Lighting and daylighting in livestock buildings for dairy cows

Circadian lighting and energy use

Karl Axel Nordin
Phoo Wint Zaw

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

Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Niko Gentile (Division of Energy and Building design)

Supervisor: Marie-Claude Dubois (Division of Energy and Building design), Sheikh Rishad Ahmmad (Department of Biosystems and Technology)

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Abstract

The industrial sector of Sweden used 136 TWh of energy 2022 out of which the agricultural sector used 6.09 TWh. The goal of the country is to become 50% more energy efficient by 2030 compared to 2005. Furthermore, Sweden's long-term target is to achieve net zero greenhouse gas emissions by 2045. From 2005-2022 the total energy use of the agricultural sector has been reduced by 16% but previous studies have shown that there is a great savings potential in the replacement of electric lighting or an increase in the utilization of daylight. A switch to newer electric lighting technology is imminent as on a European level the Ecodesign and the Restriction of Hazardous Substances (RoHS) directives have called for a phase out of T5, T8 and compact fluorescent light sources starting in 2023. These fluorescent light sources contain toxic mercury and are less energy efficient compared with LED. The replacement is calculated to save at least 42 TWh within the EU. As of 2023, the total Swedish bovine cattle population was approximately 1.5 million. These animals spend large parts of the year indoors; however, the buildings do not always provide optimal conditions in terms of daylighting and electric lighting. The reasons to consider a good lighting environment can be the cost of replacing old lighting fixtures, fire safety, the practicality of changing old non-LED light sources, energy use and cost as well as animal and worker welfare. The goal of this thesis is to suggest a good lighting environment for cows and human caretakers while achieving low energy use, which supports sustainability and low cost of food.

Switching from fluorescent to LED results in new lighting intensities and spectrums, impacting the circadian conditions indoors. Milk production rate is greatly impacted, with an average increase of 2.5 kg/cow per day by allowing responsive span of lighting availability in a day and the Swedish Board of Agriculture states that lighting and daylighting should support circadian and behavioural needs in cattle. This paper contains the results of simulations where more energy-efficient electric lighting was implemented while utilizing and improving daylighting potential in livestock buildings. The buildings studied were located at Rosdala Gård (55°34' N, 14°17 E), in the east of Skåne, Sweden. Three cattle buildings were studied; they are connected to a milking facility through a passageway. The newest, middle, and oldest buildings have areas of 3337 m², 2683 m², and 2037 m², respectively. Physical and photometric measurements were performed on site. Daylight and lighting measurements were conducted using a photometer and illuminance meter on an overcast day. The 3D modelling was performed using Rhinoceros according to site measurements. Climate Studio and ALFA from Solemma were used for daylighting, electric lighting, and circadian lighting simulations. Using measured material reflectance's as input for simulations, the resulting daylight factors are compared to those obtained through site measurements. Finally, improvements are suggested and implemented in the model and these simulation results are compared with the base case results.

In the study we show that both the replacement of fluorescent light sources with LED light sources and utilizing of daylight harvesting proved to have a high energy saving potential. The electric lighting improvements resulted in a reduction of 48 and 63% in the middle and old building respectively. The daylight harvesting potential and the circadian lighting conditions inside the old building could be greatly improved with the implementation of a skylight, increasing the daylight autonomy from 12 to 55%. Other measures, such as increasing the reflectance of interior surfaces, did not prove effective at increasing the daylighting potential. The daylighting savings potential observed on the buildings in this study were 50 to 60%. In the circadian studies it was found that the daylight provided vastly more illuminance compared with the electric lighting and the buildings with skylights showed a high melanopic illuminance during daytime.

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Abbreviation

ALAN	Artificial Lights at Night
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEC	Before Expected Calving
BST	Bovine Somatropin
CCT	Correlated Color Temperature
CRI	Color Rendering Index
DA	Daylight Autonomy
DF	Daylight Factor
DMI	Dry Matter Intake
EDI	Equivalent Daylight Illuminance
ELR	Efficacy of Luminous Radiation
EML	Equivalent Melanopic Lux
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells
LCS	Lighting Control System
LD	Lighting Dependency
LDPP	Long Day Photoperiod
MDA	Malondialdehyde
MEC	Mammary Epithelial Cells
MR	Melanopic Ratio
RoHs	Restriction of Hazardous Substances in Electrical and Electronic Equipment
PLR	Pupillary Light Reflex
RUGL	Relative Unified Glare Rating
SCC	Somatic Cell Count
SDPP	Short Day Photoperiod
SPD	Spectral Power Distribution
THI	Temperature Humidity Index
WWR	Window-to-Wall Ratio

Glossary

Cattle

"A collective term for animals held as property or reared to serve as food or for the sake of their milk, skin, wool, etc" (Oxford English Dictionary, OED, 2024).

Civil Twilight

"The period when the sun is between horizon and six degrees below the horizon." (National Weather Service).

Correlated Color Temperature (CCT)

"CCT is the temperature of a Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a modified 1976 UCS diagram." CCT is expressed in Kelvin (K) (CIE, 2024).

Cow

"The female of any bovine animal. Most applied to the female of the domestic species (Bos Taurus)" (OED, 2024).

Daylight Autonomy (DA)

DA is the percentage of occupied time over a year that a point reaches a target illuminance in a space reached by daylight. DA is expressed in %.

Daylight Factor (DF)

"DF is the quotient of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution and the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded." DF is expressed in % (CIE, 2024).

Dry cow

"A dry cow is in its dry period where it is no longer being milked until after it calves." The period is typically 45 to 60 days (Holstein Foundation, 2017).

Heifer

"A young cow, specifically one that is over one year of age but has not yet calved (or, in some areas, has not calved more than once)" (OED, 2024).

Illuminance (E_v)

"Illuminance is the density of incident luminous flux with respect to area at a point on a real or imaginary surface." Illuminance is expressed in lux (1 lux = 1 $lm \cdot m^{-2}$) (CIE,2024).

Luminance (L_v)

"Luminance is the density of luminous intensity with respect to projected area in a specified direction at a specified point on a real or imaginary surface." Luminance is expressed in candela per square meter ($cd \cdot m^{-2}$) (CIE, 2024).

Luminous efficacy (K)

"Luminous efficacy of a light source is the quotient of the emitted luminous flux of the light source and power consumed. For the luminous efficacy of daylight, it is the quotient of the emitted luminous flux and the radiant flux." It is expressed in lumens per watt ($lm \cdot W^{-1}$) (CIE, 2024).

Luminous flux (Φ_v)

"Luminous flux is the change of luminous energy with time. Luminous flux is a quantity derived from the radiant flux, Φ_e, by evaluating the radiation according to its action upon the CIE standard photometric observer." Luminous flux is expressed in lumen (lm) (CIE, 2024).

Multiparous

"A female mammal who have had two or more pregnancies" (OED, 2024).

Prolactin

"Hormone that stimulates milk production, which is released when the cow releases milk" (Holstein Foundation, 2017).

Recumbent

Lying down position.

Somatic Cell Count (SCC)

"SCC in milk is an indicator of milk quality. The most prevalent somatic cell in milk are white blood cells which usually become present in increasing number as an immune response to a mastitis-causing pathogen. A cow with a SCC of less than 100,000 is considered uninfected while a cow with more than 300,000 is considered infected with significant pathogens. SCC is quantified in number of cells per ml of milk" (Agriculture and Horticulture Development Board (ADHB), 2024).

Somatotropin

A somatotropin is a growth hormone.

Spectral Power Distribution (SPD)

SPD is a function of wavelength describing the amount of radiation across part of a spectrum. The SPD typically specifies the power emitted in the visible spectrum by a light source but can also describe reflected or transmitted radiation. The SPD is expressed in power per area per wavelength ($W \cdot m^{-2} \cdot nm$) (Chuang, 2015).

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1 Introduction

In 2022, there were 1.5 million cattle in Sweden, out of which approximately 300,000 were dairy cows. These cows produced around 2.76 million metric tons of milk (Jordbruksverket 2023). While Swedish cows spend time outdoors on pasture during the summer, they spend a significant amount of time indoors outside of the pasture season. During this time indoors, their need for adequate illumination must be accommodated to fulfill government requirements to ensure good animal welfare and maintain milk production. Adequate illumination is also necessary to fulfill the visual and biological needs of human caretakers who perform work inside the cattle buildings. Illumination can be provided using either electric lighting, or daylighting, or a combination of both.

The importance of daylight is reflected in its inclusion as a requirement in environmental certifications such as LEED and BREEAM. However, these certifications are primarily aimed at buildings housing humans. While the light requirements for cows are generally lower than those for office workers, studies have shown that increasing in photoperiod up to 16 hours per day can enhance milk production in cows (Nolan et al., 2024). To achieve this, the use of supplemental electric lightings is required for parts of the year in Sweden, where winter nights are long.

While an extended photoperiod increases milk production, it also increases the electricity consumption for electric lighting. More efficient light sources and utilizing daylight harvesting as a replacement for electric lights when daylight illuminance is sufficient are two key strategies to reduce energy use. Avoiding excessive electric lighting is another method, but it is important that the lighting fulfills the requirements and the needs of the building users. The primary purpose of electric lighting is to provide sufficient illumination for the users' needs, rather than solely aiming to minimize energy use.

The need for light is not only for visual orientation, as illumination also has non-visual, photobiological effects on animals. Disruption of the circadian rhythm in dairy cows has been shown to negatively affect the animals' milk production (McCabe et al., 2020), while providing 24-hour lighting does not contribute towards the milk yield (ASABE Standards, 2006). Due to differences in both photoreceptors and transmittance through eye lenses, both visual and non-visual sensitivity to different wavelengths of light differ between species (Lucas et al., 2024). Despite this, the requirements and recommendations in buildings whose main purpose is to house cows rely on metrics based on human perception. This study explores energy-saving potential as well as visual and circadian conditions inside cattle buildings. The main purpose of the study is to evaluate the potential for reductions in electric energy use through the use of daylight harvesting and efficient electric lighting. The secondary objective is to investigate the potential for circadian lighting in these buildings.

1.1 Research questions

This study delves into factors concerning lighting and energy use, with a specific focus on cow barns and their electric lighting systems. The research questions were carefully considered during the project's early stages to both study current conditions and explore potentials. This approach aims to identify opportunities for advancements in agricultural sectors related to both cows and farmers, emphasizing lighting energy and the exploration of circadian lighting. The research questions related to this matter are outlined below:

- Do the buildings studied fulfil the requirements set by standards and regulations with regards to electric lighting and daylighting?
- What is the effectiveness of different measures to improve electric lighting, daylighting and energy use for both animals and staff in the existing cattle buildings?
- What is the improvement potential for illumination and energy use?
- What are the existing circadian lighting conditions in the buildings?
- Does the intensity and period of light and darkness within the buildings favour the circadian rhythm in cows?

2 Literature review

2.1 Current regulations

A short summary of Swedish regulations regarding electric lighting, daylight access and outdoor access with regards to cattle is found below:

1. *Cattle shall have access to windows or other openings that provide daylight and electric light without causing discomfort to the animals. The daylight and electric lighting shall support the circadian rhythm and behavioural needs of the animals while enabling staff to easily monitor them day and night. Windows and lighting should be designed to prevent injury to the animals. If the cattle are milking cows, dimmed lighting shall be provided during the dark hours of the day.*
2. *The access to pasture in the summer is a requirement for keeping cattle in Sweden. Dairy cows must have at least six hours of continuous time on pasture each day. Cattle for meat production must have access to pasture or other outdoor areas continuously for at least 24 hours per day during the pasture season. The animals are required to be allowed on pasture for 60 days in northern Sweden, 90 days in central Sweden, and 120 days in southern Sweden. In southern Sweden, at least 60 days of pasture time must fall between May 1st and September 15th. Bulls are allowed to be kept completely indoors, and access to pasture is not required during the summer.*
3. *In newly constructed cattle buildings, there is a requirement for cattle to be kept loose indoors and not tied up during summer or winter. However, tying up cattle is still permitted in existing older buildings, and temporary tying up of cattle is allowed if necessary*. (Jordbruksverket, 2019).

2.1.1 Requirements and recommendations

General requirements for Swedish workplace environments can be found in AFS 2020:1. These requirements in AFS 2020:1 refer to the European Standard SS-EN 12464-1:2011. However, a newer standard from 2021 is available. The required light level for farm buildings relevant to this study is therefore found in Table 14 of SS-EN 12464-1:2021. The minima requirement for illuminance in animal pens is 50 lux while the adapted value is 75 lux. The adapted value is set for specific tasks that may require higher illuminance or to account for staff with impaired vision. The are also a requirement of a uniformity ratio of 0.4 and minimum CRI of 40. In areas for handling goods and equipment the illuminance requirements are 200 and 300 lux for minimum and adapted respectively. The uniformity requirement is 0.4 and the CRI requirement is 80. In this area there is a requirement for the Relative Unified Glare Rating (RUGL) of minimum 25. While the Swedish Board of Agriculture states that electric lights should not cause discomfort in the animals, there are no requirements in the standard for the RUGL in the animal pens.

An approximation for required illuminance is provided by the Agricultural Fire Protection Committee (Lantbrukets Brandskyddskommitté, (LBK). LBK is a non-profit association that develops common standards and regulations for various industries while supporting research and development in fire safety. LBK recommends 150 lux for orientation purposes in animal pens. Compared to SS-EN 12464-1:2021, the recommendation of 150 lx for animal pens from LBK is two to three times higher. The luminaires must provide protection from dust and water spray, as indicated by the IP-rating, while reducing the fire risk, given by the D-marking. The IP rating recommended in animal pens is IP54. A luminaire with a D-marking has a limitation in maximum surface temperature of 90°C under normal operating conditions (Brandskyddsföreningen, 2023).

The American Society of Agricultural and Biological Engineers (ASABE) states that to stimulate milk production, the lighting system must provide 150 lux of illumination for a continuous 16 to 18 hours. It does not recommend the use of 24-hour continuous light as this wastes energy and does not sustainably increase the milk yield. ASABE also notes that dry cows receiving 8 hours of light and 16 hours of darkness has experienced an increase in milk yield in the next lactation. Furthermore, the recommendations for illuminance in drive-through feed alleys are 200 lux (ASABE Standards, 2006).

Another common recommendation in cow pens is an illuminance of 15 to 20 foot-candles (FC) during daylight hours at a 3-foot plane, equivalent to 162 to 215 lux at a plane 91 cm above floor level, and 1 to 5 FC (11 to 54 lux), during the dark period (Harner and Zulovich, 2014; Niaurla, 2021).

2.1.2 WELL and circadian lighting design

Melanopic illuminance is a measure of the amount of light that affects the body's biological clock, primarily through the melanopsin photoreceptors in the eyes. The standard SS-EN 12464-1:2021 does not consider the non-visual (photobiological) effects of light in recommendations, but Appendix B.5 in the standard states that it is important to recognize the importance of the circadian rhythm. On the other hand, the WELL requirements for melanopic light intensity, measured in equivalent melanopic lux (EML), comprise four parts, covering different types of environments: work areas, living environments, break rooms, and learning areas, as seen in Table 1. The requirements are stated to comply with human environments, using human-based metrics. Note however that WELL is dedicated to humans and that there are no equivalent requirements for animals.

Table 1 - WELL requirements to support circadian health in humans (International WELL building institute, 2020)

Area	Scope	Illuminance (EML)	Hight (M)	Time	Type of Measurement
Work (a)	75% of workstation	200	1.2	9:00-13:00	Point towards Vertical plane
Work (b)	100% of workstations	150	1.2	On demand	Point towards Vertical plane
Living (a)	Point in center of room facing wall	200	1.2	Daytime	Point towards Vertical plane
Living (b)	Point in center of room facing wall	Less than 50	0.76	Nighttime	Point towards Vertical plane
Break room	Any point	250	1.2	On demand	Point towards Vertical plane
Learning	75% or more of desks	125	1.2	4 hours per day	Point towards Vertical plane

2.2 Visual functions in cows

Within lighting measuring technologies, one does not only measure wavelength and irradiance, as photometric devices also include a filter mimicking the different sensitivity of wavelength known as photopic luminous efficiency, V(λ) in humans. The resulting outputs are in luminous intensity (lumens), luminance (cd/m²), and illuminance (lm/m², lux) (Lucas et al., 2014).

Illuminance is commonly used as a proxy for assessing light quality, yet it is derived from human observation and lacks intentional weighting according to animal perception. Subjective measures conducted by humans involve assessing various hues and brightness levels of light to formulate the V(λ) function, using the minimum flicker method (Schubert, 2006). Despite being a human based metric, lux is commonly used when studying the effects of varying intensity and duration of illuminance on cows and other animals.

