulation are marked in black whereas those from the on-site measurements in red. The comparison of the two methods used revealed that the values gained from the simulations were always lower than the ones achieved in real life. This is quite important as it creates a safety limit for real-life conditions. The comparison also showed that both outputs are similar and thus, the *.ies files of the fixtures are reliable for simulations.

4.2 Parametric study

4.2.1 Lighting simulations

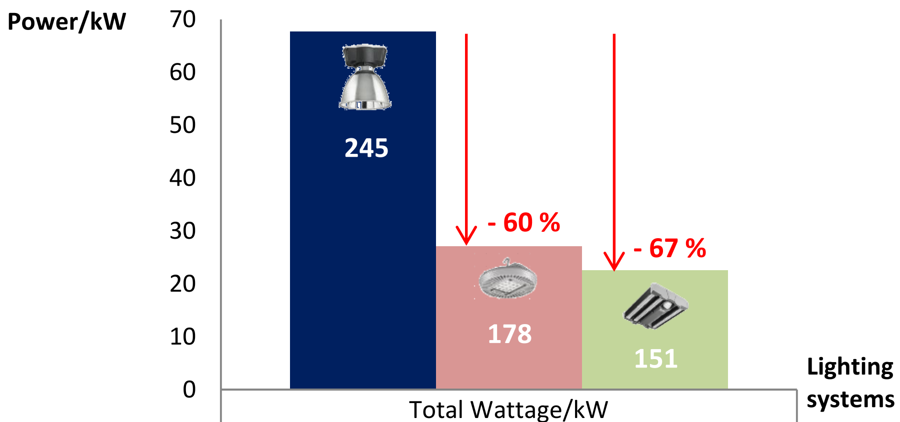
Table 5 shows the distribution and the total output of the fixtures in the building according to the three scenarios studied.

Table 5: Fixtures' distribution in spaces and total power.

a. Simple lighting technology				
Type of fixture	Type of room	Power / W	Pieces	Total power/ W
Waterproof 2×58W	Office + Cold room + Garage	110	69	8729
Cabanas 250W	Warehouse + Corridor + Production + Cold room	326	138	51736
Floodlights 150W	Cold room	166	38	7254
		Summation	**245**	**67719**
b. LED technology				
LED Cabanas	Warehouse + Office + Cold room + Garage	108	42	4536
LED Cabanas	Warehouse + Cold room + Production + Corridor + Office	197	110	21670
LED W60L60	Warehouse + Cold room + Production + Corridor	27.5	12	330
LED tubes	Warehouse	40	14	560
		Summation	**178**	**27096**
c. Smart Lighting				
12-N-750 10-10	Warehouse + Office	123.1	45	4889.4
12- N-750 40-40	Cold room	121.6	4	486.4
12- W-750 0-0	Cold room + Warehouse + Corridor	120.7	10	1086.3
12- W-750 40-40	Warehouse	121	2	242
18- N-750 20-0-20	Warehouse + Cold room	181	5	796.4
18- N-750 40-0-40	Cold room + Corridor	181.6	12	1725.2
18- W-750 0-0	Cold room + Warehouse	181.1	14	2300
18- W-750 20-0-20	Cold room + Warehouse	181.5	8	1415.7
18- W-750 40-0-40	Warehouse + Garage	183.2	12	2061
24- N-750 40-20-20-40	Cold room + Production	241.6	18	4339.8
24- W-750 20-0-0-20	Production	243.4	10	2434
LED 1×42W 20×120	Warehouse + Office	42	6	252
LED 1×90W	Warehouse	90	5	450
		Summation	**151**	**22562**

It is worth mentioning that significantly fewer fixtures are needed to achieve the desired illuminance levels and uniformity ratio in each room; 245, 178 and 151 fixtures corresponding to 27% and 38% of reduction in luminaires when comparing the initial conditions with simple LED lighting and smart lighting respectively.

Figure 17 yields the results from the parametric study for lighting on full power, without applying any sensors or dimming control yet. The reduction in the total installed power when LED technology is applied reaches up to 60% in comparison to conventional lighting technology. Yet, the reduction in the total power need is remarkable when smart lighting is introduced, up to 67% compared to simple lighting technology. An additional reduction of 17% can be achieved compared to LED technology.



	Total Wattage/kW
Conventional Lighting	68
LED Lighting	27
Smart Lighting	23

Figure 17: Comparison among the three different lighting scenarios.

The reduction of the total energy demand for lighting can be further improved reaching up to 90.3% compared to simple lighting and up to 69.1% compared to LED lighting, as seen in Table 7, under subchapter 4.2.2 bellow. This is possible by applying occupancy, motion and daylight harvesting sensors, the operation hours and finally, by installing the necessary software to control and monitor the electrical lighting installation, as the smart lighting principles imply.

It highly important to mention that the comparison amongst the three different scenarios presumes the maximum light output of the fixtures regardless the impairment due to ambient temperature. Generally, the rule that governs the relationship between the light output of the fixtures and ambient temperature is that maximum light output is achieved at certain temperatures for each fixture and deviations from that temperature cause degradation of their total luminous output. In other respects, the fixtures of conventional lighting needed to achieve the minimum illuminance levels would have been more in number or, otherwise, if their number is kept as described above in Table 5, the desired illuminance levels for these rooms of specific use will not be achieved and the area could be characterized as notably underlit.

On the other side, the smart lighting fixtures operate on full capacity in a wide range of environments wherein ambient temperature may fluctuate from -30° C to +50° C. This fact ensures the accuracy of a photometric study using smart lighting technology and underlines the superiority of the latter over conventional lighting technology.

4.2.2 Cost analysis of the lighting installation

The calculation of the cost analysis of the lighting installation takes into consideration the following parameters:

- Initial cost of investment.
- Annual maintenance costs.
- Annual energy costs for lighting.

Several assumptions are made too, so that the final cost analysis reflects real life and the accuracy of its results is preserved. First of all, the electricity cost per kWh reaches up to 0.11€/kWh while the interest rate for the electricity is assumed to be 5%. Secondly, the smart sensors' timeout is 30 seconds, which is the lowest possible amongst a series of options. The shortest timeout is chosen due to its significant contribution to energy reduction; the shorter the timeout delay, the least electrical lights are switched on when not needed and hence, the lower the total energy demand due to lighting.

Lastly, the average occupancy rate is 100% for both simple and LED lighting and 50% for smart lighting systems.

Further explanation on the occupancy rate is necessary at this point. International standards indicate the following mean values depending on the use of different industrial spaces. These values are showed in Table 6:

Table 6: International standards for occupancy rate.

Cold storage	15 %
Dry storage	30 %
Dock	40 %
Manufacturing	35 %

Thus, the occupancy rate is kept to 100% for both simple and LED lighting assuming that the lighting system is continuously switched on. This assumption is based on the fact that, due to the slow ignition and the significantly abated light output these lamp technologies present in cold rooms wherein the ambient temperature is low, the lighting installation is preferred to be on all the time. On the other hand, the occupancy rate for the smart lighting system is slightly augmented to 50%, for safety reasons.

Given all the aforementioned parameters and assumptions, the cost savings due to lighting on an annual basis modulate up to 90.3% and 69.1% when comparing of every smart lighting system with the simple and the LED one respectively.

Moreover, the payback period for a smart lighting system is notably abridged; 2.5 years when it is compared to simple lighting technology and 4 years when compared to LED lighting technology. The junction points between the lines in Figure 18 unveil the payback time for each system comparison. This suggests that it is cheaper and more cost-effective to install simple lighting for 2.5 years but once this period of time passes, the lighting installation becomes energy-consuming and inefficient. The same occurs for the LED lighting, after a 4-year period. Thus, the short payback period renders the proposed lighting system not only energy but also cost-efficient.

More precisely, the cost analysis when the smart lighting system is compared to simple and LED lighting technology is presented in Table 7:

Table 7: Cost analysis of the energy use for lighting of smart lighting technology compared to simple and LED lighting.