2.2.1 Photopic vision of cattle

Vertebrates possess one type of opsin genes belonging to rod photopigments and four types of opsin genes linked to cone photopigments. Each opsin gene has relative sensitivity ranges based on visible wavelength spectral distributions, namely ultraviolet (UV), short wavelength (S), middle wavelength (M), and long wavelength (L). Among the three mammalian categories, cattle belong to the Eutherians. Eutherian mammals' cone photopigments are derived only from two of genes families, SWS1 and LWS. For instance, within SWS1, which includes S and UV wavelengths, certain animals such as humans and cows can perceive only the S wavelengths. Within the Eutherians all non-primate mammals possess dichromatic colour vision, having only two types of cone pigments and are in possession of two gene families (SWS1 and LWS). LWS genes in cows enable the perception of only the L spectrum of the wavelength. Cows have peak sensitivities at 451 nm in S-cones and 555 nm in L-cones (Jacobs et al., 1998), while humans have peak spectral sensitivity for S, M, and L at 420, 535 and 565 nm, respectively, during photopic vision. (Jacobs, 2009). This difference in spectral sensitivities, illustrated in Figure 1, results in different visual perceptions.

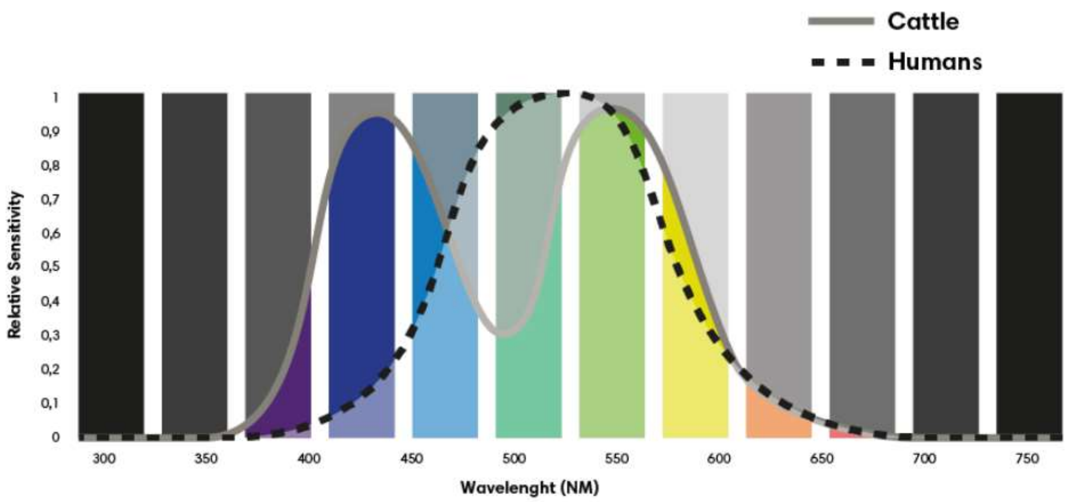


Figure 1 - Spectral sensitivity of dairy cows compared to humans, used with permission from HATO (HATO, 2023).

2.2.2 Extended photoperiods

Photoperiod designed for cows is the duration of light exposure within 24-hour period. Natural photoperiod is governed by the rising and setting of the sun which is influenced by the latitude. The photoperiod can be extended by electric lighting, especially common in the agricultural settings where extending the photoperiod have benefits, such as maintaining milk production in winter. The length of the day in Sweden vary significantly over the year as can be seen in Figure 2. The natural photoperiod in south Sweden varies between approximately 7 to 17 hours (Sveriges metrologiska och hydrologiska institute [SMHI], 2011).

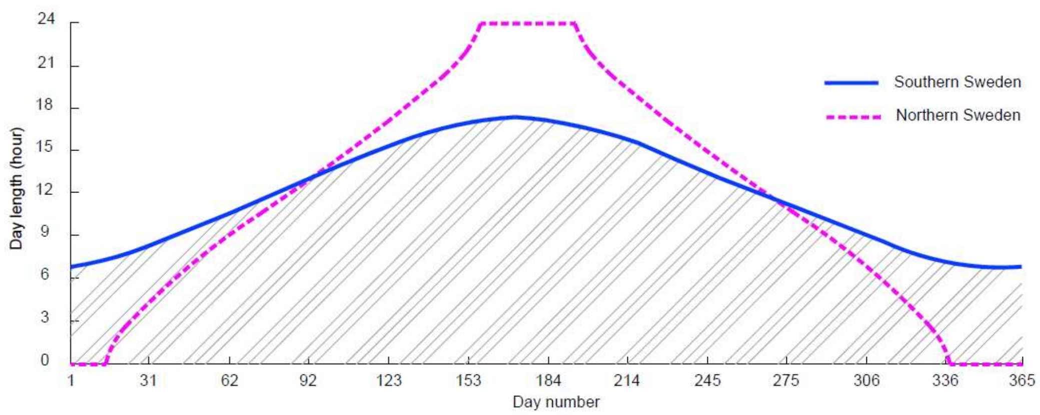


Figure 2 – Day length over the course of one year, adapted from (SMHI, 2011)

Dairy cows have shown an increased milk yield as a response to extended photoperiods. When increasing the light exposure from less than 12 hours to 16 to 18 hours, the production of milk could be increased by an average of 2.5 kg/cow, day. (Dahl et al., 2000). Tucker (1982) found an increase in production at 14 to 16 hours compared to below 12 hours of illumination. He also found a correlation between conception rates and daily light duration, where cows exposed to longer photoperiods had a higher conception rate, but the author noted that this could be due, in this specific study, to failure of the dairy men to inseminate the cows during winter. An extended photoperiod also increased the growth rate in heifers and hastened the onset of puberty.

While an extended photoperiod has been shown to increase the milk yield for lactating cows, dry cows do not appear to benefit from long-day photoperiods (LDPP). Instead, these respond to a short-day photoperiod (SDPP). Providing a SDPP of 8 hours followed by a dark period of 16 hours during a 60-day dry period have shown to increase the milk yield in the following lactation by 3.2 kg/cow, day compared with dry cows exposed to LDPP with 16-hour light, when both groups were returned to ambient light conditions postpartum. The treatment did not affect the calf development (Miller et al., 2000). In a later study Velasco et al., (2008) found an increase in milk production from dry cows under SDPP corresponding to an increase of 1.4 kg/cow, day, 40.4±1.1 kg/d compared to 36.8±1.1 kg/d. The SDPP cows also had a higher dry matter intake during the dry period. The dry period in the study was 42 days, while it is normally 60 days. The authors suggested that a shortened dry period could increase the overall milk yield, but they also stated that fewer than 30 days dry period could result in significantly lower milk yield.

An extended photoperiod has also been found to have an effect in other mammals. In milking goats, the production of milk was increased when the animals were exposed to longer days, but their ability for reproduction was reduced (Logan et al., 2020). Guilts that had their day extended to 14.5 and 16 hours of illumination from a 12-12-hour light-dark cycle had their ability to reach puberty inhibited compared to guilts that with a shortened day length (Paterson and Pearce, 1990).

2.2.3 Effect of lighting intensity on milk yield

Lim et al. (2021) conducted a study involving four different groups of cows. The control group was exposed to natural light, while the three other groups had their photoperiod extended to 16 hours using three different lighting intensities: 50, 100, and 200 lux at cow eye level. The results of the study showed that all three groups exposed to an extended photoperiod had increased milk yield compared to the control group, with the groups exposed to 50 and 100 lux experiencing the greatest increase. Additionally, the group exposed to 100 lux showed a higher milk fat concentration than the other groups. The group exposed to 200 lux had the highest average melatonin level, followed by the 100, 50, and control groups, respectively. Furthermore, all treatment groups had lower levels of cortisol.

Other studies have used greatly varying levels of illuminance from electric lighting when studying the effects of extended or altered photoperiods, see Table 2. In the studies where the illuminance has been under the authors control, excluding Reksen et al. (1999), the illuminance was between 107 and 350 lux with an average value of 237 lux. Most of the studies have opted for measuring the illuminance at cow eye level.

Table 2 - Adapted table showing results from previous studies with used photoperiod, illuminance, light source and resulting increase in milk yield from lactating cows using supplemental lighting (Dahl et. al, 2000).

Study	Photoperiod (h)	Illuminance	Light source	Milk yield increase (kg/cow, day)
Peters et al. (1978)	16	114 to 207 lux	Fluorescent	2
Miller et al. (1999)	18	350 lux at cow eye level	Metal halide	1.9
Reksen et al. (1999)	>12	Average of 36 lux at feed alley	Fluorescent	0.5
Evans and Hacker (1989)	8 (05.00-11.00 + 18.00-20.00)	200 lux at cow eye level, no natural light	Fluorescent	2.8
Dahl et al. (1997)	18	350 lux at cow eye level	Metal halide	2.2
Biladeau et al. (1989)	16	107 lux at cow eye level	Fluorescent	2

Looking at other mammals, Bano-Otalora et al. (2021) found that increased lighting intensity using 12-12-hour light-dark cycles affected the activity pattern in Rhabdomys pumilio, a diurnal rodent. Periods of sustained immobility were less fragmented and occurred less frequently during the day in rodents exposed to higher illuminance. Sustained immobility, the study's proxy for sleep, also occurred with higher rhythmicity in day-to-day measurements, and the circadian rhythm was better maintained when the rodents were placed in darkness after light entrainment. In other words, the animals sustained a more stable sleep-wake schedule between days after being exposed to higher illuminance; they also became less sensitive to circadian rhythm disruptions.

2.3 Circadian Studies

Melanopsin is the photopigment that is part of retinal ganglion cells. Unlike rods and cones, melanopsin's retinal illumination is non-image forming, which is why it is sometimes called 'non-visual'. Melanopsin has initially influences circadian rhythms, then leads to physiological, metabolic, and behavioural contributions. Since light also serves a neurophysiological stimulant, leading to pupil constriction, pineal activity, cortisol production, body temperature regulation, and heart rate modulation, it is widely utilized for therapeutic applications such as in jet lag, space flight, dementia, chemotherapy, cognitive and fatigue problems, etc. In comparison, melanopsin photon absorption is 1 million times lower than that of rod and cones, and there is a threshold when phototransduction (the process where photosensitive cells convert light into electrical impulses to the brain) in melanopsin starts to be activated. The peak spectral sensitivity for melanopsin phototransduction (λ_{max}) is approximately 480 nm (blue), and according to Lucas et al. (2014) this is similar between mammalian vertebrates. Low variation of peak melanopsin sensitivity was found by McDowell et al. (2023), where the value for cows was 484±1.1 nm and for humans 481±1.1 nm. While daylight encompasses all spectra, the sky, which dominates our visual field throughout much of the day, typically appears vibrant blue or cyan. This is due to the scattering of light at the blue end of the sunlight spectrum, around the 480nm peak of melanopsin phototransduction, a phenomenon known as Rayleigh scattering (Dubois et al., 2019).

The size of the pupil, influenced by the pupillary light reflex (PLR), depends on irradiance. The intensity of irradiance and the spectral contributions of the light source determine whether rods, cones, and melanopsin control the PLR alternately or jointly. When the threshold for melanopsin activation is not surpassed, the pupil constricts, primarily under the control of rods and cones within a specific range of spectral distribution and irradiance. As light levels fluctuate and exceed the threshold for melanopsin activation, the pupil dilates until it reaches a constant diameter. During this phase, melanopsin's release dominates the control of PLR (Lucas et al., 2013). PLR exists even in the absence of rods and cones; however, it exhibits different behaviour.

2.3.1 Metrics for measuring the non-visual effects of light

Equivalent melanopic lux (EML) (Lucas et al. ,2014) and melanopic equivalent daylight illuminance (m-EDI (D65)) are two metrics recognized by WELL and the International Commission on Illumination (CIE) for measuring the non-visual effects of light on humans (Huang et al. ,2023). According to CIE S 026/E: 2018 , a CIE publication, m-EDI was introduced along with other parameters and the CIE S 026 toolbox for calculating EML using different light sources (International Commission on Illumination [CIE] ,2019). EML and m-EDI metrics are interchangeable since they are based on individual photoreceptors, where the only difference is the absolute value. EML uses the equal energy illuminant, while m-EDI uses D65 photopic illuminance (Huang et al., 2023) for calculating the area under each photopic and melanopic spectral sensitivity curve, which is equivalent to 1 radiant watt, see Figure 3 (Miller & Irvin, 2019).

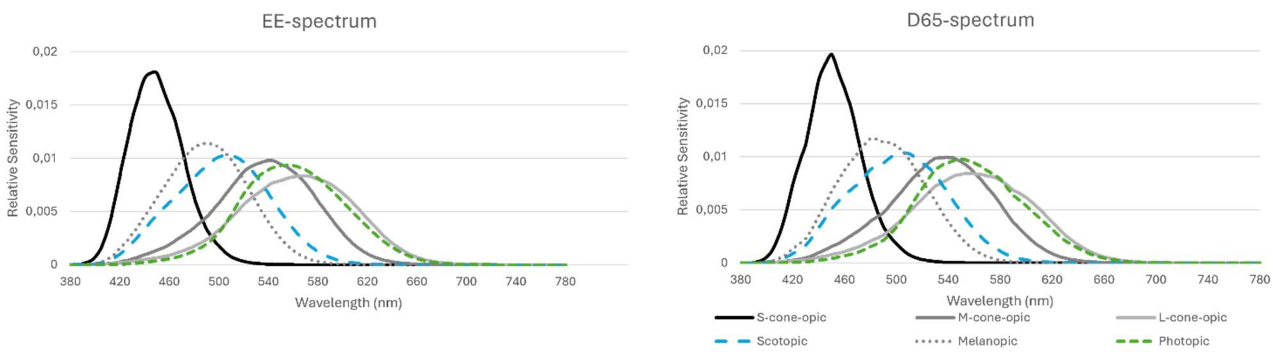


Figure 3 - Adapted figure showing the same 1 radiant watt results from (left) equal energy illuminant and (right) photopic illuminance D65 (Miller & Irvin, 2019).

2.3.2 Melanopic Ratio for equivalent melanopic lux

The WELL building standard has adopted EML, and calculations for EML are derived from the Melanopic Ratio (MR). WELL calculations utilize a spectral sensitivity curve normalized to have the same area under each curve using an equal energy illuminant for calculating the MR.

The process begins with obtaining the Spectral Power Distribution (SPD) of the light source for visible wavelengths, either from the lighting supplier or by measurements using a spectrometer. Then, the SPD is multiplied by the melanopic weighting function and photopic weighting functions, followed by summing all radiant power bands (W) separately for the photopic and melanopic content. Finally, dividing the melanopic radiant power by the photopic radiant power yields the MR (Miller & Irvin, 2019). EML is calculated by multiplying the acquired MR with the measured lux (L) (IWBI, 2020), see Equation 1.

$$EML = L\ x\ MR \quad \text{Equation 1}$$

Where:

EML	= Equivalent melanopic lux
L	= Photopic lux
MR	= Melanopic ratio

2.3.3 Melanopic Ratio for equivalent daylight illuminance

M-EDI for different photoreceptors can be calculated not only for humans but also for other mammals by utilizing spectral sensitivity functions specific to each species. MR for the m-EDI metric is processed similarly, using photopic and melanopic functions with the absolute value calculated based on the photopic illuminance D65 (Miller & Irvin, 2019). Another method involves calculating the Melanopic Daylight Efficacy Ratio (m-DER), as shown in Equation 6 (CIE, 2019) and then multiplying it by 1.103 (Esposito & Houser, 2022) to obtain the MR.

$$MR = 1.013\ x\ (m - DER) \quad \text{Equation 2}$$

Where:

MR = Melanopic ratio	[-]
m-DER = Melanopic D65 daylight efficacy ratio	[-]

2.3.4 Equivalent daylight illuminance and α-Optic irradiance

Although ambient light levels for animals are also defined in lux, which is a measurement of perceived sensitivity of photoreceptors specific to the human eye, it may not accurately represent the lighting environment for other species due to differences in perceived wavelengths and peak spectral sensitivities. The unit, weighted towards the human-perceived light spectrum, does not necessarily provide an equivalent description of the lighting environment as perceived by other species (Lucas et al., 2024). Hato agriculture lighting have invented a light measuring device called Hato One, able to derive the light level perceived by chickens in the unit called Gallilux, along with lux and foot candle.