Executive Summary		
	Smart lighting technology compared to simple one	**LED lighting technology compared to simple one**
Current annual energy cost	38865 €	19811 €
LED + Smart Lighting annual energy cost	4964 €	6869 €
Annual energy cost savings	33901 €	12942 €
Annual energy cost savings	**87.20 %**	**65.30 %**
Current annual maintenance	12.250 €	2.450 €
LED+ Smart Lighting annual maintenance	0.00 €	0.00 €
Annual maintenance cost savings	12.250 €	2.450 €
Annual maintenance cost savings	**100 %**	**100 %**
Annual Savings	**46151 €**	**15392 €**
Annual Savings	**90.30 %**	**69.10 %**
Project cost	169370 €	169370 €
Simple payback / years	2.52	4.00
Return on investment	27 %	9 %
Net present value (10 years)	379532 €	17914 €
Internal rate of return (10 years)	40 %	2 %

Therefore, the total cost of ownership (TCO) for a time period of 10 years for all the three lighting scenarios investigated appears as in Figure 18. The superiority of smart lighting technology (blue curve) over the simple one (red curve) over a period of 10 years is evident, even though the initial cost of the latter is notably lower. This occurs because of high maintenance costs and energy use for the simple lighting technology that raise the total costs significantly.

The green curve stands for the LED lighting technology the characteristics of which are the abridged energy use and the increased initial cost of investment compared to simple lighting. Yet, when compared to the smart system, the latter is still the most energy- and cost-efficient system over a period of 10 years, despite the initial cost of investment.

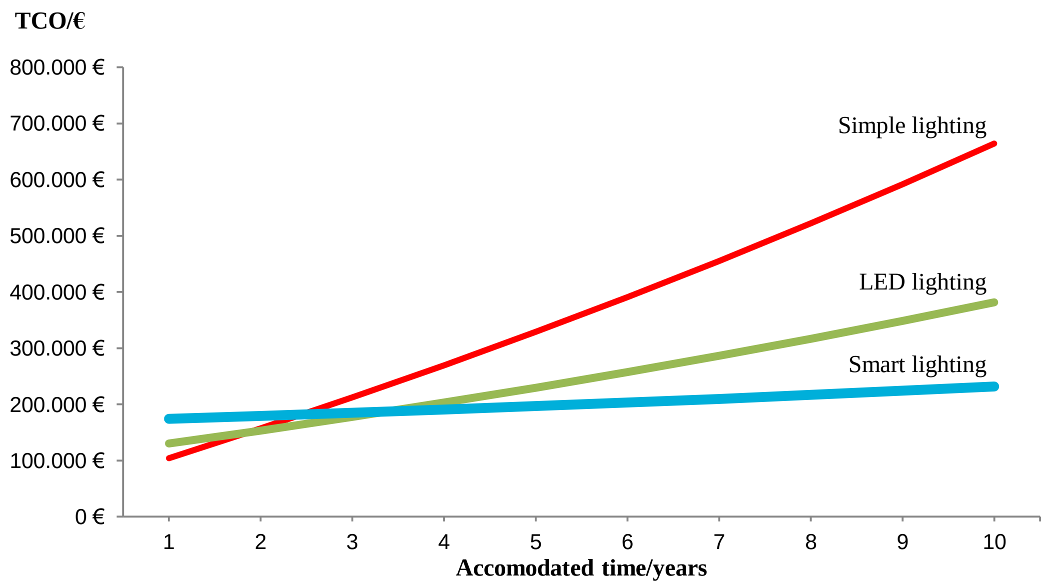


Figure 18: 10-year total cost of ownership for smart lighting technology.

To sum up, despite the increased initial cost of investment, the maintenance and energy savings achieved over a 10-year period render the smart lighting system the optimum lighting solution presenting the lowest total cost of ownership (TCO) amongst the three different lighting scenarios.

4.2.3 Cost analysis of the cooling machine

The calculation of the cost analysis concerning the installation of a cooling machine yields the potential cost savings achieved due to the reduction in the power demand in lighting. No heat storage is assumed to occur during the night; thus, the total power is equal to the maximum power for lighting for each lighting scenario. It should be mentioned that this only applies under the assumption that a new cooling machine is needed for the facility. The results are presented below:

$$\mathbf{Existing\ conditions\ (Simple\ lighting)}: Cost\ for\ cooling\ machine\ (€) = [100057 + 2.344 \times Power\ for\ lighting\ (W)] \times € \times VAT = (100057 + 2.344 \times 67719W) \times 23\% = 34544.2€$$

$$\mathbf{Improvements\ (LED\ lighting)}: Cost\ for\ cooling\ machine\ (€) = (100057 + 2.344 \times 27096W) \times 23\% = 21830.7€$$

$$\mathbf{Improvements\ (Smart\ lighting)}: Cost\ for\ cooling\ machine\ (€) = (100057 + 2.344 \times 22562W) \times 23\% = 20415.1€$$

$$\mathbf{Potential\ cost\ savings\ for\ cooling\ machine}\ (€) = Existing\ conditions - Improvements\ (€) = 34544.2€ - 20415.1€ = 14129€$$

The cost analysis for cooling machine due to lower power need in lighting yields significant cost savings of 41% compared to simple lighting technology and of 7% compared to LED lighting technology, if smart lighting systems are introduced to the facility.

Thus, if the installation cost of a new cooling machine is included in the 10-year total cost of ownership for smart lighting technology, then the initial cost of investment for the facility is slightly increased; however, the payback period for each lighting scenario is notably reduced, see Figure 19.

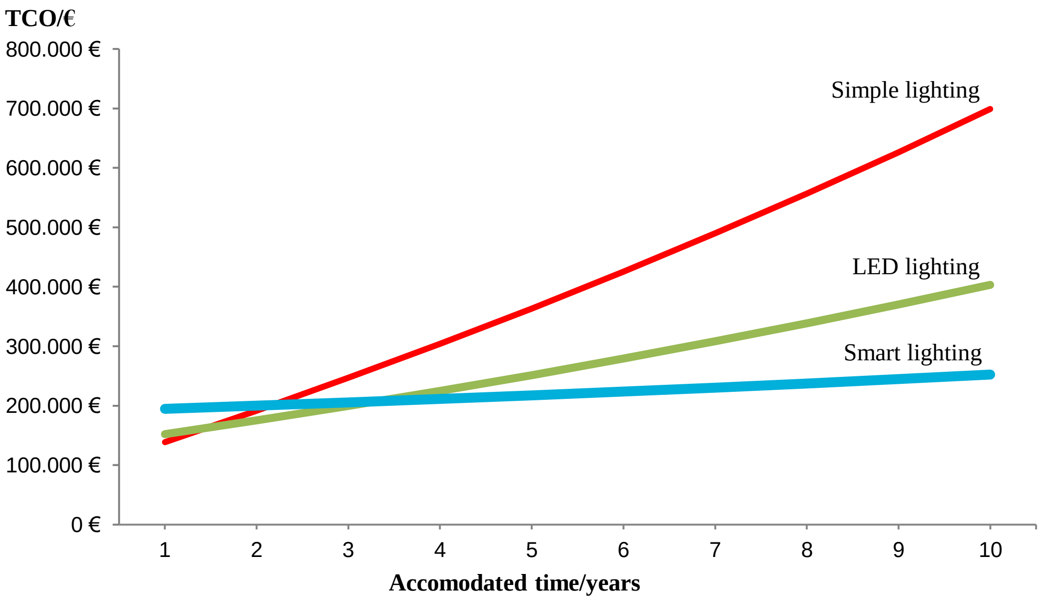


Figure 19: 10-year total cost of ownership for smart lighting technology with the cooling machine cost reduction included.

More specifically, when comparing smart lighting technology to the simple one, simple payback period drops to 2 years, whereas when comparing smart lighting technology to the LED one, it drops to less than 3.5 years. Once again, installing simple LED lighting technology appears to be more profitable during the first years because the energy demand for lighting is significantly reduced and in combination with the low cost of investment, it leads to a short payback period.