A lack of sensitivity in M cones and differences in peak sensitivity in S and L cones imply that cows perceive brightness differently compared to humans. Instead of weighting the power across the spectrum against the wavelength sensitivity in humans, it should be weighed against the sensitivity of other animals or the separate sensitivity in melanopsin, rod opsin, SWS, and MWS cones. In their exploration of this topic, Lucas et al. (2024) suggested the use of α-Opic irradiance rather than species-specific lux. α-Opic irradiance is the effective irradiance of each individual opsin. Redeveloping the V(λ)-function for separate species would be possible, but it would only capture visual perception and not describe, for example, the circadian effect of illumination. As each photopigment absorbs light according to its own spectral sensitivity profile, the α-Opic irradiance can describe the irradiance experienced by the photoreceptor under a specific light spectrum and can be calculated using different photoreceptor sensitivity profiles to represent different species. Furthermore, the α-Opic irradiance can be expressed in equivalent daylight illuminance (EDI). The α-Opic EDI describes the amount of daylight in photopic lux required to achieve a specific α-Opic irradiance. α-opic quantities are defined in the international standard CIE S 026/E:2018, example of which are shown in Equation 3, Equation 4, Equation 5, and Equation 6 (CIE, 2019), displayed in Table 3.

Table 3 - α-opic quantities (CIE, 2019)

Description of quantity	Equation	Equation number
α-opic irradiance is a metric describing the effective irradiance of individual photoreceptors.	$E_\alpha = \int E_{e,\lambda}(\lambda) s_\alpha(\lambda) d\lambda$	*Equation 3*
α-opic ELR describes how effective a light source is at producing a specific α-opic irradiance compared with the lux produced.	$K_{\alpha,v} = E_\alpha / E_v$	*Equation 4*
α-opic EDI expresses how much daylight is needed to achieve a specific α-opic irradiance.	$E_{v,\alpha}^{D65} = E_\alpha / K_{\alpha,v}^{D65}$	*Equation 5*
α-opic DER describes how effective a light source is at producing a specific α-opic irradiance compared to daylight.	$\gamma_{\alpha,v}^{D65} = K_{\alpha,v} / K_{\alpha,v}^{D65}$	*Equation 6*
Metric		**Unit**
E_α = α-opic irradiance		[W·m^{-2}]
$E_{e,\lambda}(\lambda)$ = Weighted spectral irradiance		[W·m^{-2}]
$s_\alpha(\lambda)$ = α-opic action spectrum		[-]
$K_{\alpha,v}$ = α-opic ELR		[W·lm^{-1}]
E_v = Illuminance		[lx]
$E_{v,\alpha}^{D65}$ = α-opic EDI		[lx]
E_α = α-opic irradiance		[W·m^{-2}]
$K_{\alpha,v}^{D65}$ = α-opic ELR under D65		[W·lm^{-1}]
$\gamma_{\alpha,v}^{D65}$ = α-opic DER		[-]
$K_{\alpha,v}^{D65}$ = α-opic ELR under D65		[W·lm^{-1}]

Still under development, the authors suggest using human melanopic irradiance for general animal husbandry, noting a difference of 1 to 19% in melanopic irradiance when comparing humans and mice for broad-spectrum illuminants. This simplification would allow the use of light meters measuring human melanopic irradiance to follow guidelines in that unit (Lucas et al., 2024).

2.3.5 Circadian effects on cattle

Disruption to the circadian clock by altering the schedule of lighting can impact cattle's ability to produce milk. Studies indicate that a functioning circadian system is important for mammals' milking capacity, and thus, a disruption in this system can alter the length of gestation in pregnant animals. Cows exposed to chronic jet lag, where their day-night phase was shifted six hours every three days, had their gestation (the period between conception and giving birth) prolonged, while dairy cows in mid-lactation exposed to the same jet lag had their milk production reduced (Casey et al., 2021). Teng et al. (2021) found significant differences in the composition of milk from cows milked at night, such as reduced levels of MDA proinflammatory factors, as well as increased proportions of beneficial unsaturated fatty acids and melatonin. However, there were no differences in milk fat, protein, lactose, or total milk solids. The study also noted differences in milk composition if there were notable changes in the circadian rhythm.

A study conducted from February to June 2019 at Purdue University's ties tall barn examined the effects of disrupting circadian clocks on 16 multiparous (females that have already given birth to more than one calf) Holstein cows. The cows, in the 35-day period before expected calving (BEC) , were divided into two groups: a control (CON) light treatment group exposed to light from 05:00 to 21:00 hours, and a phase shift (PS) treatment group where the dark phase was shifted by six hours every three days, see Figure 4. Circadian rhythm was measured using internal temperature loggers, recording results every 30 minutes. Natural light in the barn where the PS experimental space for cows was located was controlled by covering windows and gaps at door openings. LED light sources, illuminated to meet 150 lux, were positioned at eye level for all cows. The application of Smart Electrician LED lights, scheduled with a timer to accommodate light-night shifts, was specified as 5000 lumens (McCabe et al., 2020).

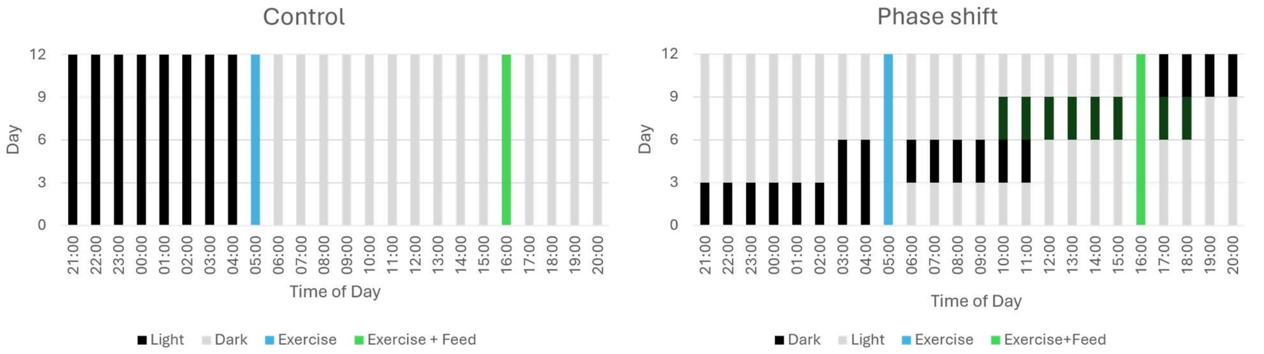


Figure 4 -Adapted figure showing lighting schedule for CON group and PS group where the PS had their timing shifted 6 hours forward every 3 days (McCabe et al., 2021)

Cows subjected to the PS treatment were less productive in some key respects when their circadian clock was disrupted. The CON group produced more milk than those in the PS group, but the amount of DMI was not influenced by the treatment during either the prepartum or postpartum period. Furthermore, the Mammary Epithelial Cells (MEC) index, responsible for lactation, was lower for PS cows. Additionally, insulin, a major contributing factor to building MEC, was compromised due to insulin resistance discovered in PS cows (McCabe et al., 2021).

2.3.6 Effects of night lighting on cattle

The current regulations, by the Swedish Board of Agriculture, stipulate that dim light should be provided for milking cattle during the dark hours of the day, but they do not specify any required illuminance. It is plausible that providing light during the night could affect the animals. Bal et al. (2011) found no increase in milk yield or any significant change in milk composition from dairy cows when they were exposed to night lights with an illuminance of 40 to 60 lux compared to a control group kept at 1 to 5 lux, with both groups following a 12-12-hour light-dark cycle. However, this study identified a tendency for night lighting to affect the diurnal rhythm of prolactin release.

In a more recent study, Asher et al. (2015) found no significant difference in milk composition, apart from somatic cell count (SCC), which was higher in the group exposed to night lights. Similarly to the previous study, there were no significant differences in milk yield. However, a significant difference was observed in the melatonin concentrations in the milk, with higher levels in the cows not exposed to electric lights at night (ALAN). The study advises against the use of ALAN due to the higher SCC and lower melatonin concentrations, which are associated with lower milk quality. The melatonin concentrations were found to be 30.70±1.79 and 17.81±0.33 pg/ml in night milk samples cows kept without ALAN compared to cows with ALAN respectively.

Lindkvist (2023) found that cows displayed no indicators of stress when navigating an obstacle course under varying dim light conditions, including the absence of light. There were also no significant differences in the time taken to navigate the course between light and dark conditions. However, under uneven lighting conditions using red lights, the cows took longer time to navigate the course, while an even distribution of red lights resulted in faster navigation. These findings further support the idea that ALAN is not needed for cows as they do not require it to navigate their surroundings, and the absence of ALAN does not induce stress in the animals. ALAN might, however, be needed for human caretakers tending to the animals after dark. Additionally, the study highlights the importance of light uniformity for cows. A lack of uniformity in lighting may lead to changes in behaviour which could cause problems. Cows could for example hesitate or stop on their way to the milking robot and potentially block the way for other cows behind them.

According to Hörndahl et al. (2013), a light level of 5 to 10 lux is recommended during the night, as this does not seem to affect the resting or sleep of the cattle. Another recommendation is to dim all existing lights to achieve an even light distribution, which will also reduce glare risks from individual lighting fixtures. Interestingly (Phillips et al., 2019) found 10 lux to be the illuminance required for sensitive humans to experience more than 50% of melatonin suppression. Their study outlined large differences between individuals (27 male and 29 female) regarding timing and light intensity in melatonin suppression, ranging from 10 to 400 lux. The group average for more than 50% melatonin suppression was 30 lux.

In a review article (Grubisic et al., 2019) compiled minimum melatonin suppression thresholds across vertebrates such as fish, birds, and different groups of mammals, revealing that cows begin to suppress melatonin at levels as low as 2.5 lux, which is just about the illuminance at the onset of civil twilight.

2.3.7 Cattle sleeping patterns

Early studies, primarily based on observations, failed to find conclusive evidence of cattle sleeping, as the observed animals only intermittently closed their eyes for short durations, often accompanied by signs of consciousness such as ear movement. Balch (1955) conducted investigations on cow respiration rates using a modified kymograph, which is a device that records variations in physiological processes over time. Periods of slow breathing, lasting from one to ten minutes with an average duration of five minutes, were identified in the recorded data, frequently ending abruptly. These slow, deep breathing patterns were observed exclusively when the animal was lying down and resting at night, never during rumination. Rumination is where plant matter fermented in a specialized stomach is regurgitated and chewed again. Although there were no observable signs of unconsciousness, the author speculated that since these periods represented maximal relaxation in cattle, they might occasionally close their eyes. It was concluded that if cattle do sleep, it likely involves polyphasic patterns and is characterized by very light sleep states.

In a subsequent study, Ruckebusch (1972) employed electroencephalograms (EEG) to identify two stages of electrocorticographic (ECoG) patterns: slow-wave sleep (SWS), characterized by high voltage, slow activity, and paradoxical sleep (PS), distinguished by low voltage, fast activity, and the absence of muscle tone. PS is the stage where dream episodes and rapid eye movement (REM) sleep occur.

Two stages of wakefulness were also defined: stable wakefulness or drowsiness (DR) and alert wakefulness (AW). During the transition from DR to SWS, distinct spindling (high-frequency transitions back and forth between stages) was observed before settling into one or the other. In farm animals, the PS stage duration was determined by the loss of postural tone, and it was associated with a reduction in gastric motility. Note that the study involved cows, as well as horses, sheep, and pigs, in ordinary barn stalls over the winter period from November to March.

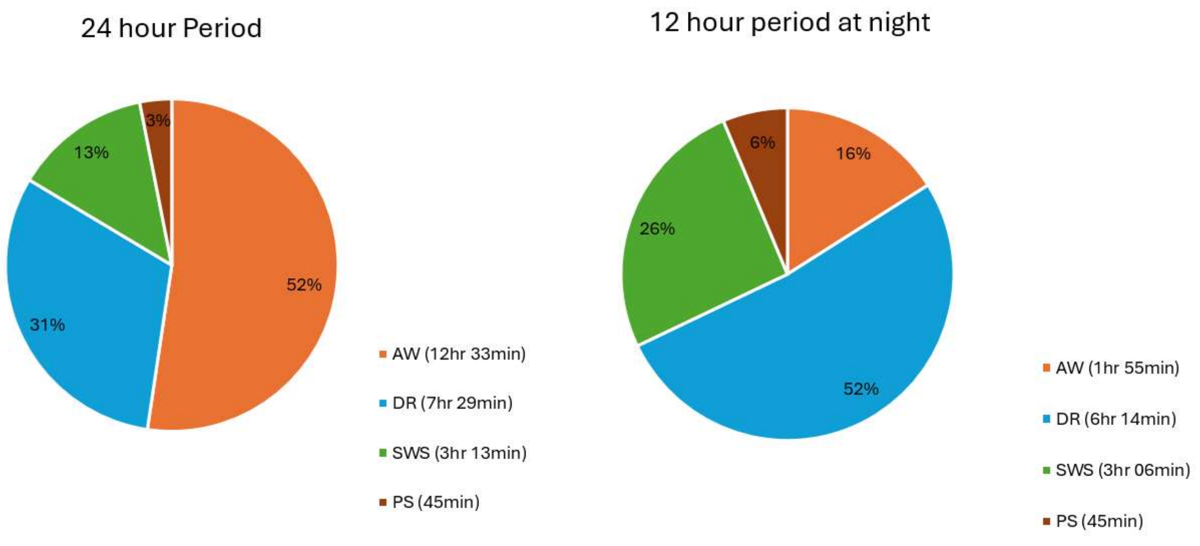


Figure 5 - Cows sleep, awake schedule, adapted from (Ruckebusch, 1972)

In the 12-hour nights, cows spent 51.9% of the time in a drowsy (DR) state, as shown in Figure 5. During both awake states, animals can ruminate. Rumination could also occur slowly and frequently during the SWS state, which accounted for 25.8% of the nighttime. When the cow enters the PS state, they stop rumination completely, and there is a sudden loss in body posture tone, occurring for 6.3% of the nighttime or 45 minutes. The rest of the night, 16%, is spent in the AW state of alert wakefulness (AW). Over a 24-hour period, cows spent approximately 20 hours in a state of wakefulness and 4 hours in a state of sleep. The mean duration of PS sleep periods was 4 minutes and 30 seconds and occurred only during the night. This value is close to the average length of slowed breathing observed by Balch (1955). The cows spent 87.5% of the night in a lying position. Each species of animal in the study had its own sleep and wake cycle. For cows 97% of sleeping time was recorded during nighttime when the light level is very low, or it is completely turned off..

2.4 Livestock buildings

2.4.1 Categories and public acceptance

Kühl et al. (2019) in their study on public acceptance of livestock buildings, categorized two types of buildings: Warm Loose Housing (WLH) and Cold Loose Housing (CLH). WLH is completely enclosed and mechanically ventilated, while CLH is ventilated by fresh air from open sides. Their findings revealed that public acceptance for WLH was low, at 4%, whereas it was slightly higher for CLH, at 17%. However, when CLH was paired with a paddock or pasture, public acceptance increased significantly to 55% and 96% for CLH with paddock and CLH with pasture, respectively. Access to paddock and pasture emerges as crucial features for enhancing public acceptance of livestock buildings. This aspect is vital for ensuring the social sustainability of the industry. Very low public acceptance could potentially lead to regulatory measures that ban unpopular practices or affect the public's willingness to purchase products from the industry.

The public perception of pasture as a preferred environment for cows aligns with the cows' own preferences. When given the choice between indoor and outdoor environments, cows prefer to spend most of their time outdoors during the summer (Shepley et al. 2017). Moreover, access to grazing correlates with a lower prevalence of lameness in animals; grazing animals are less affected, indicating a health benefit associated with access to pasture (Haskell et al., 2006). Another type of housing for cattle is the tie stall, where animals are tethered to their stall. Studies have demonstrated an increased injury rate, particularly hock lesions, in animals kept in tie stalls compared to those in free stalls or loose housing (Adams et al., 2017).

2.4.2 Energy use

Hörndahl and Neuman (2012) mapped the energy use of 16 farms from 2005 to 2006 and two additional farms from 2010 to 2012. Among these, four dairy farms had their energy use categorized, with feeding, milking, and electric lighting identified as the three primary sources of energy use. Electric lighting accounted for 12% to 25% of the total electricity use and 12% to 15% of the total energy use. In farms with mechanical ventilation, ventilation represented approximately 5% of the total energy use. The other sources of energy use were feeding (14 to 43%), milking (26 to 62%), fertilizers (1 to 3%), and Other (9 to 15%). In Other, various electrical equipment such as computers, brushes as well as heating for an office area were included.