On the other hand, whilst smart lighting technology presents the highest initial cost amongst the different lighting scenarios studied here, it also presents the lowest energy demand. As a result, during a 10-year period, smart lighting technology finally stands out as the most energy-efficient and profitable solution of all in this study.

4.3 Moisture safety design

Testing the existing versions of wall structure in WUFI® Pro 5 shows that moisture safety is achieved as the relative humidity (RH) does not exceed the limit of 75% in the middle of the insulation layer, with the tendency to stabilize at around 65%, Figure 20.

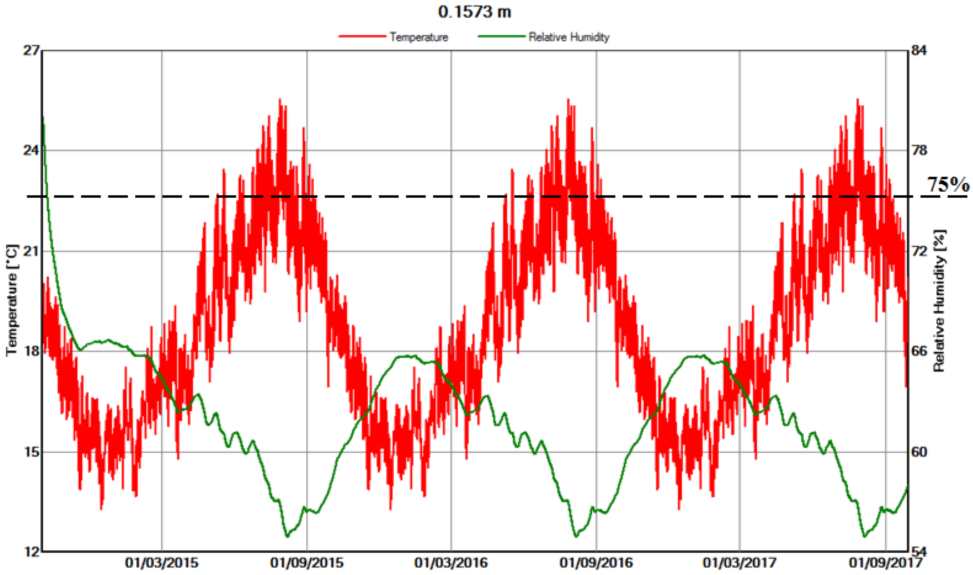


Figure 20: Moisture safety design for the wall.

Nevertheless, the need to enhance the energy-efficiency in the building leads in a new wall, roof and ground floor structure, as presented in Figure 21:

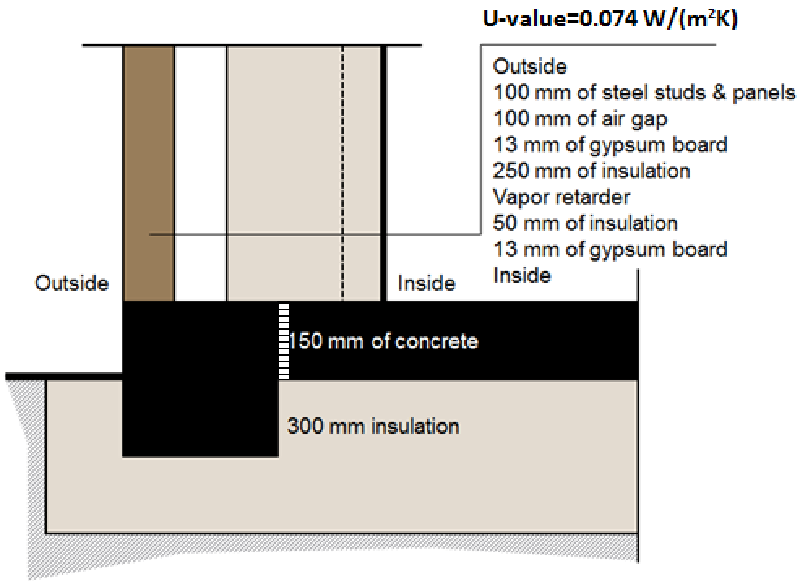


Figure 21: The proposed structure.

The structure proposed follows the rationality that lays behind a structure oriented for cold climates, in order to test whether such building structure could be used for buildings with specific needs in warm climates as comfortably and with no discounts in the indoor thermal comfort as in cold ones. The wall consists of the bearing metal construction, a 100mm airgap, a thick layer of insulation with vapor retarder inside and gypsum boards outside of it. The vapor retarder is placed in between the insulation layers for it to be protected from careless or accidental hits and holes on the wall from inside. Finally, the floor made of concrete is placed on a 300mm layer of insulation to minimize thermal bridges and prevent moisture transfer throughout the construction due to vapor or temperature changes.

The new U-values of the structure can be found in Table 8. The proposed building construction is in complete allowance with the Greek energy regulations given that the new U-values are much lower than the recommended ones.

Table 8: Thermal conductance of the construction elements.

U-values / [W/(m²K)]	
U_{wall}	0.074
U_{roof}	0.064
$U_{gr.floor}$	0.075
$U_{openings}$	1.337

Testing the proposed wall structure in WUFI revealed that the moisture safety design is further improved, see Figure 22, whilst being noticeably energy efficient at the same time. Once again, the relative humidity is kept below 75%. Its trend is descending over time with its variations always kept below 55%, whereas the line appears to be smoother and with fewer fluctuations compared to the old structure.

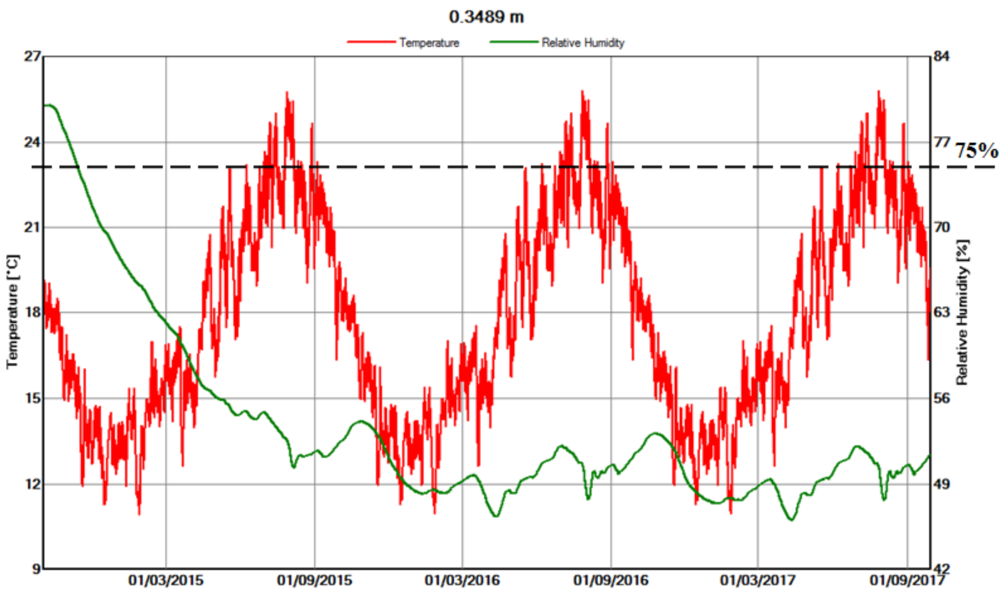


Figure 22: Moisture safety design for the new wall.

4.4 Energy simulations

The short parametric study conducted in Design Builder in order to investigate the effect each single improvement may have on the energy savings, reveals a great potential to reduce the energy demand as well as the magnitude of the effect that lighting has on the total amount of the energy use of the building, see Figure 23.

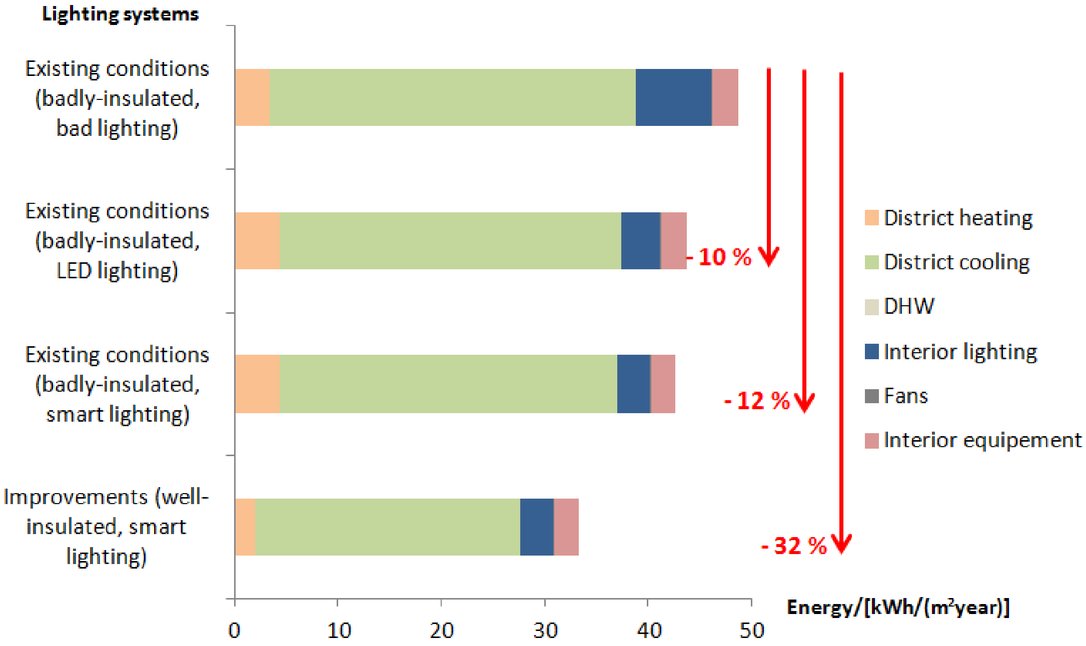


Figure 23: Energy demand.

Simply by applying the first improvement, which is replacing the conventional lighting with LED lighting, the total energy demand is reduced by 10%. Heating demand is slightly increased, mostly in warm rooms, whereas cooling demand is notably reduced, as LED technology emits less heat that is unnecessary in cold rooms, like refrigerators. As expected, the load corresponding to the interior lighting is almost half, when comparing to existing conditions.

An additional reduction of 2% compared to the first improvement may occur with the introduction of smart lighting technology, which is the second improvement. Note that at this moment, the principles of smart systems have not been included yet into the calculation and the energy demand for lighting refers only to the installed power for lighting. Braver energy savings are to be expected when these are applied. Generally, energy demand for cooling, heating and interior lighting follow the pattern explained above.

Changing the structure is of great significance as it results in the reduction of total energy needed. The energy simulations in Design Builder reveal the potential to reduce the annual energy demand of the building by 32%.

Note that the 32% of reduction achieved comprises of reduction in lighting, cooling and heating demand; it is worth noticing that the heavy machinery operating in the factory was not taken in consideration in the energy simulations as it is impossible to correctly estimate its full extent.

More specifically, the reduction in the cooling load reaches up to 27% whereas the heating load is limited by 42%. The reduction in the cooling load appears notably lower than the reduction in the heating load. This is because the building is originally well insulated in general, except from the spaces that do not serve as cold rooms or refrigerators where the insulation layer is thinner by 33%, refer to subchapter 3.1, resulting in greater energy losses from these areas. Hence, an increase in the insulation layer in those rooms leads in a total decrease in energy demand of 42%.

4.5 Energy cost versus insulation cost

The comparison between the energy cost and the insulation cost is influenced mainly by two reasons; the electricity rate of 5% and the cost of investment. Figure 24 below shows that by adding insulation, the initial cost of the structure is bigger. (Alibaba, 2014). Yet, after a 10-year period, the total cost including the insulation cost and energy cost is significantly lower than the one of the existing conditions. This occurs because of the magnitude of the energy savings achieved by introducing a better insulated and moisture safe building structure.

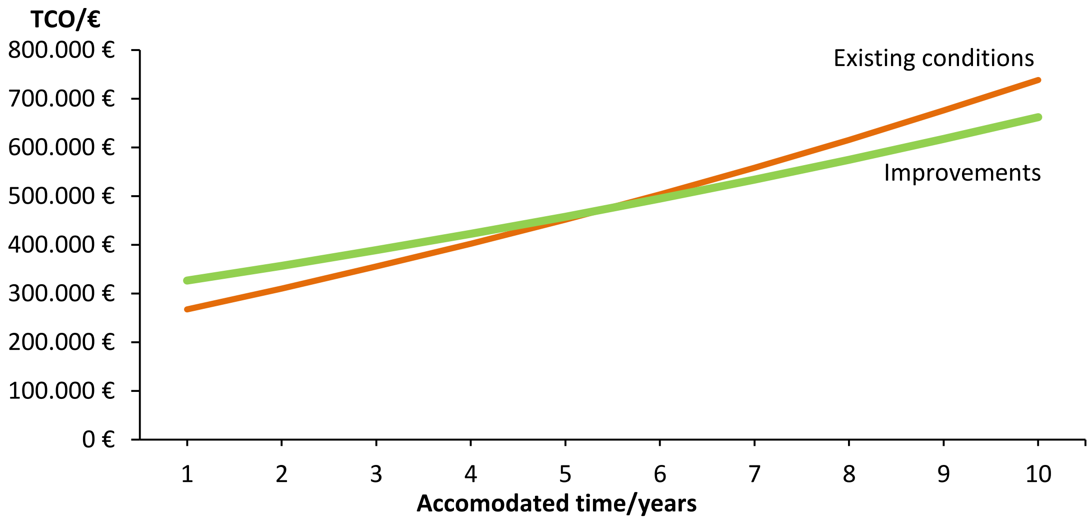


Figure 24: Insulation cost versus energy cost for existing conditions (badly insulated, bad lighting system) and improvements (well insulated, smart lighting technology).

If the improvements on the building structure are applied, the payback period is calculated to 5.5 years, with a return on investment of 20%. This suggests that the existing conditions are profitable in terms of energy use and costs during the first 5.5 years. After that time, the system is inefficient and costly.

Yet, the payback period of the whole system is lessened even more if the replacement of the cooling machine is added in the comparison, see Figure 25 below. The new payback period is calculated to 2.5 years.

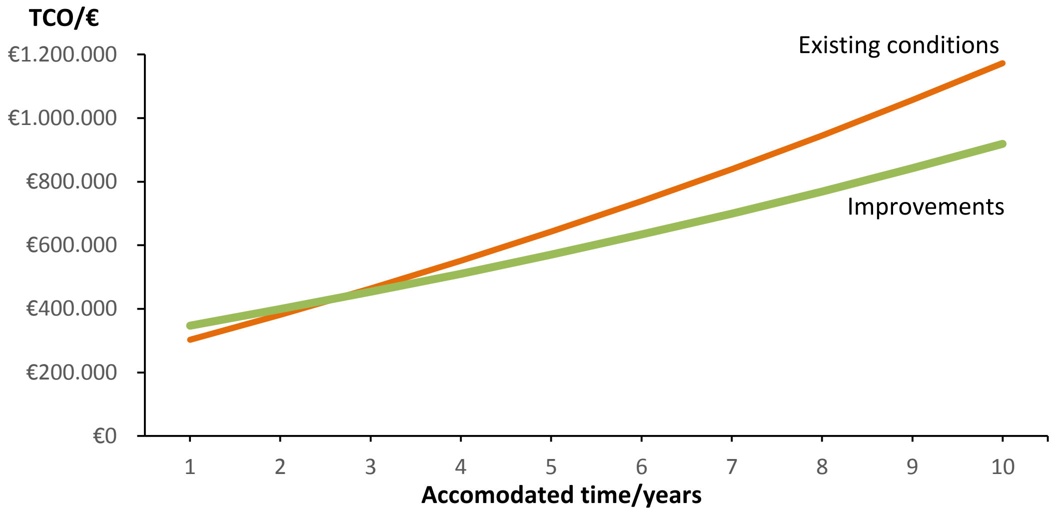


Figure 25: Insulation cost vs energy cost for existing conditions and improvements (with the replacement of the cooling machine included).