The energy use for lighting per cow varied significantly, ranging from 57 to 231 kWh/cow, year. Installed power for lighting varied between 16 and 69 W/cow, while for ventilation, it ranged from 7 to 29 W/cow. However, there might be errors in the data provided, as one area would require 9,250 hours of lighting per year to match its stated energy use using the stated installed power, which exceeds the total hours in a year (8,760 hours). Removing this outlier, the calculated operating hours range from 1,700 to 6,800 hours, with an average of 3,800 hours. The average energy use was estimated at 125 kWh/cow, year, with an average power consumption of 36 W/cow.

It is worth noting that in 2012, LED light sources comprised only 1.8% of the global market (Thormundsson, 2023). Reksen, et al. (1999) found that the mean lighting intensity from farms using fluorescent lighting in Norway was 2.8 W/m², ranging from 0.4 to 9.9 W/m².

2.4.3 Energy saving potential

It is important to point out that the European Ecodesign and RoHs directives have started to phase out T5, T8, and compact fluorescent light sources, beginning from 2023. These sources contain mercury and have lower luminous efficacy than LEDs. The replacement of fluorescent light sources with LEDs is projected to save at least 42 TWh within the EU (Energimyndigheten, 2023a). By 2030, all light sources containing mercury will be completely phased out in the EU.

The energy use when using LEDs instead of fluorescent light sources is approximately 50%, and the total energy saving for Sweden is estimated to be 2.5 TWh (Energimyndigheten, 2023b). In cattle buildings, studies have shown that electric lighting often exceeds the recommended illuminance due to outdated practices where lighting was sized based on power intensities (W/m²). This has resulted in oversized lighting systems, with an average of 300 to 500 lux found in 13 out of 14 studied buildings. The largest energy-saving potential lies in utilizing daylight as a replacement for electric lighting, along with implementing lighting control systems and dimmable lights (Hörndahl et al., 2013).

In pig stables, Von Wachenfeldt et al. (2015) discovered that the mean daylight autonomy (DA) of 48% and 55% could be achieved by using two different light tube systems. The requirement was 40 lux at pig level between 08:00-16:00 hours. In their experiment, House 1 utilized flat collectors with bent pipes, while house 2 employed domed collectors with straight pipes. The system in house 2 demonstrated superior performance in terms of DA. Despite significant potential energy savings, the systems were not economically profitable due to the low cost of electricity at the time. Additionally, it is worth noting that the illuminance requirements of pigs (40 lux) are lower than the recommendations for dairy cows, which often have extended photoperiods exceeding 8 hours, as observed in the study. Therefore, the achieved DA is not directly applicable to cattle buildings.

In a case study on energy-saving potential in a small-scale dairy farm, Houston et al. (2014) investigated the energy use with an active milking herd of 95 cows on Prince Edward Island, Canada. The system boundary of the study encompassed direct energy input for milking, milk cooling and storage, cleaning and disinfection, livestock keeping, farmhouse operations, as well as waste management. The lighting, mainly consisting of incandescent light bulbs operating 16 hours per day, consumed 29% of the electricity within the system boundary. Refrigeration accounted for 28% of the energy use, while ventilation used 14% of the total energy use. Interestingly, no heating was required in the main facilities. The average daily electricity consumption decreased during the summer months. This reduction can be attributed to the cattle moving outdoors, thereby reducing the need for indoor lighting and equipment operation. Additionally, longer daylight hours in summer also contributed to decrease the reliance on electric lighting.

The study suggested that replacing incandescent lighting with T8 fluorescent lamps and extending the operating hours from 16 to 18 hours could increase milk production while reducing energy use for lighting, as well as potentially affecting ventilation needs due to reduced heating load. With the same operating hours, energy use for lighting is estimated to decrease by 68%. While T8 fluorescent lighting was recommended, the study also acknowledged the emergence of LED technology and its potential for further energy savings. Other suggestions included implementing a lighting control system and connecting the milk cooling system and sanitation washing system with a heat recovery unit. Recovered heat can then be utilized to reduce the cooling demand for milk and the heating demand for the sanitation system. Furthermore, heat recovery for the sanitation outlet water, which is heated to at least 82°C, was also recommended.

2.4.4 Heat stress in cows

Replacing electric lighting with daylighting can significantly reduce the internal heat loads in a building, due to the high luminous efficacy of daylight. Direct sunlight typically has a luminous efficacy ranging from 70 to 105 lumens per watt (lm/W), while diffuse light from a clear blue sky can reach around 130 lm/W, and from an overcast sky, it is approximately 110 lm/W. Under average conditions with a clear sky, the global efficacy is estimated to be around 105 lm/W (Littlefair, 1985). However, despite its effectiveness as a light source, excessive daylight can lead to building overheating due to the substantial amount of heat gained, particularly from direct sunlight. Excessive daylight can be avoided by proper sizing of windows or the use of shading devices.

While heat strain is internal and influenced by stress, heat stress is primarily affected by the external environmental conditions surrounding the resting body. Heat stress in cows becomes particularly challenging in regions closer to the equator. In hot climates, traditional cooling mechanisms such as radiation, conduction, and convection become less effective due to higher ambient temperatures, as well as factors like the temperature humidity index (THI) and rectal temperature. THI incorporates the effect of ambient temperature and relative humidity as a single value which is used to quantify the effect of heat stress in animals (Habeeb et al., 2018). To cope with heat stress, cows rely heavily on evaporative cooling, which involves processes like sweating and panting. However, in hot and humid regions, this natural cooling mechanism is compromised by the high relative humidity. Consequently, cows experience a decrease in dry matter intake (DMI) and milk yield, which ultimately leads to a deterioration in milk quality (West, 2003).

The ambient air temperature required to meet thermal comfort requirements for dairy cows typically ranges from -15°C to 25°C. However, relative humidity (RH) also plays a crucial role in milk production. Studies have shown that Holstein, Jersey, and Brown Swiss milk yields remain at around 97%, 93%, and 98% of normal levels, respectively, when RH is at 40% and the ambient air temperature is 29°C. However, when RH increases to 90%, the milk yield decreases significantly to 69%, 75%, and 83%, respectively, for these breeds. To assess the comfort level of cattle and estimate the impact of heat stress on their production, the THI is commonly used. Temperature above 77°F (25°C) indicate conditions where cattle may experience heat stress, leading to declines in DMI and milk yield. This decline is primarily due to climatic changes rather than changes in body temperature. (West, 2003).

In addition to environmental factors like temperature and humidity, milk yield is influenced by various internal factors such as metabolism, feed intake, and the digestive nature of cows. Metabolic heat production, which is correlated with physical movements, accounts for approximately 60% of the energy expenditure for a cow weighing 600 kg and producing 40 kg of milk with a 4% fat content. The use of bovine somatotropin (BST), an FDA-approved drug aimed at increasing milk production, is prevalent in some regions. However, BST promotes heat production in cows, regardless of whether they are in thermoneutral or hot conditions. Both lactating and non-lactating cows experience increased respiratory rates and body temperatures in hot and humid climates due to BST (West, 2003). The use of BST is banned in the EU since 2000 (EUR-Lex, 1999).

Heat stress significantly affects cows' physiology, leading to a range of responses including reduced feed intake, decreased activity, increased peripheral blood flow, sweating, elevated respiratory rate, and a preference for seeking wind and shade. Any of these factors can dictate the physiological status and production of cows. THI exceeding 70 can trigger hormonal changes and decrease milk somatotropin concentration. When cows experience heat stress, they pant and sweat as their primary mechanisms for cooling. This shift from relying on conduction, convection, and radiative cooling to evaporative cooling alters their blood acid-base chemistry and disrupts the critical balance of blood pH (West, 2003).

Modifying the environment can effectively mitigate the occurrence of heat stress in cows. Improvement can be achieved through a range of methods, including the installation of shading, ventilation systems, cooling systems (such as fans and sprinklers), genetic selection, and optimizing nutrition. Solar shading protects cows from direct and indirect solar radiation. Studies have shown that providing shading can improve milk yield by up to 10%, reduce respiratory rate, and lower rectal temperature. In humid climates, it is recommended to provide 4.2 to 5.6 square meters of shading per cow and allow north-south sunlight penetration to dry the ground, especially with earthen flooring. Trees can also be used positively as shading elements in the landscape particularly for low cow population densities. Reflective coatings applied to roofs can reduce indoor temperatures by 2-3°C in enclosed buildings lacking ventilation systems. Additionally, implementing open or capped ridge ventilation on high-pitched roofs can decrease infrared radiation and facilitate cross ventilation from eaves to ridge, further aiding in cooling cows (West, 2003).

3 Methodology

In this report ChatGPT was used as a proof-reading tool to correct grammar. The methodology contains four parts. The case study chapters describe the current conditions with building constructions, material properties and electric lighting types. The information in the case study was largely collected on site or are assumptions made based on on-site observations. The lighting simulations chapters describe the process of simulating the visual lighting conditions in the buildings. It contains information on software, which metrics are used and selection of luminaires for electric lighting simulations. The circadian lighting simulation chapters provide information on how the circadian lighting simulations were performed, software use and how the metrics for cows and humans differ. The energy use calculation chapter describes how the energy use for the electric lighting was calculated.

3.1 Case study

This thesis is based on a case study involving measurements in full-scale stables as well as light simulations. The case study comprises three cattle buildings situated on Rosdala Gård (55°34’ N, 14°17 E), northeast of Simrishamn, Sweden. These buildings were constructed in 1990, 2005, and 2014, respectively. The site sits at an elevation of 71 meters above sea level. Each building employs different fenestration systems for daylighting. A site visit was conducted on February 15, 2024, during near-perfect conditions for daylight factor measurements, characterized by an overcast sky with fog. The buildings are oriented in a north-south direction with an 8° rotation towards the east Figure 6.

The compound consists of buildings serving various functions, including three barn buildings and one milking building. These structures are interconnected by corridors that extend from the midpoint of each barn, positioned between the old and middle cow barns. Dry cows are housed in the northern section of the milking building.

During the visit, the ground was covered with damp grass, and the gravel circulation pathways and car parking lots within the compound were also dampened by rain and fog. All buildings feature overhangs protruding about 650 mm from their side elevations. The main doors of each barn building were fully opened to allow small vehicles and caretakers access to cows and fodder. Additionally, the floors in the barns are level with the external ground, facilitating easy vehicle access. Among the buildings, the newest one stands out as the largest in both area and height when compared to the middle and old buildings.

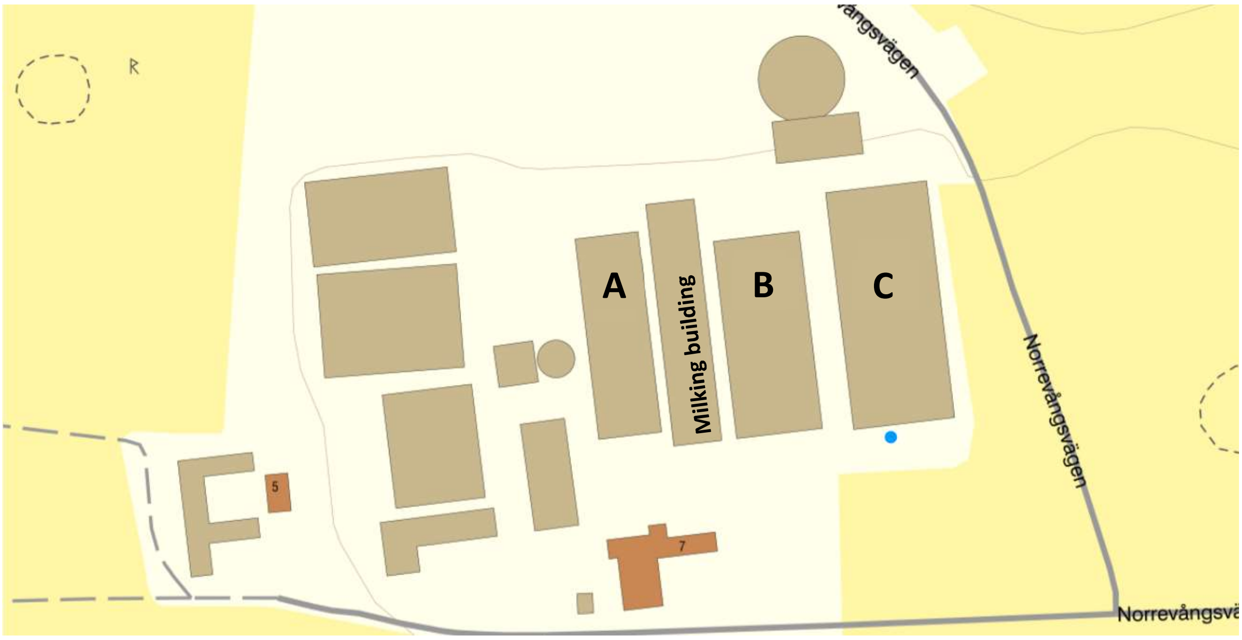


Figure 6 – Site with old building (A), middle building (B), new building (C), and surrounding buildings.

The new building, as depicted in Figure 7, covers an area of 3337 m^2 and stands out as the longest and widest among the barns. It was constructed with additional columns within the span to accommodate its width. The window-to-wall ratio (WWR) is 54%, and the skylight-to-floor ratio is 6%. This building is designed to house both dairy cows and cattle, with pens located alongside the corridor. It has a capacity to accommodate 370 cows.

The pen area features a raised middle rectangular platform for resting in a lying position. The pen and service corridor are separated by feed troughs and high rails, allowing cows easy access to feeding pods. The building is well-lit, with natural light provided by skylights and side lighting, supplemented by electric lighting. An overview of materials and colours are found in Table 4.

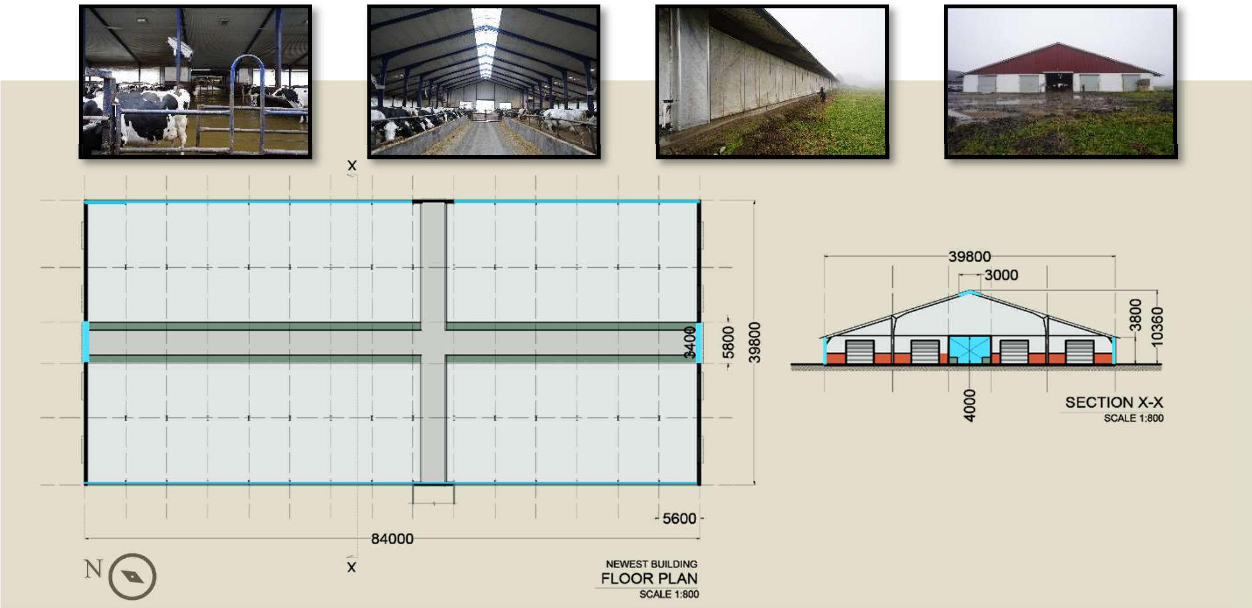


Figure 7 - Floor plan, section and pictures of new building.

The middle building, shown in Figure 8, has a floor area of approximately 2683 m². It features a window-to-wall ratio (WWR) of 21% and a skylight-to-floor ratio of 7%. Cattle are housed in pens situated on each side of a central corridor; the building has a capacity to house 250 cows and one bull. Clerestory windows run along the entire longitudinal elevation of the building, providing ample natural light. Additionally, there are a few fixed windows located at the gable, just above the main entrances. The building is brightly illuminated, both by natural and electric light. An overview of materials and colours are found in Table 4.

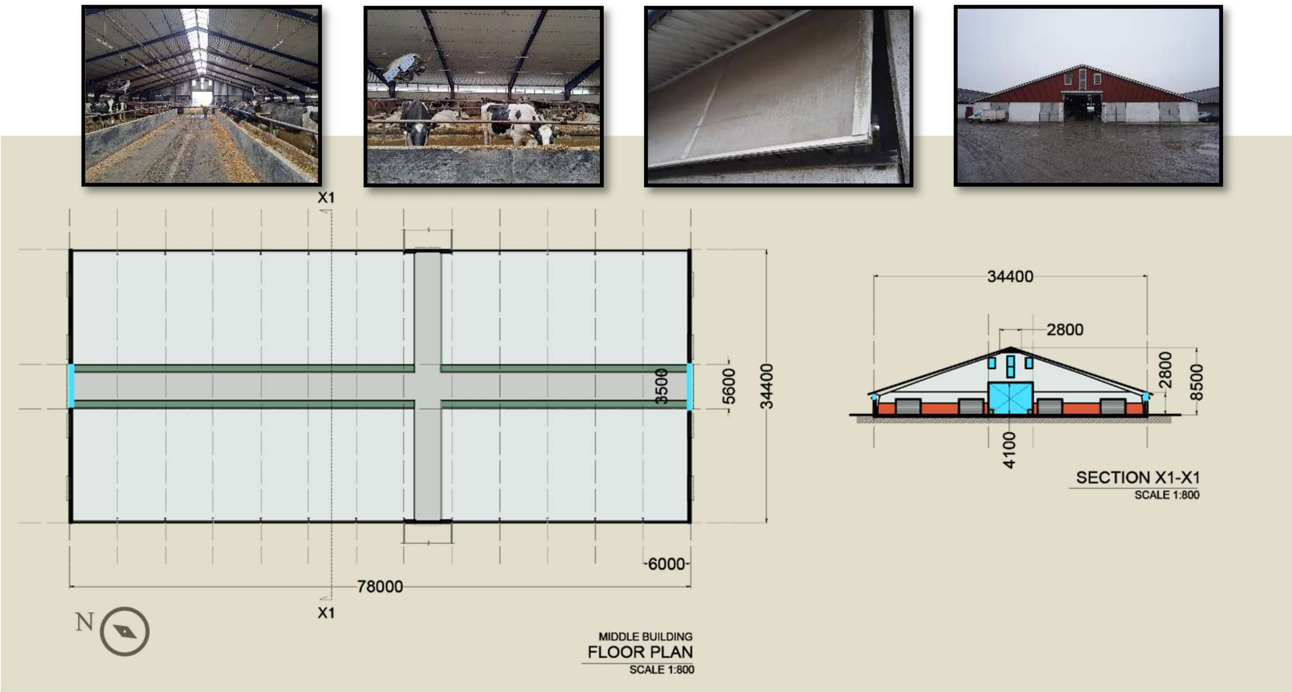


Figure 8 - Floor plan, section and pictures of middle building.

The old building, depicted in Figure 9, is the smallest and narrowest among all buildings. Its floor area is 2037 m^2, including a storage room occupying 232 m^2 of the gross floor area, which is not considered in the simulations. The accessible part of this area uses the same fluorescent luminaires as the rest of the building. Cattle are housed in pens located on each side of a central corridor, with the building accommodating 30 cows, 130 heifers, and 20 calves. With a resulting window-to-wall ratio (WWR) of 14%, the barn was constructed with the lowest daylight provision of the buildings. Side window openings are positioned centrally between the columns. Additionally, the feed trough in this building is levelled to the ground. An overview of materials and colours are found in Table 4.

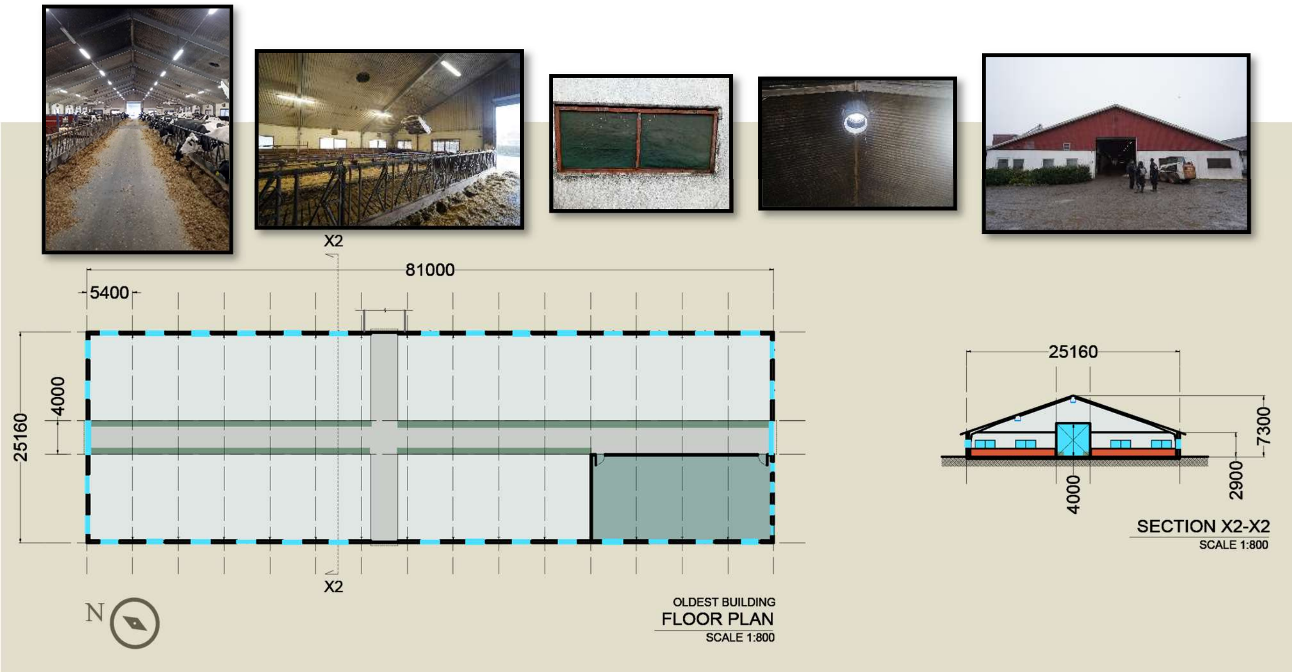


Figure 9 - Floor plan, section and pictures of old building.

3.1.1 Building construction

Details about the building construction were collected at the site and an overview of the materials and colours are shown in Table 4.

Table 4 - Overview of building material and colours.

Building	New	Middle	Old
Supporting structure	Steel frame, blue.	Steel frame, blue.	Steel frame, light grey.
Floor	Gravel feeding alley in middle. Concrete in cow walking area. Straw in cow resting area.	Gravel feeding alley in middle. Concrete in cow area. Straw in cow resting area.	Gravel feeding alley in middle. Concrete in cow area. Straw in cow resting area.
Wall	Concrete, red/brown and tan, gable end up to ceiling white metal.	Concrete red/brown and tan, gable end up to ceiling light grey metal, dirty.	Concrete, red/brown and white. Gable ends up to ceiling light grey metal, dirty.
Ceiling	White metal.	Light grey metal.	Light grey metal, very dirty.
Windows	Canvas, light tan. Small opening between canvas and eave.	Channel plastic along long side, very dirty. 3 windows over central gates, dirty.	Dark green fabric over window frame. Red frames.
Skylights	Along roof ridge, multi layered plastic.	Along roof ridge, multi layered plastic, dirty.	4 light wells along roof ridge, 2 light wells in northwest corner.
Doors and gates	Grey metal, lower part in cow area black rubber.	Grey metal.	Grey metal.

3.1.2 Surface reflectance

In situ measurements were conducted to determine diffusive surface reflectance of Lambertian surfaces using a Newly calibrated Hagner S5 spot luminance meter with resolution 0.01 cd/m2 and accuracy better than ±3%. Multiple sets of measurements were taken on each type of surface, and the average of these measurements was used to ensure higher accuracy. Measured values from a reflective reference plate, with a known reflectance of R_plate = 95.4%, were utilized along with measured illuminance values from non-specular surfaces to calculate the reflectance (R_surface) for Lambertian (diffuse) surfaces using Equation 7. In cases where surfaces were inaccessible for direct measurements, estimates were made based on the surface's colour and material properties (Spectral Material Database, 2021; Jakubiec, 2022).

$$R_{surface} = \frac{L_{surface} \cdot R_{plate}}{L_{plate}}$$ *Equation 7*

Where:

$R_{surface}$	= Reflectance of surface	[%]
R_{plate}	= Reflectance of plate	[%]
$L_{surface}$	= Luminance of surface	[cd/m²]
L_{plate}	= Luminance of plate	[cd/m²]

The reflectance for different surfaces later used for electric lighting, daylighting and circadian lighting simulations are summarized in Table 5, Table 6, and Table 7.

Table 5 - Reflectance values New Building

New Building	Color	$R_{Diffuse}$ %	$R_{Specular}$ %	R_{Total} %	$R_{Melanopic}$ %	M/P	Source
Wall up to 1.5M from floor		9.0	0.0	9.0	0.9	0.1	1
Wall from 1.5M to 3.8M		39.0	0.0	39.0	13.0	0.5	1
Feeding pot		27.0	0.0	28.9	12.0	0.4	1
Corridor		14.3	0.0	14.3	11.1	0.8	1
Floor (cows pen)		4.8	5.0	9.8	2.2	0.2	3
Metal Roof		44.5	7.7	52.2	50.1	1.0	4
Metal roller shutter doors		44.5	7.7	52.2	50.1	1.0	4
Metal columns		6.6	3.8	2.8	9.1	3.2	4
Ground		13.7	0.0	13.7	13.2	1.0	4
Context		64.1	0.0	64.1	63.2	1.0	4

Table 6 - Reflectance values Middle Building

Middle Building	Color	$R_{Diffuse}$ %	$R_{Specular}$ %	R_{Total} %	$R_{Melanopic}$ %	M/P	Source
Wall up to 1.5M from floor		23.0	0.0	23.0	1.4	0.1	1
Wall from 1.5M to 2.8M		63.0	0.0	63.0	10.8	0.2	1
Feeding pot		28.9	0.0	28.9	12.0	0.4	2
Corridor		14.3	0.0	14.3	11.0	0.8	2
Floor (cows pen)		4.8	5.0	9.8	2.0	0.2	3
Metal Roof		44.5	7.7	52.2	50.1	1.0	4
Metal roller shutter doors		44.5	7.7	52.2	50.1	1.0	4
Metal columns		6.6	3.8	2.8	9.1	3.2	4
Ground		13.7	0.0	13.7	13.2	1.0	4
Context		64.1	0.0	64.1	63.2	1.0	4

Table 7 - Reflectance values Old Building

Old Building	Colour	$R_{Diffuse}$ %	$R_{Specular}$ %	R_{Total} %	$R_{Melanopic}$ %	M/P	Source
Wall up to 1.0M from floor		16.6	0	16.6	1.7	0.1	1
Wall from 1.0M to 2.9M		68.4	0	68.4	46.2	0.98	1
Wall from 2.9M to ceiling		45.15	2.07	47.21	46.6	0.98	4
Window frames		14.08	0	14.08	2.8	0.14	4
Corridor		14	0	14	10.6	0.79	2
Floor (cows pen)		5	5	10	4.6	1.01	3
Metal Roof + Columns		34.71	2.45	37.17	35.3	0.95	4
Metal roller shutter doors		41.01	3.16	44.17	46.6	0.98	4

1 - Measurement in building
2 - Previous measurement in similar building
3 - Previous measurement and specular assumption
4 - Assumed CS default or Spectral DB material based on observation

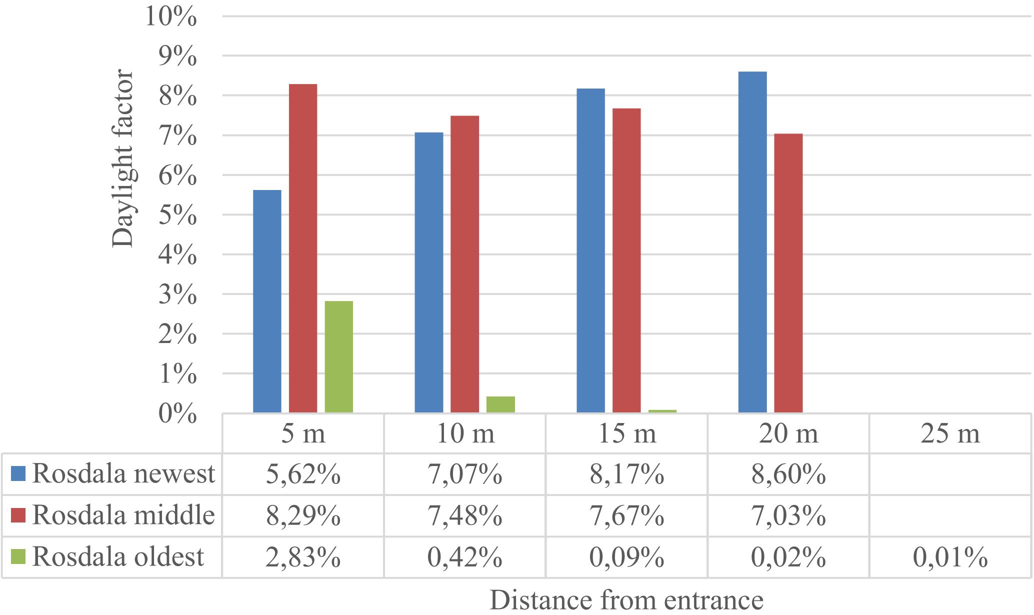
3.1.3 Measured Daylight Factor

The illuminance was measured using a newly calibrated Hagner EC1-X with resolution 0.1 lx and accuracy better than ±3% with a spectral correction i.e., V(λ) for humans. The measuring device was placed 762 mm above the floor surface, pointing towards the ceiling. The daylight factor (DF) was calculated by simultaneous measurements outside according to Equation 8. Due to the size of the buildings as well as the presence of animals in certain areas measurements were collected in a linear fashion from the southern main entrance with 5-meter intervals, up to 20 meters from the entrance, see Figure 11. While the buildings are longer than 20 meters the daylight contributions further than 20 meters from the 4 meter high open entrances would not be significant. Due to the symmetrical design of the buildings the DF would thus remain at a similar value until approaching the northern entrance where the DF would mirror the measured values from the south entrance. The calculated DF for the three buildings are shown in *Figure 10* where the diminishing daylight contribution from the entrance is clearly shown by the result for the old building.

$$DF = \frac{E_i}{E_o} \times 100\% \qquad \text{Equation 8}$$

Where:

DF = Daylight Factor [%]
E_i = Illuminance indoors [Lx]
E_o = Illuminance outdoors [Lx]



	5 m	10 m	15 m	20 m	25 m
Rosdala newest	5,62%	7,07%	8,17%	8,60%	
Rosdala middle	8,29%	7,48%	7,67%	7,03%	
Rosdala oldest	2,83%	0,42%	0,09%	0,02%	0,01%

Figure 10 - Measurement results for DF in 3 buildings measured from the open entrance