4.6 CO_2 emissions

By restraining the energy use, the CO_2 emissions of the building are also reduced, see Figure 26.

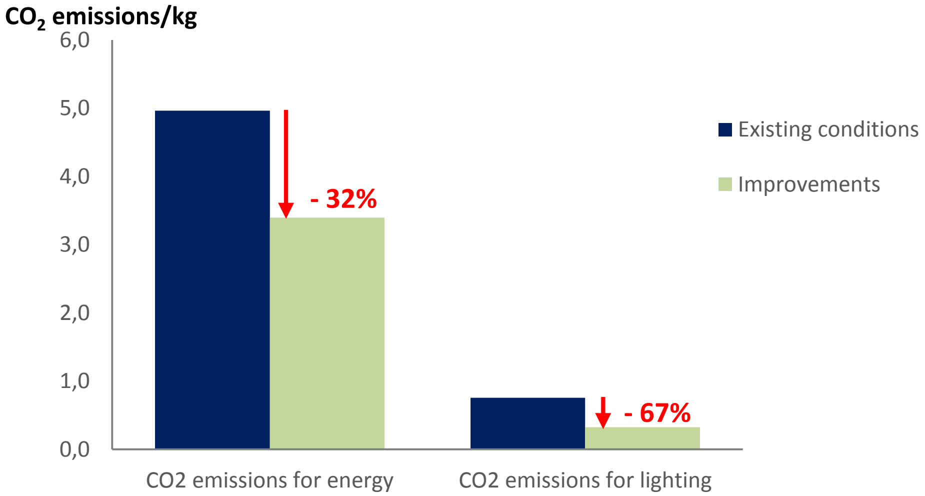


Figure 26: CO_2 emissions.

Figure 26 yields that 32% of the CO_2 produced due to higher energy demand can be avoided if more insulation is added. Plus, the CO_2 emissions due to lighting, which is responsible for 15% of the total energy demand, can be reduced further by 67% if Smart Lighting systems are integrated in the building.

4.7 Standards and regulations

4.7.1 Greek Energy Regulation

The energy simulations took place in consideration with the Greek energy regulation regarding the U-values of the construction elements of the building. Table 9 unveils the comparison between the Greek energy regulation and the old and new construction:

Table 9: U-values for the different construction elements.

U-value / [W/(m²K)]	Greek Energy Regulation	Old structure		New structure	
U_{roof}	0.40	0.416	✗	0.064	✓
U_{wall}	0.45	0.397 (120mm) 0.543 (80mm)	✓ ✗	0.074	✓
$U_{gr.floor}$	0.75	0.455	✓	0.075	✓
$U_{openings}$	2.80	2.951	✗	1.337	✓

According to Table 9, the old structure's U-values exceed the limits set by the Greek energy regulation for the roof, wall (80mm) and the openings whilst the ones for the wall (120mm) and the ground floor comply with the regulation. On the other hand, the new structure's U-values are clearly kept below these limits.

4.7.2 ASHRAE Energy Standard

Table 10 presents the resulting lighting power density for the three scenarios studied. The LPD of the simple lighting technology appears to be higher than the ASHRAE threshold in all spaces except the production line and the warehouses. Yet, there is still room for improvement when Smart lighting is introduced, achieving a reduction in the total LPD of around 66.2%.

Table 10: LPD for the different lighting scenarios.

LPD / (W/m²)	ASHRAE Energy Standard	Simple lighting		LED lighting		Smart lighting	
Office (enclosed)	12	15.8	✗	5	✓	4.5	✓
Low-bay manufacturing facility Warehouse	13 10-15	7	✓	2.7	✓	2.4	✓
Corridor for manufacturing facility	5	7.6	✗	4.2	✓	2.6	✓
	2	6.9	✗	2.1	✓	1.6	✓
Total		**7.1**		**2.8**		**2.4**	

It is important to repeat once again that all LPD results presume the maximum light output of the fixtures regardless the impairment due to ambient temperature that occurs for conventional and LED lighting technology. The total amount of light fixtures needed would have been much higher resulting in higher LPD for these two lighting scenarios, if the impairment due to temperature were to be taken into consideration. In such case, it would be safe to assume that failures in meeting ASHRAE Energy Standard in certain categories could occur.

4.7.3 BREEAM evaluation in the offices

BREEAM criteria are assessed for the offices. A series of improvements are suggested in order to meet these criteria concerning daylight and well-being. These improvements include the following:

- Changing the window's height from the ground floor, to increase daylight penetration deeper into the spaces.
- Changing the Window-to-Wall ratio, by adding extra windows where necessary, to increase the amount of daylight indoors.

Figure 27 below illustrates the comparison between before and after the application of the suggested improvements:

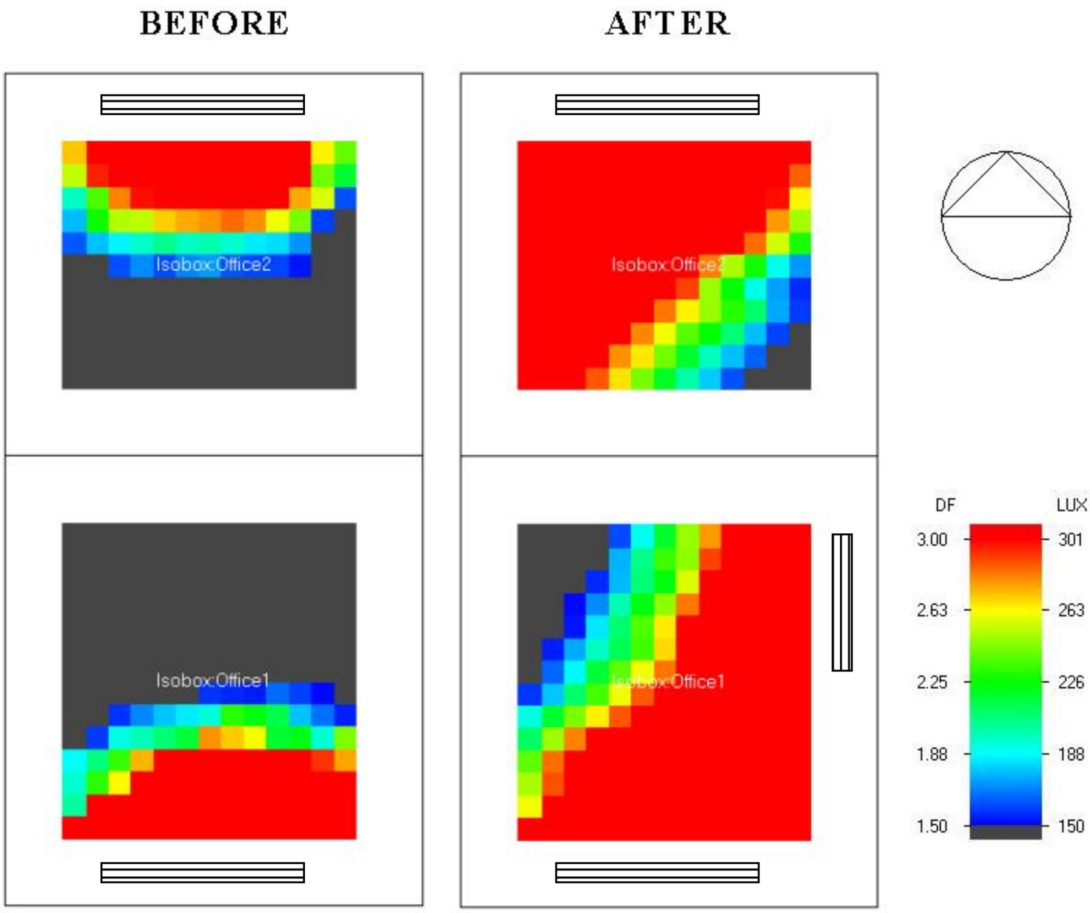


Figure 27: BREEAM assessment in the offices.

According to Figure 27, the offices fail in BREEAM assessment and therefore, improvements are compulsory. More specifically, all windows are placed 0.2m higher than their original placement and their geometry is kept intact. This small change allows more daylight penetration deeper into the offices which is more obvious in the upper part of the office area (Office2, Figure 27).

Yet, this improvement is not enough for the rest of the office area that is bigger in size and seems to fail BREEAM assessment. So, another window is placed on the eastern facade and the Window-to-Wall ration is increased from 10.35% to 14.22%. This awning is smaller in size and it is placed closer to the partition wall because it is expected that daylight bounces on the partition wall and the reflectance will spread the light more evenly indoors. After the application of these changes, the daylighting conditions in the office areas appear more improved and BREEAM criteria are met for both rooms.

5 Discussion

KRI KRI S.A. diary factory, being a newly built facility, aimed to design the electrical lighting installation as more energy efficient as possible in order to achieve great energy savings that will result in the reduction of the operational costs, to enhance the visual experience into different spaces and to minimize the thermal effect the light might have on the cooling load too.

As there were no existing conditions to compare with, a parametric study regarding lighting was conducted. The three different lighting systems studied were:

- Simple lighting technology,
- LED lighting technology,
- Smart Lighting systems.

The parametric study revealed the great potential of energy and cost savings from the deployment of smart lighting systems, a rather prosperous and continuously developing technology. More specifically, the energy savings accounted to 67% and 17% compared to conventional and LED lighting technology respectively, if only installed power is taken into consideration and without applying any sensors or control systems. This reduction may reach up to 90.3% and 69.1% respectively, if occupancy, motion, daylight harvesting sensors and dimming control are introduced to the system. Hence, the criteria set by the Greek Energy Regulation were satisfied.

Moreover, the introduction of smart lighting systems also affected the lighting power density (LPD). The latter was diminished and finally, the facility managed to fully comply with ASHRAE's international guidelines.

Finally, BREEAM criteria were assessed in the office area. These criteria were met if the following improvements are made:

- Slightly changing the awnings' height from the ground floor.
- Slightly increasing the Window-to-Wall ratio.

Then, the LCC of the lighting systems was calculated. Even though the initial cost, also known as cost of investment, seemed to be higher for the smart lighting system, the vast amount of energy savings and the lack of maintenance cost in comparison with conventional lighting rendered the system cost effective. Consequently, the payback period was calculated to 2.5 years and the return on investment to 27%, when comparing Smart lighting technology to conventional one. The payback period can be further abridged to 2 years if the installation cost for a new cooling machine is included in the calculation.

The mitigation of the total energy need due to lighting had also a great effect on the building as the cooling need and the CO_2 emissions were significantly reduced by 67%. This reduction appears to be of paramount significance given the fact that lighting covered 15.2% of the total energy need of the facility.

Thereafter, energy simulations took place in order to improve the energy efficiency of the facility. These simulations aimed for:

- Improvement of the envelope of the facility by redesigning the structural layers of the construction, adding insulation and reassuring the existence of vapor protection.
- Moisture safety design.
- Reduction of the cooling demand.
- Reduction of the heating demand.

The results from the energy simulations promised a reduction of the total energy demand by 32%, provided that smart lighting principles are applied in the electrical lighting installation and that more insulation is added in the construction elements. Improving the thermal conductance of the structural elements played significant role at the energy calculations.

Again, the LCC of the insulation against the energy savings achieved was examined to check if and to what extend the improvements made on the building envelope and the lighting installation are profitable. The comparison of the two systems (existing conditions and improvements) unveiled that despite the slightly higher investment cost due to greater amount of insulation, after a 10-year period, the improvements suggested in this study pay back to the owners. In fact, the payback period was calculated to 5.5 years and the return on investment to 20%. This payback period is lessened to 2.5 years in case the cooling machine of the system is replaced.

The reduction of the CO_2 emissions was also in accordance with the total reduction of the energy demand. The facility appeared to have abridged its harmful emissions towards the environment by 32% due to lower energy use.

The operation of the factory could be improved further by the introduction of systems based on renewable energy sources, such as PV panels, since Greece offers great quantity of solar radiation on a regular basis. This could contribute to more clean energy use and less CO_2 emissions in the environment. Yet, the integration of renewable energy systems was not the subject of this study.

Another interesting subject to investigate is the disadvantages and the effect Smart lighting systems might have on human's behavior due to the fixtures' photometric properties, especially in working places. In addition, converting all mechanical and electrical systems of a building into smart ones could notably improve its footprint, as the systems would operate only when completely necessary. Unfortunately, these were also not subject of this study either.

Finally, the lack of regulations and guidelines concerning the energy use in industrial facilities was a restraining factor as no clear goals were available. However, given the fact that significant energy and cost savings were achieved, it could be claimed that the objectives of this study were met.

In conclusion, there is always room for additional energy savings to occur in a building despite how modern the technology used is, since technology is constantly improving. Smart Lighting Technology has been proved to be the most energy and cost efficient system at the moment regardless its high cost of investment, as it generously provides the desired illuminance levels with the minimum energy demand and CO_2 production, even in buildings of specific use, such as the industrial ones, contributing to a better and cleaner environment.

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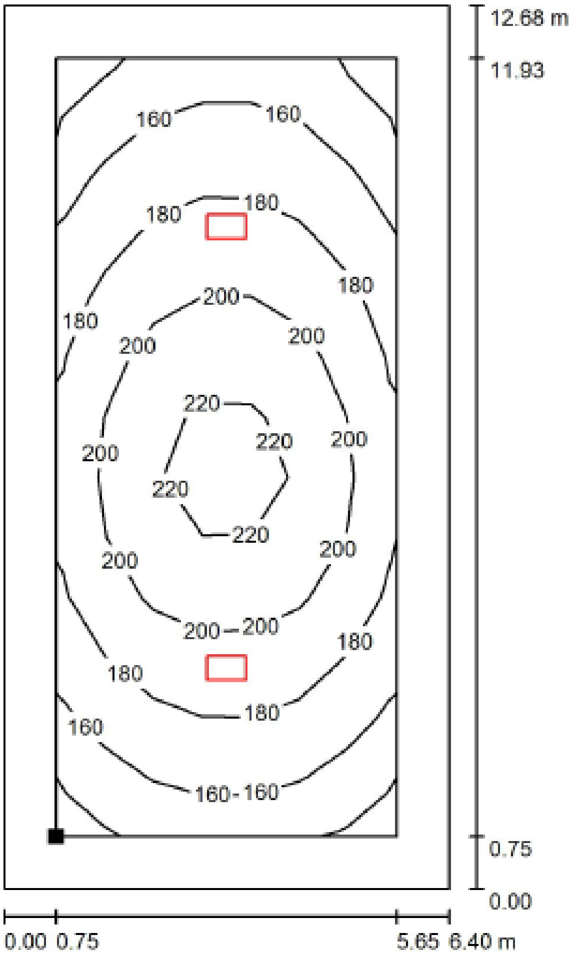
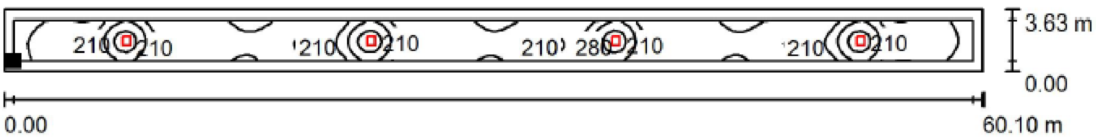
Appendix A