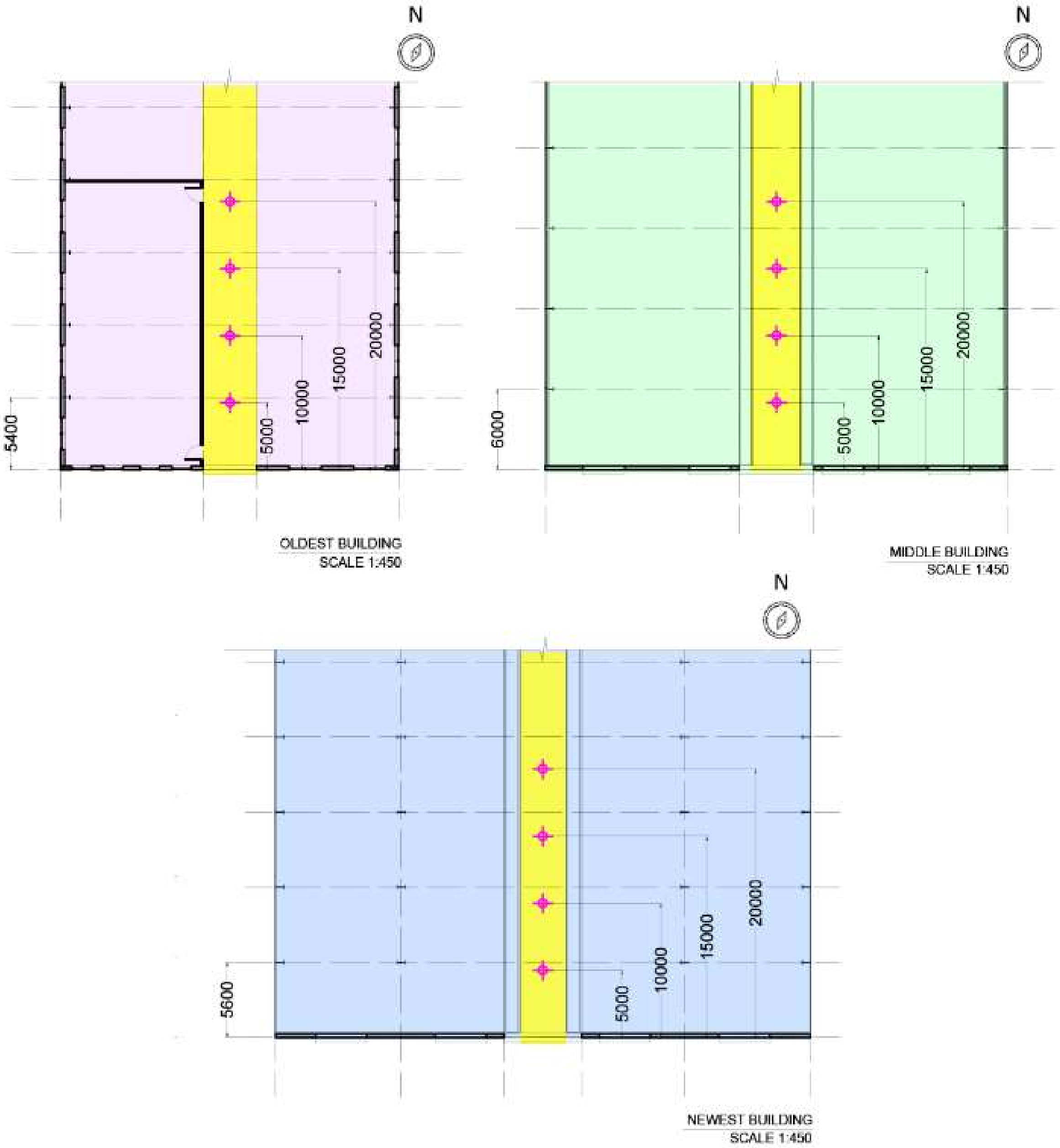


Figure 11 - Measurement points both on site and in simulation software.

One difference between the newest and middle buildings is the existence of windows above the gate and the proximity of the skylight to the gable wall. In the middle building, windows are situated above the gate, and the skylight extends closer to the gable wall. Specifically, the skylight in the middle building is approximately 3 meters from the entrance, whereas in the new building, it is around 5.6 meters from the entrance. As one moves away from the entrance, the importance of light from the entry and above-gate windows diminishes. Despite this difference, both the newest and middle buildings provide a bright environment at their centres, suggesting potential for daylight autonomy.

The lower illumination near the entrance of the oldest building can be attributed to several factors. Firstly, trees located south of the entrance and the absence of a skylight contribute to reduced light penetration. Additionally, the entrance of the oldest building is narrower compared to the other buildings, despite having the same height. This design feature limits the amount of natural light entering the building. Moreover, the oldest building features only a few relatively small circular skylights, Figure 9, in contrast to the other two buildings.

Furthermore, sidelight from one side near the south entrance is blocked by a storage room, further reducing natural illumination. The importance of the skylight becomes evident in later measurements further from the entrance, as the DF quickly diminishes in the oldest building. Despite being the narrowest, the windows in the oldest building do not appear to provide significant illumination in the canter compared to the newer buildings.

3.1.4 Window transmittance

The transmittance of windows and translucent surfaces was not directly measured on site, so their properties were estimated based on in situ observations of the type of material observed and their cleanliness. Manufacturer data for PVC-coated glass fibre screen fabric from Warema (2018) was used as a reference. The light transmittance for the screen fabrics ranged from 4% to 18%.

In the newest building, the closest estimate in terms of colour (no. 3534, white and linen) was used to represent the wall canvas material, with a light transmittance of 14% and reflectance of 61%. Conversely, a different type of dark green fabric was used to cover the windows in the oldest building. This material was thinner, allowing visibility of the interior from the exterior. While the visual transmittance value (Tvis) for this type of fabric could not be found, it was estimated based on privacy screen types, which typically block 80% to 95% of vision (Fencescreen, 2024). For shade cloth, a transmittance of 75% or higher is commonly used to protect animals from intense sun exposure (Farmplasticsupply, 2024). For simplicity, the same transmittance values for fabrics were used in both buildings. However, the reflectance value in the old building was set to 10%. In the simulations, custom descriptions through rad files were created based on these values.

Since the skylights were inaccessible for direct measurements, their material properties were estimated based on manufacturer information from the Technical Manual Exolon® Multi UV (Exolon, 2024) and previous measurements in similar buildings. Depending on the number of layers and colour of the multi-layered plastic used, the visual transmittance can vary from 46% to 82% for clear plastic and 32% to 80% for white plastic. However, due to overcast conditions on site, it was unclear whether clear or white plastic was used for the skylights.

It is unlikely that a plastic with very low transmittance was used, considering the higher cost of windows with more layers and the intended purpose of allowing daylight into the building. Therefore, a visual transmittance of 60% for clean windows was assumed. This value corresponds to a previously measured value (Ahmmad, 2023) ,where a clean surface had a transmittance of 59.7% and a dirty surface had 44.4%. For simulation purposes, a value of 44% was used in the base case, which is also applied to the windows in the middle building. In the oldest building's small circular skylights, with visual transmittance of 76.8% was used. A summary of the values used in the simulations is shown in Table 8.

Table 8 - Summary of window and fabric transmittance

Building	Location	Fabric/window	Transmission	Reflectance
New	Wall	Warema 3534	14.0%	61.0%
New	Roof	Multi-layered plastic	44.0%	-
Middle	Wall	Multi-layered plastic	44.0%	-
Middle	Roof	Multi-layered plastic	44.0%	-
Old	Wall	Privacy screen type	14.0%	10.0%
Old	Roof	Solexia	76.8%	-

3.1.5 Electric lighting

The electric lighting system is categorized by type, system power, number of luminaires, and lighting schedule. Lux meters were used to assess illuminance levels from electric lighting, with measurements taken at various distances from the luminaires. In the old and middle buildings, linear fluorescent light sources were used, and their properties were determined based on available replacement light sources. Specifically, the Philips MASTER TL-D Super 80 58W/840 1SL/25 was used as the light source, as depicted in Table 9 and Table 10. However, in the case of the new building, the properties of the luminaires could not be determined on site. Only the type and number of luminaires were noted, leading to an assumption for simulation purposes.

Table 9 - Light source properties for fluorescent light source used in middle and old building (Philips, 2024).

Product data, fluorescent light source			
Name	MASTER TL-D Super 80 58W/840 1SL/25	Colour code	840 (CCT of 4000 K)
Life to 50% failures	15000 hours	Luminous flux	5240 lm
Dimmable	Yes	Colour Designation	Cool White
Power consumption	58.5 W	CCT (Nom)	4000 K
Energy use	68 kWh/1000 hours	Luminous efficacy	90 lm/W
Bulb shape	T8	CRI	>80

Table 10 – Luminaire information from site visit and manufacturer information

Building	New		Middle	Old
Lighting technology	Linear fluorescent	LED	Linear fluorescent	Linear fluorescent
Light source name	MASTER TL-D Super 80 58W/840 1SL/25	-	MASTER TL-D Super 80 58W/840 1SL/25	MASTER TL-D Super 80 58W/840 1SL/25
Light source power /W	58.5	-	58.5	58.5
Light source per luminaire	2	1	2	2
Number of luminaires	3+3	15+13+15	13+12+12+13	10+14+14+15
Total power /W	702	-	5850	6201
Lifetime /h	15000	50000 (estimated)	15000	15000

Fluorescent lighting uses an additional driver or ballast to function. In linear fluorescent luminaires, these are often external components, while in compact fluorescent, the driver is integrated into the light source. These components increase the total power needed by the luminaire compared to the power draw of only the light sources. From the manufacturer information, Table 10, the energy use is rated as 68 kWh/1000 h whereas the power consumption for the light source is 58.5 W. Therefore, for energy calculations a value of 136 W per luminaire was used rather than 117 W corresponding to the power of the two lamps per luminaire.

3.2 Lighting simulations

3.2.1 Climate Studio

Climate Studio is a plug-in designed for Rhinoceros 3D, commonly referred to as Rhino. Rhino utilizes Non-Uniform Rational B-Splines (NURBS) modelling (Dassault Systems, 2024) to create 3D surfaces derived from complex mathematical formulas of geometries. In addition to Climate Studio, Rhino offers various features such as a connection to Grasshopper, rendering capabilities, and digital fabrication tools (Rhinoceros, 2024). Climate Studio's material library is constructed from validated resources, including glass properties from the International Glazing Database (IGDB), ASHRAE standards, and US Department of Energy (DOE) benchmarks. (Solemma, 2023)

Climate Studio utilizes Radiance, originally developed by Berkeley Lab (Ward & Georgy, 1994), to aid architects and engineers in visualizing light levels and analysing the effects of daylight in a space. The method involves tracing rays backward from measurement points located on defined surfaces toward the light emitters. Radiance calculates three sectors based on surface and directionality: the direct component, specular indirect component, and diffuse indirect component. Additionally, a subsidiary light source is incorporated for windows and skylights (Radsite, 2019). Shadow rays are cast beyond the plane to determine if the sensor point is illuminated by the light source through direct, diffuse (hemispherical sampling), or speculative methods (Mardaljevic, 2014).

Climate Studio's Radiance engine features a progressive path tracing setting, which continuously updates results as a few paths are completed during the simulation process. This results in faster simulations in Climate Studio compared to its predecessor DIVA for Rhino (Solemma, 2023) .

3.2.2 Climate file selection

A climate file, SWE_SN_Skillinge.026250_TMYx.2004-2018, from the nearby location of Skillinge (55°28' N, 14°16 E) was utilized for simulating daylighting. Skillinge is a small community of around 1000 residents, situated 13 km south of Rosdala Gård. The selection of this file is based on its proximity and minimal difference in longitude with the test site.

3.2.3 Daylighting simulations

Simulations were performed using Rhinoceros 3D with Climate Studio. The daylighting model contains measured geometric and reflectance values from site visit as well as surrounding context buildings and other features that could affect the daylight results. Context buildings were mainly painted white, and the ground consisted of dirt or gravel.

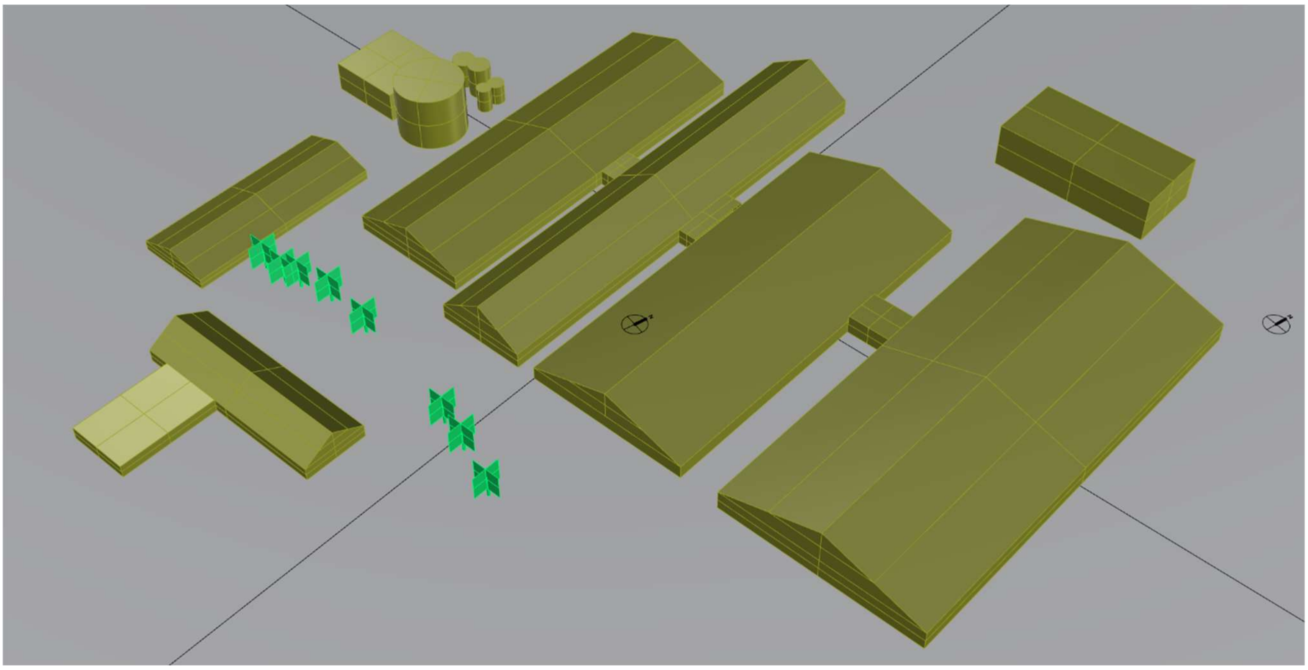


Figure 12 - Modelled context on site used in simulations.

Two metrics were used to assess the daylight conditions: the Daylight Factor (DF) and Daylight Autonomy (DA). The Daylight Factor was utilized to evaluate the general light level and validate the simulation model by comparing it with site measurements. Daylight Autonomy was employed to estimate the potential for replacing electric lighting with daylight.

Daylight Autonomy is the percentage of occupied hours during which the provision of daylight is sufficient to meet a predefined minimum illuminance target. Previous studies have used various requirements and recommendations, with illuminances ranging from 50 to 350 lux. In this study, a target illuminance of 150 lux, measured at a plane 0.76 meters from floor level, was selected. This illuminance value aligns with recommendations from ASABE and LBK to enhance milk production and ensure adequate illuminance for performing tasks in the area. Additionally, the level of the plane is based on human based illuminance measurement level according to LEED and Climate Studio. The simulation settings are shown in Table 11.

It was assumed that the cows require 16 hours of illumination each day, as this has been shown to increase milk production in lactating cows, as indicated by the literature review. In ClimateStudio, a schedule comprises 8760 values (hours), which can be absolute values of any size or fractional values between zero and one. To simulate the cows' time on pasture, a custom fractional light schedule was created. We assumed that the cows require the target illuminance between 05:00 and 21:00, excluding a period from the beginning of May until the end of August. During this time, a fraction of 0.625 is used in the schedule, resulting in 10 hours of electric lighting per day, assuming that the cows spend 6 hours outside. The fraction of 0.625 is applied to all hours during the pasture season, as the exact time the cows spend outside is unknown. If the exact time outside was known, a fraction of 0 would be used for outdoor hours and a fraction of 1 for hours spent indoors. The resulting schedule is illustrated in Figure 13. This schedule results in an operating time of 4922 hours per year.

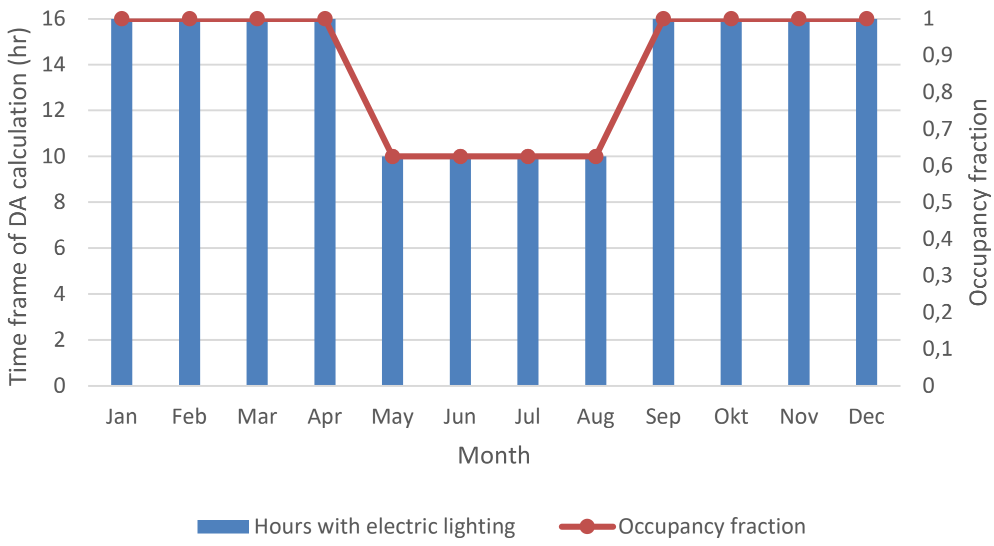


Figure 13 - Resulting hours requiring electric lighting over the year when using different occupancy fractions.