Photometric study: Illuminance Levels & Light Distribution

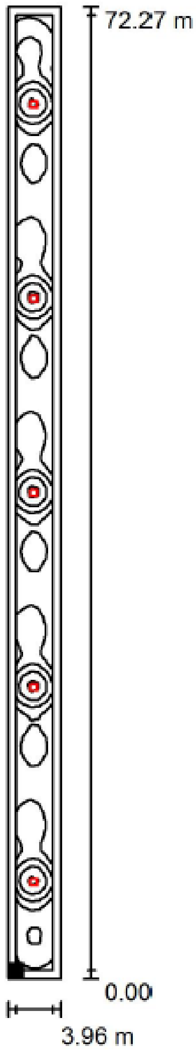
1. Storage warehouse



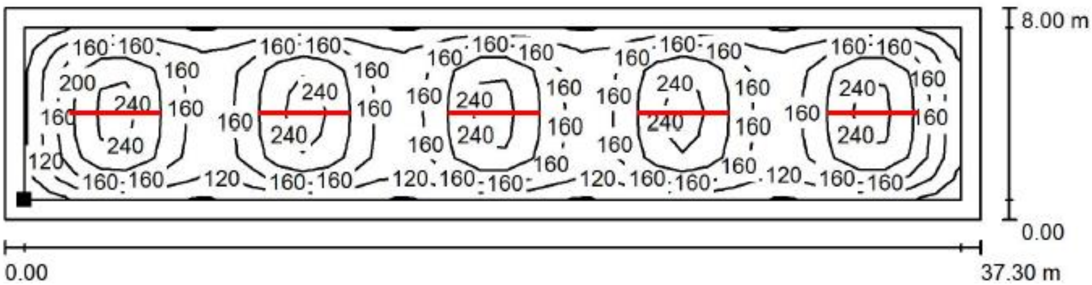
E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
184	138	229	0.748	0.602



E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
200	95	397	0.474	0.238

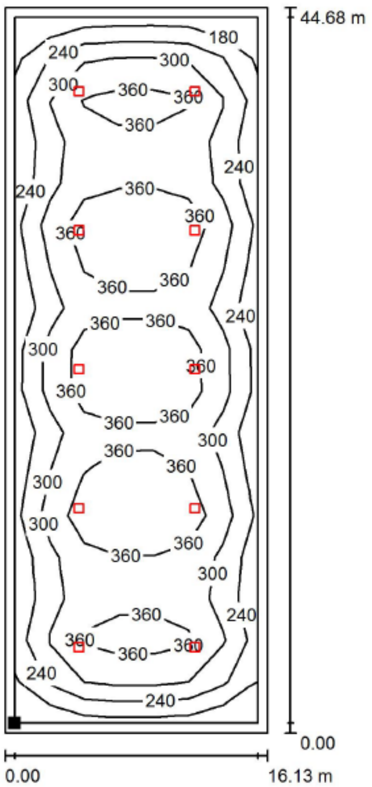


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
200	102	393	0.511	0.260

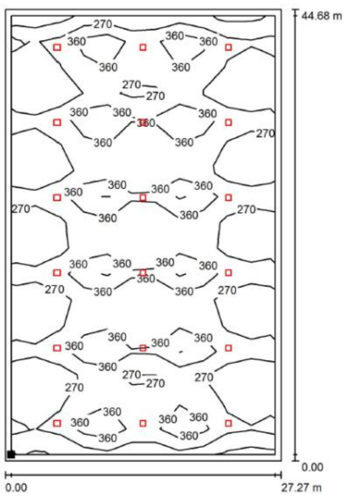


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
173	73	262	0.419	0.277

2. Production line

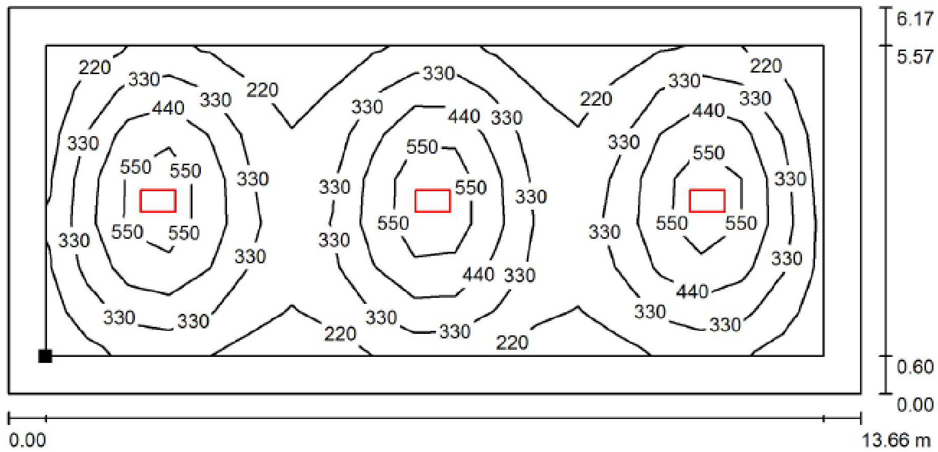


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
316	147	438	0.465	0.335

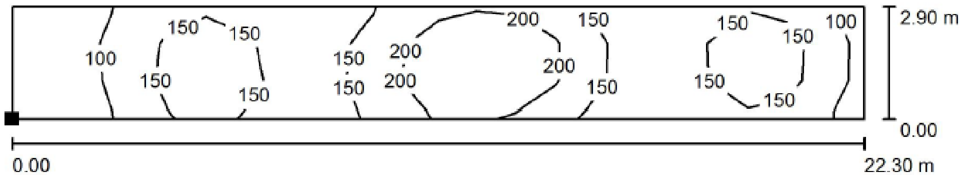


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
300	122	561	0.407	0.218

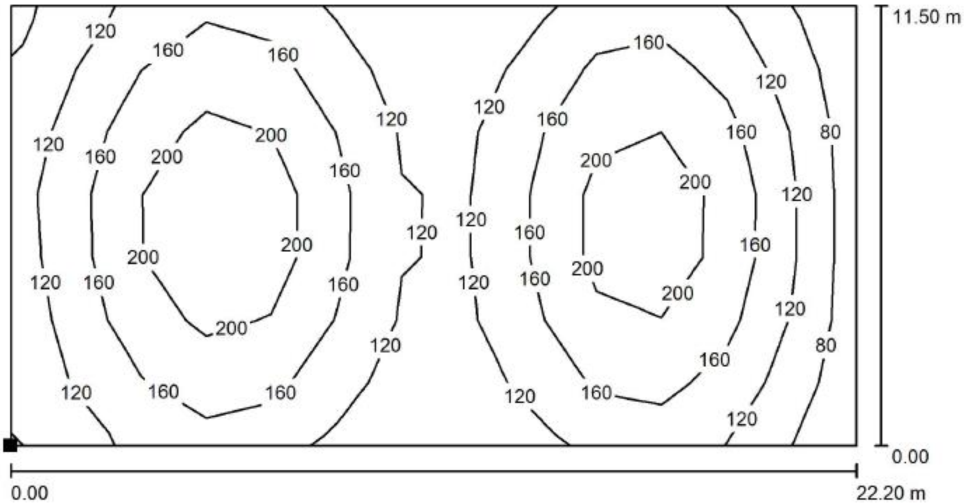
3. Cold rooms



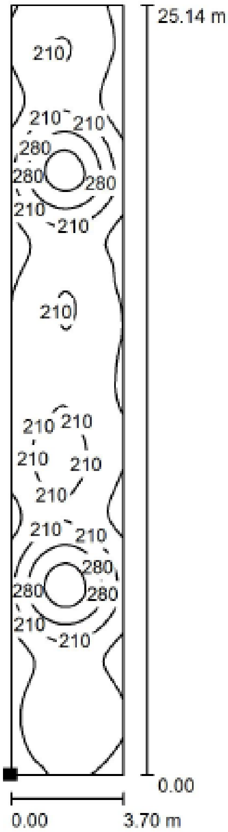
E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
357	155	676	0.434	0.229