Table 11 - Simulation settings for DA, DF and point in time simulations.

Sensor spacing	500 mm
Sensor target inset	500 mm
Sensor minimum inset	200 mm
Workplane offset	762 mm
Target illuminance (DA only)	150 lux
Supplemental illuminance (DA only)	50 lux

To enhance the daylighting conditions in the buildings, various measures were implemented into the model and simulated, and the resulting impact on DA was analysed. The measures aimed at improving DA in the old building are summarized in Table 12.

Table 12 - Old building improvements

Improvement area	Code	Description
Window	W1	The dark fabric covering the windows is replaced by a light fabric with the same T_{vis} of 0.14 but an R_{vis} of 0.61 instead of 0.1.
	W2	The dark fabric covering the windows is replaced by a window with a T_{vis} of 0.44.
	W3	The dark fabric covering the windows is replaced by a window with a T_{vis} of 0.60.
Skylight	S1	A skylight measuring 1.2 x 70 meters is added along the ridge of the building with a T_{vis} of 0.44.
	S2	A skylight measuring 2.4 x 70 meters is added along the ridge of the building with a T_{vis} of 0.44.
Paint surfaces	F	Window frames are painted light grey with a R_{vis} of 0.72.
	C	Ceiling is painted white with R_{vis} of 0.70.
	Co	Columns are painted white with R_{vis} of 0.70.

Measures aimed at enhancing DA in the middle building are summarized in

Table 13. Due to this building's significantly higher initial DA compared to the old building, fewer measures are available for improvement.

Table 13 - Middle building improvements

Improvement area	Code	Description
Windows	W	The side windows are cleaned and receives a T_{vis} of 0.60 from 0.44.
Paint surfaces	P	The upper part of the wall is cleaned or painted, receiving a R_{vis} of 0.71 from 0.64.
	Co	Steel structure painted white or light grey with R_{vis} of 0.70.

3.2.4 Electric lighting simulations

The electric lights were added to the model in Rhinoceros 3D and incorporated into Climate Studio. Based on observations during the site visit and luminaire requirements, the 3F LINDA INOX 2X58 HF luminaire was selected to represent the fluorescent lighting in the middle and oldest building. The IES-file for this luminaire was obtained from the DIALux Finder (DIALux, 2024). As the illuminance under the light was measured on site as well as the luminaire height the luminous intensity of the luminaires in the new building could be estimated using the inverse square law, Equation 9. Although typically applicable only, the inverse square law can be adapted for practical applications if the light source has a uniform and isotropic luminance distribution and the largest dimension of the source of light is five times smaller than the distance to the illuminated surface. (Dubois et al., 2019).

$$E = \frac{I}{h^2}$$

Equation 9

Where:
E = Illuminance [Lx]
I = Luminous intensity [cd]
h = Distance to light source [m]

As the measured illuminance includes the contribution of daylight, a point-in-time simulation was conducted using an overcast sky at the same time and date as the measurements. The measurement plane was positioned at the site measurement location. The resulting illuminance from this simulation was then subtracted from the measured illuminance, and the luminous intensity of the light source was calculated using the inverse square law. The luminaire employed in the test simulation was the LED VALUE CANOPY MSF 90W 840 M, and the outcome of this approach is detailed in Table 14. A power multiplier was applied within Climate Studio to generate the correct luminous flux.

Table 14 - Estimation of LED-lighting in new building using inverse square law.

Measured illuminance at 0.8 m (lx)	Simulated daylight illuminance (lx)	Required illuminance from luminaire (lx)	Calculated luminous intensity (cd)	Simulated result (lx)	Illuminance provided by luminaire (lx)
225	51	174	5457	169	118

Since the resulting illuminance derived from the luminaire when estimated using the inverse square law only amounts to 67.8% of the required illuminance as per measurements, it is considered insufficiently accurate. Consequently, the luminous intensity of the luminaire was recalculated to be 8046 cd. Considering this, the LED VALUE CANOPY MSF 60W 840 M, which provides 8100 lumens, was selected to represent the LED lighting in the new building. Subsequently, simulations were conducted comparing both the fluorescent lighting and the LED lighting, incorporating all measured values.

For the middle and old building, when implementing the suggested improvement, the Pacific LED gen5 Value, WT475C 72S/840 PSD WB TW1 L1200, (Philips, 2024) from Philips was chosen as a replacement for the existing fluorescent lighting. An overview of the luminaires used and their comparison with requirements and site observations can be found in Table 15. We assumed that all lights were fully on.

Table 15 - Properties of selected luminaire for simulations compared to requirements and site observations.

	Requirements	Site visit		Simulation base case		Improved Cases
Type	-	Fluorescent	LED	Fluorescent	LED	LED
Power per light source /W	-	58	-	58	60	55
Luminous flux per light source /lm	-	5240	-	5200	8100	7200
Light sources per luminaire	-	2	-	2	-	-
Luminous flux per luminaire /lm	-	-	-	7290	8100	7200
Color temperature	-	4000 K	-	4000 K	4000 K	4000 K
Casing protection	IP54	Enclosed	-	IP66	IP66	IP66
CRI	40 to 80	>80	-	80	80	>80
UGR	None or 25	-	-	<22	-	22
Light distribution	-	Direct	Direct	Direct	Direct	Direct

3.2.5 Assessing uniformity ratio

Studies have shown that cows take longer to navigate obstacles and reach the other side when the light levels are unevenly distributed Lindkvist (2023). Moreover, according to SS-EN 12464-1:2021, a minimum uniformity ratio (UR) of 0.4 is recommended for caretakers who require access to pens.

The uniformity ratios are calculated as the ratio of minimum to average illuminance (Dubois et al., 2019). In this study, the DIALux evo application was used to assess the entire cow shed area when determining the uniformity ratio. Calculation focuses separately on cows' pens area and the entire floor area. This is important because cows move around the pen and have visibility through the corridor, while caretakers access the pens through the corridor as well.

3.3 Circadian lighting simulations

It is suggested to adopt human melanopic irradiance for broad spectrum lighting (Lucas et al., 2024). Based on WELL guidelines, simulation results are analysed to determine if the lowest melanopic illuminance benchmarks targeted for humans are achieved (Internal Well Building Institute, 2020). These benchmarks are measured in equivalent melanopic lux (EML). In this study a benchmark value was set at 125 EML according to the lowest requirement for humans in WELL standard that is dedicated for learning environment. The lowest benchmark value was targeted as the illuminance requirements for animal pens in general are lower than that of those in workspaces. The target of 125 EML, however, was not selected to symbolize the optimal circadian conditions for cows as these conditions has not yet been researched. For simulating circadian lighting conditions ALFA from Solemma was used. For estimating the difference between cows and humans with regards to melanopic irradiance from electric lights the species-specific toolbox was used.

3.3.1 Calculating species specific EML

Targeting circadian lighting tailored specifically for cows is indeed feasible. However, Equivalent Melanopic Lux (EML) results from ALFA are based on the spectral sensitivity of photoreceptors in the human eye. To customize lighting to the visual needs of specific animals, including cows, α-opic irradiance (W/m^2) must be derived. The photopic sensitivity function $V(\lambda)$, which is based on perceived brightness, varies among different animal species and is not sufficient for expressing circadian, behavioural, and physiological conditions accurately.

For this reason, the spectral sensitivity of photoreceptors in cows, which include two cones, one rod, and ipRGCs (Intrinsically Photosensitive Retinal Ganglion Cells), along with measured spectral power distribution obtained through on-site spectrometer measurements, is necessary. An additional step involves incorporating the α-opic efficacy of luminous radiation to derive α-opic Equivalent Daylight Illuminance (α-opic EDI) lux for each photoreceptor (Lucas et al., 2024). The toolbox provided in (Lucas et al., 2024) accounts for species-specific calculations while considering spectral lens transmission in various species.

During the site visits, we did not have access to a spectrometer to obtain SPD at cow's eye level. However, ALFA simulations can provide insights to a certain extent, given the current adoption of human spectral irradiance in this area. The difference in melanopic irradiance between mice and human has been found to be 1 to 19% and using melanopic irradiance for humans would therefore be acceptable given the small difference (Lucas et al., 2024). For cows, the difference can be similarly estimated. By utilizing the toolbox with SPDs for CIE standard LED and fluorescent illuminants, or manufacturer specific SPDs for selected luminaires, a comparison between the irradiances of the melanopsin of humans and cattle can offer an estimate of the error stemming from using EML based on human opsin.

The error in EML from electric lighting due to the difference in human and cow opsin is estimated using the species specific light exposure calculator. This toolbox, as detailed in (bioRxiv, 2023), incorporates the SPD of the CIE standard illuminants that closely resemble the selected luminaires' SPD. The SPDs of the CIE illuminants, which in the toolbox both provides an illuminance of 200 lux, are shown in Figure 14. The metric used to estimate the difference is α-opic irradiance, as this is proportional to EML.

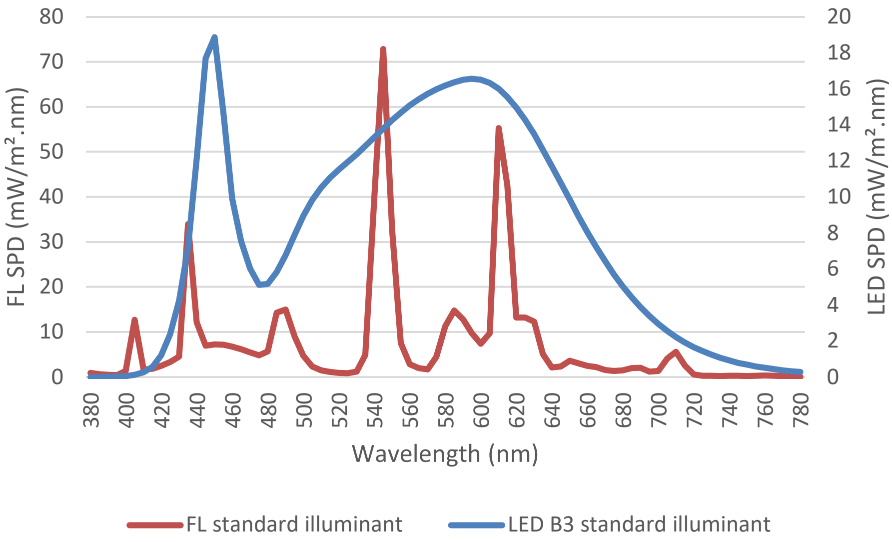


Figure 14 - SPD of CIE standard fluorescent and LED illuminants (CIE, 2018)

3.3.2 ALFA

ALFA (Adaptive Lighting for Alertness) is a commercially available plug-in for Rhinoceros 3D that simulates the non-visual effects of daylight and electric lighting on human circadian response. The simulation results provided by ALFA are presented in EML, where standard parameters are adapted to aim for human health and well-being according to the WELL circadian lighting design standard. WELL standard primarily targets work areas, learning environments, and break rooms (IWBI, 2020). The ALFA results are presented in EML represent the final targeted value, which is acquired from the melanopic ratio (M/P). Figure 15 illustrate how EML and Lux are calculated under the same light source.

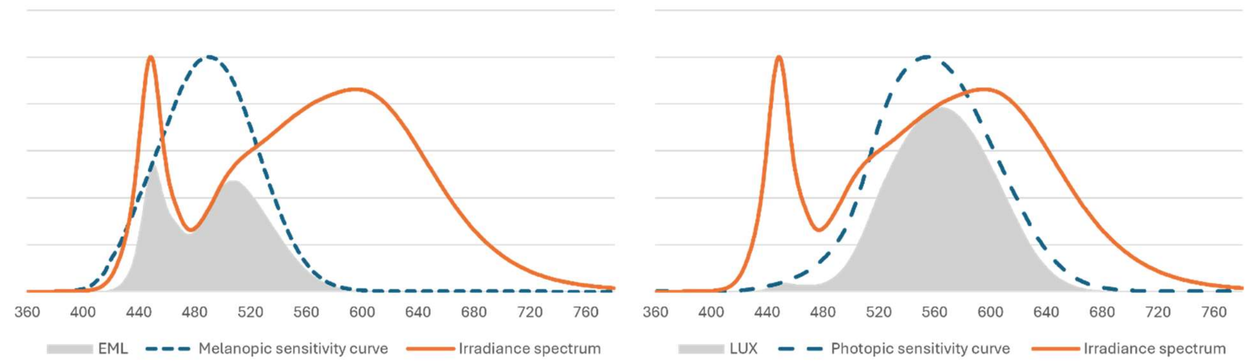


Figure 15 – Melanopic (left) and photopic (right) sensitivity curves with resulting EML and Lux under the irradiance of a CIE standard LED illuminant.

Traditional rendering using red, green, blue (RGB) followed by tristimulus X, Y, Z values are sufficient to represent the perception of the human eye, which saves computational time compared to calculating over all wavelengths (ECLAT Digital, 2023). Metamerism in colour theory describes how one tristimulus colour can correspond to many different spectra (Otsu et al., 2018). For achieving physically accurate values, circadian lighting simulations in ALFA utilize 81 colour spectra integrated within the Radiance lighting engine (Solemma, 2023).

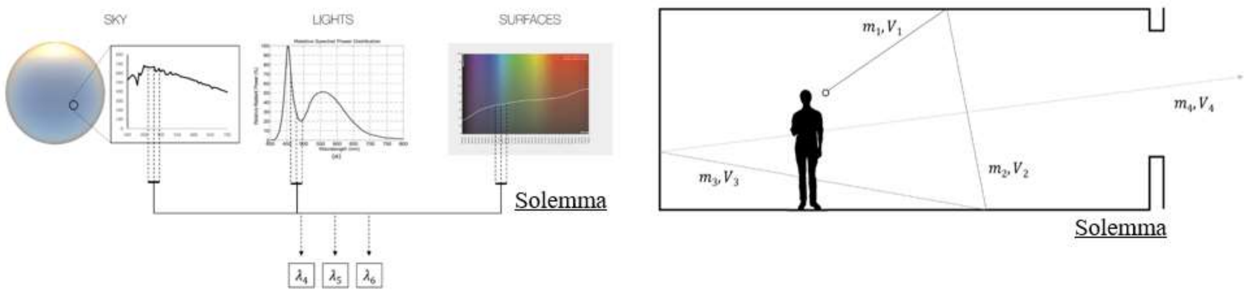


Figure 16 - ALFA color spectra sources, with permission from Solemma. (Solemma, 2023).

Standard sky models are mathematically formulated to generate luminance values based on factors such as altitude, cloud appearance, atmospheric turbidity, and sky brightness. These models are commonly utilized within simulation programs (Dubois et al., 2019). The CIE and PEREZ standard sky models are colourless and coupled with a constant spectral distribution RGB (1,1,1), while adjustments are made to the sky and sun's correlated colour temperature (CCT), typically set at 5455 K (Inanici et al., 2022).

ALFA utilizes the LibRadtran software package, which originated from the uvspec radiative transfer model. This software conducts pre-calculated radiative transfer calculations, considering various atmospheric conditions (Inanici et al., 2022), to create a spectral representation of the sun and sky (Balakrishnan & Jakubiec, 2019).

LibRadtran spectral irradiance calculations encompass the ultraviolet, visible spectrum, and infrared spectrum, covering a range from 120 to 10000 nm, based on interactions with different atmospheric conditions (Brelsford, 2016). ALFA provides users with the flexibility to select sky conditions ranging from overcast, hazy, and heavy rain clouds, as well as various ground conditions.

ALFA integrates a light source library along with IES luminaire files, comprising various spectral power distributions corresponding to specific light sources. The material library in ALFA is constructed from materials measured by spectrometers, boasting over 500 different materials in its catalogue (Solemma, 2023). Measurements of opaque surface reflectance were obtained using spectrometers, covering wavelengths between

360 and 740 nm. Utilizing the standard observer's colour matching functions, CIE tristimulus reflectance, RGB radiance colour space, as well as melanopic and photopic reflectances, were calculated. (Jakubiec, 2022).