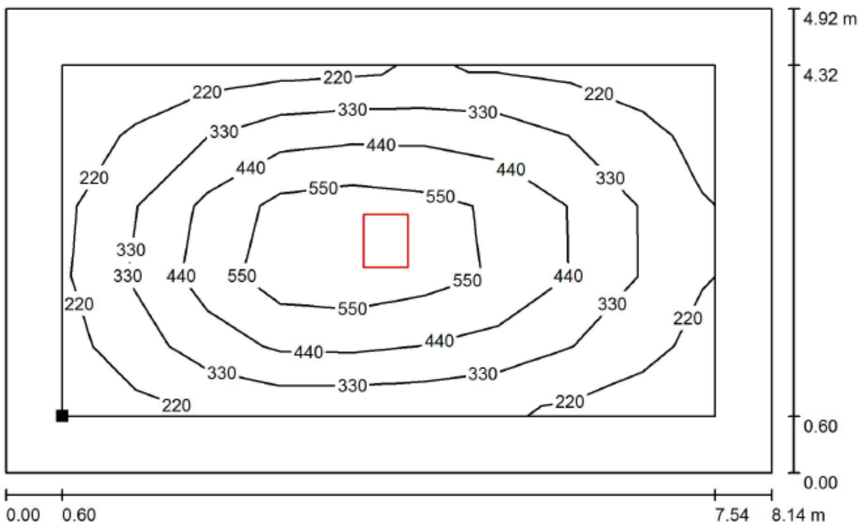
E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
152	66	278	0.430	0.236



E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
150	66	247	0.439	0.266

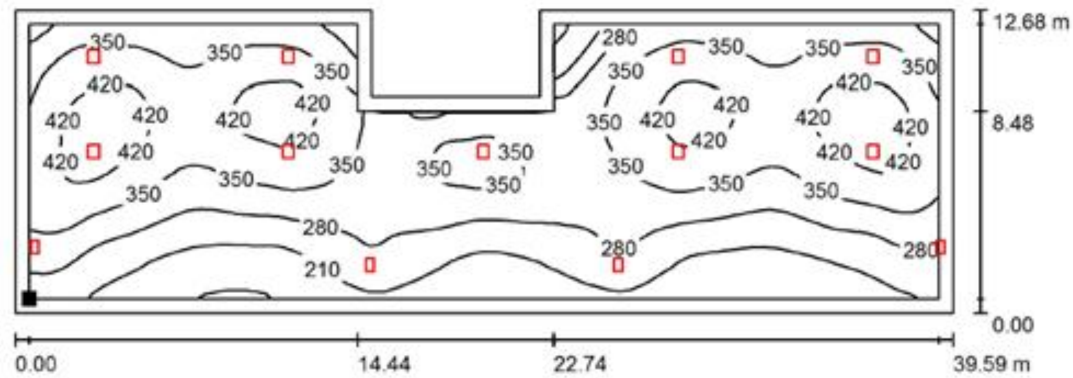


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
197	91	394	0.460	0.231

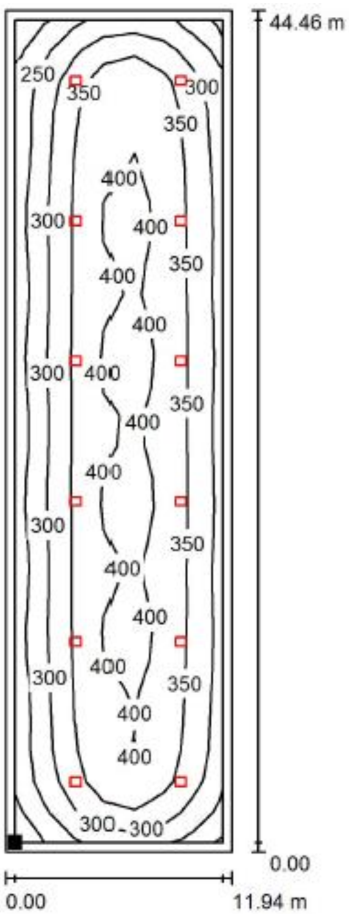


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
377	158	693	0.418	0.227

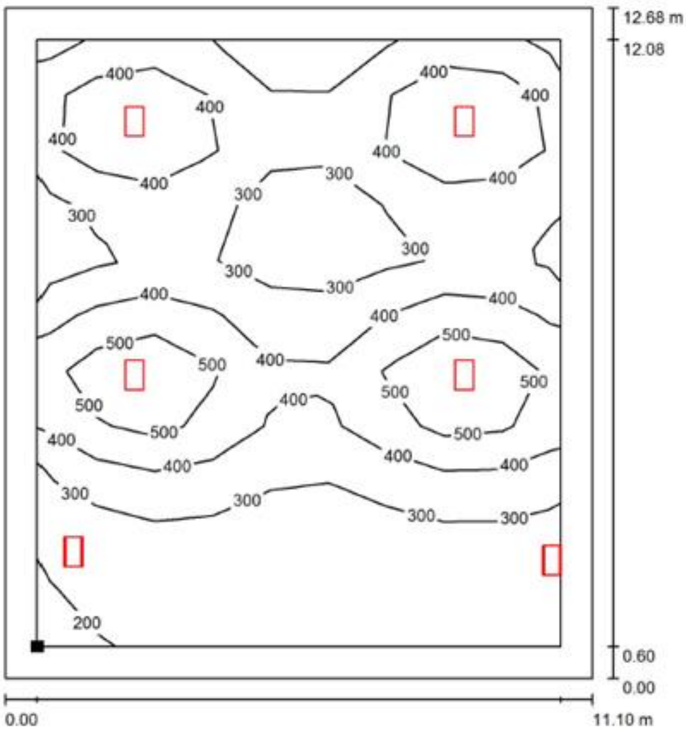
4. Tanks



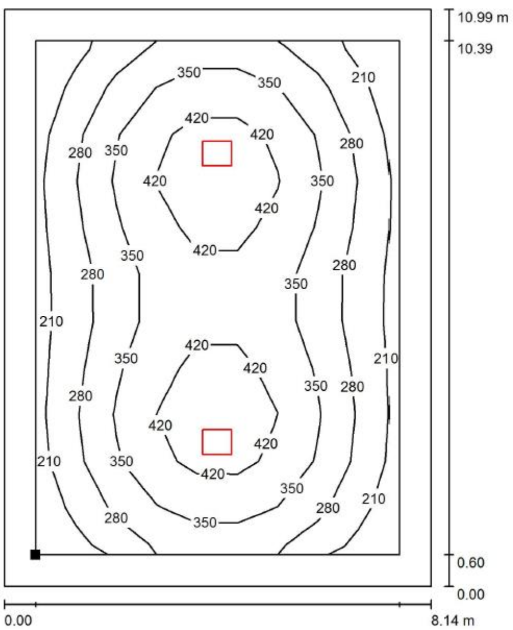
E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
319	133	451	0.418	0.295



E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
342	195	424	0.572	0.416

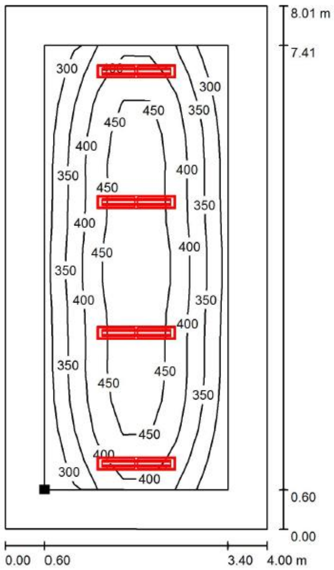


E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
357	191	643	0.534	0.297



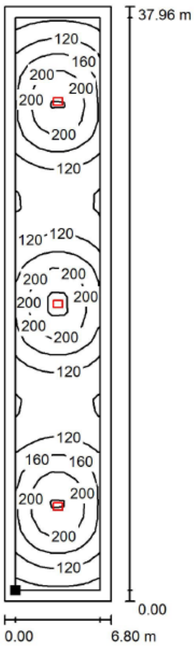
E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
327	171	472	0.522	0.362

5. Offices



E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
396	273	502	0.689	0.543

6. Parking garage



E_{av} (lx)	E_{min} (lx)	E_{max} (lx)	U_0	E_{min} / E_{max}
150	75	259	0.498	0.289

Figures

Tables