3.3.3 ALFA settings

The same luminaire derived from supplier's website in terms of IES file was inserted in ALFA as a first step, then SPD profile that matched the source of luminaire was chosen in ALFA based on lighting source specifications from the supplier. The same SPD profile for the LED lighting was used in the new building's base case and the improved old and middle buildings as the selected luminaires share the same colour temperature and CRI. The M/P ratio of each luminaire obtained through our calculations are presented can be observed in Table 16. Likewise, the number and detail information of luminaires can be seen in Table 10 and Table 15.

Table 16 - M/P ratio of luminaire in ALFA

	Type	Applied Building	Lumens (melanopic)	Lumens (photopic)	M/P
Base Case	LED	New, Middle	7047	8100	0.87
	Fluorescent	Old, Middle	5613	7290	0.77
Improved	LED	Old, Middle	6253	7200	0.87

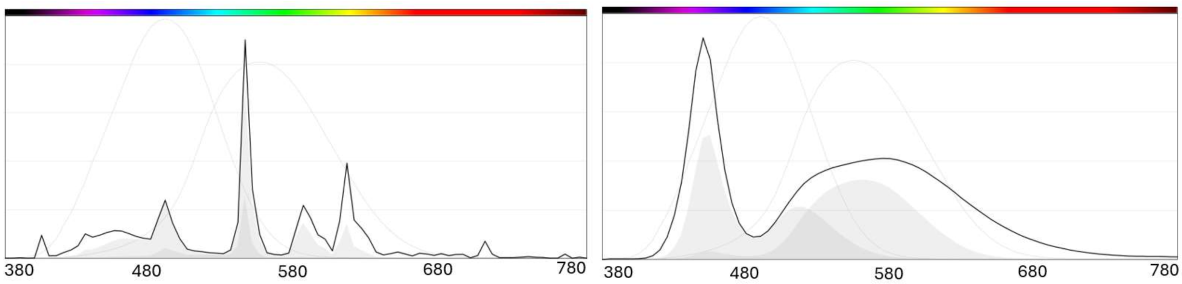


Figure 17 - Spectral power distribution of fluorescent (left) and LED (right) light source chosen in ALFA.

The grid plane was determined in relation to the general size of a Holstein cow (Dimensions, 2024). Sensors for measuring melanopic lux were uniformly distributed in place at points where the cows are present, stretching towards the end of the feeding area. The sensor spacing was 2.5m in the X and Y directions, as illustrated in Figure 19, resulting in 347 sensor points in new building. The cows have monocular vision on the sides and binocular vision towards the front, with a range of 25° to 50° where depth perception is possible, while also having a blind spot directly at the back of their heads see Figure 18. Their visual field encompasses approximately 330° for both eyes (Phillips, 2015). Each sensor points in the simulation measured melanopic lux incident on a vertical plane at eye level for each eye, considering a total of 360° since cows' exhibit behaviour that is not stationary. There are two view projections per sensor, each split into 180° for each eye Figure 19.

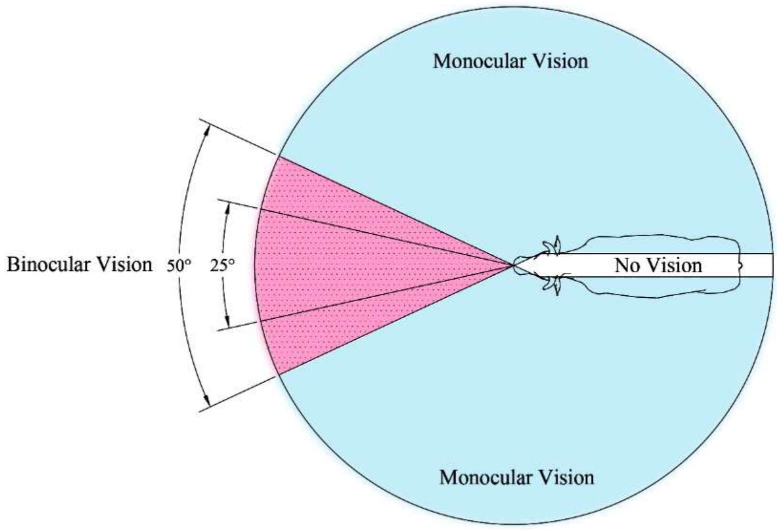


Figure 18 – Binocular and monocular vision in Cows

The view plane was located at 1.5 m above ground level to resemble the position of cow's eyes in corresponding to eye level for a standing cow. Since cows spend about 10 hours/day standing and 14 hours/day lying (Ruckebusch, 1972), the simulation was considered according to the eye level only at standing posture that happens 10 hours/day. Every attribute of materials in ALFA is characterized by both melanopic reflectance and photopic reflectance. ALFA provides outcomes for point-in-time radiance simulation, expressed in EML, photopic lux, and the M/P ratio.

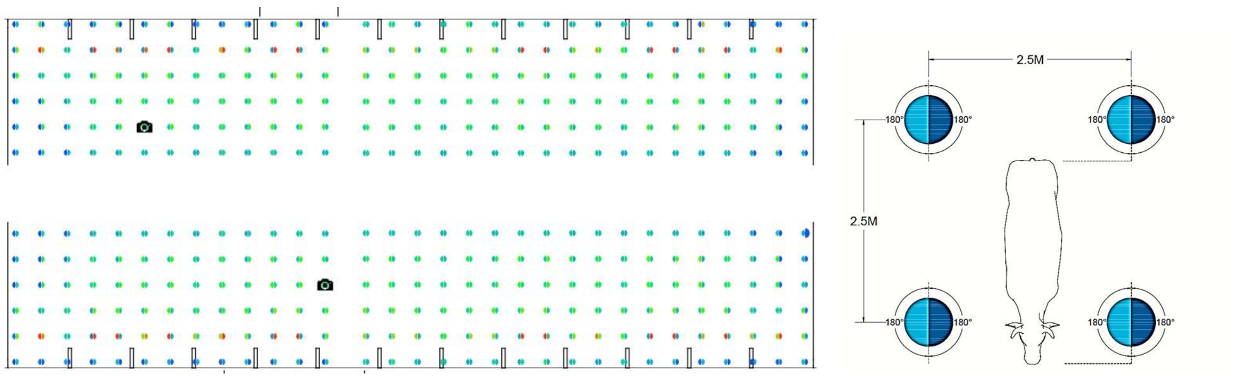


Figure 19 – (Left) Sensor distribution, (Right) Sensor spacing and view angle

Many studies reported that a certain photoperiod for lactating cows with a given illuminance level promote milk yield Table 2. Circadian lighting simulation was conducted on an hourly basis, following the schedule for electric lighting and daylight autonomy simulations Figure 13. Point-in-time simulations were performed for a total duration of 16 hours duration i.e., from 05:00 to 21:00 hour at the spring equinox and winter solstice when the cows are indoors. To be able to access hourly changes in melanopic lux, the lights were turned on for the whole simulation period since sunset and sunrise hours are different from day to day. Therefore, illumination was measured both for electric light and daylight in combination.

3.4 Energy use calculations

Energy use for existing electric lighting and improved cases were calculated using the program Excel based on simulation results. Energy savings were obtained by replacing existing electric lighting with more efficient solutions and by using an increasing portion of the available daylight, measured in DA. When calculating energy savings from DA supplemental daylight was not considered. It is assumed in the energy calculations that all electric lights in the buildings are operational.

$$E = t \times (1 - DA) \times P$$ *Equation 10*

Where:

E = Energy use per year	[kWh/year]
t = 4922 hours per year	[hours/year]
DA = Full daylight autonomy	[%]
P = Total power for electric lights	[kW]

4 Result

4.1 Daylighting

4.1.1 Daylight factor

The DF_{median} obtained in the newest building was 3%, while it was 2% in the middle building and 0.1% in the oldest building. A side-by-side comparison of the simulation results can be seen in Figure 20. The effect of the skylight is clearly visible in the false colour images, and that the windows in the old and middle buildings providing less daylight compared to the new building.

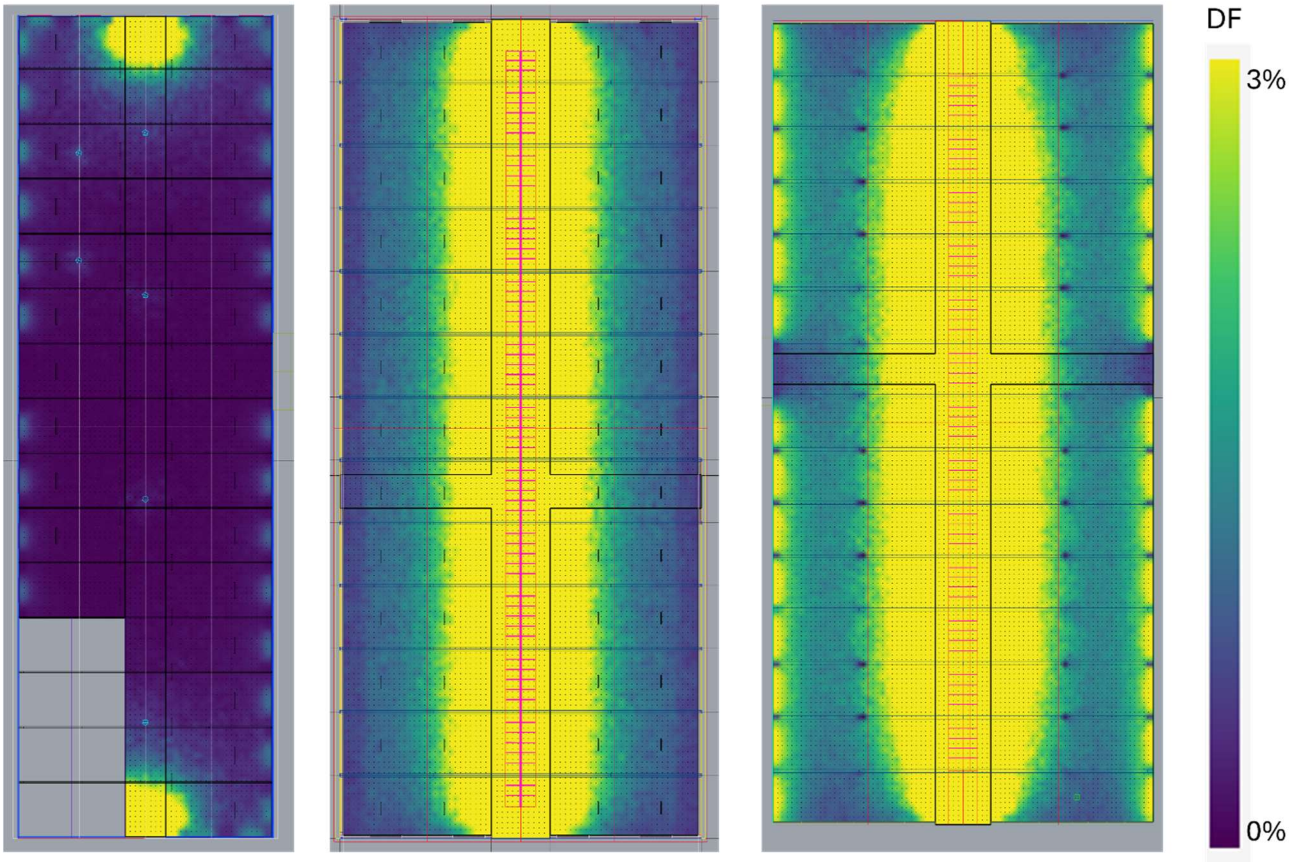


Figure 20 - DF in old (left), middle (middle) and new (right) building.

To validate the model, the simulated values were compared to results obtained during the site visit with simulation points in the same locations as the on-site measurement points. However, these measurement points were located only along the centre of the building. This limitation may introduce inaccuracies in accounting for the transmittance of windows and canvas materials providing side lighting in the buildings.

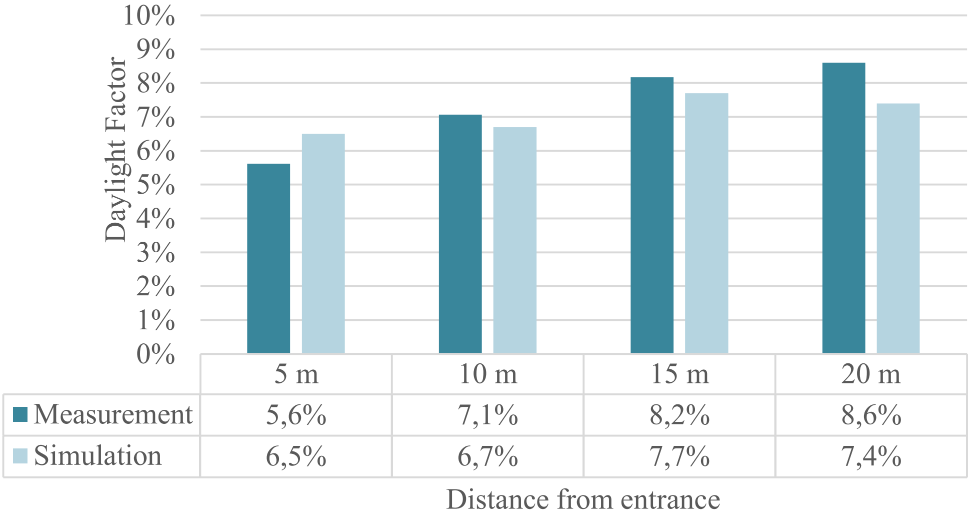


Figure 21 – DF point measurements compared to simulated value for the newest building.

Figure 21 shows that the measured and simulated values for the newest building were generally similar. The simulated values between 10 and 20 meters are slightly below the measured values while they are slightly above at 5 meters. This discrepancy suggests that the real transmittance of the skylights may be slightly higher than what was accounted for in the simulation. On average, the difference in DF was 0.73% with a standard deviation of 0.38%.

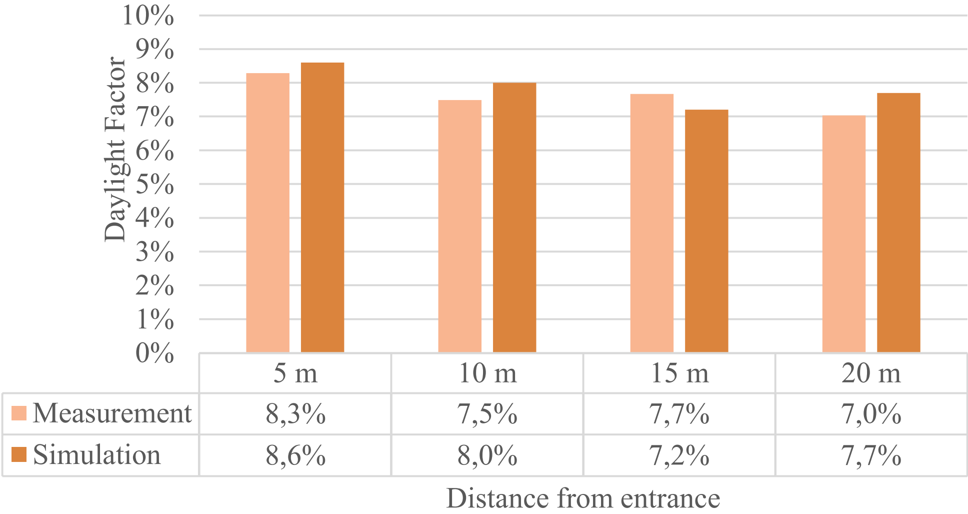


Figure 22 - DF point measurements compared to simulated value for the middle building.

Figure 22 shows that the results for the middle building closely matched the simulated values, indicating that the model accurately represents the real case. On average, the difference in DF was 0.49% with a standard deviation of 0.15%. The relative difference was only 6.6% with a standard deviation of 2.4%, which is remarkably small for daylight simulations. This minimal difference suggests that the impact of surrounding surfaces' reflectances (such as roofs and walls) becomes negligible due to the very low reflectance of the floor.

In the case of the middle building, where the floor reflectance varied between 10% and 14% and the ceiling reflectance was estimated to be approximately 50%, up to 90% of the incoming light was absorbed after the first bounce on the floor. Once it is reflected off the ceiling, a total of 95% of the light was absorbed. If the ceiling had a higher reflectance of 70%, then 93% of the light would have been lost. Therefore, the main source of discrepancy between measurement and simulations appears to be the transmittance of the skylight.

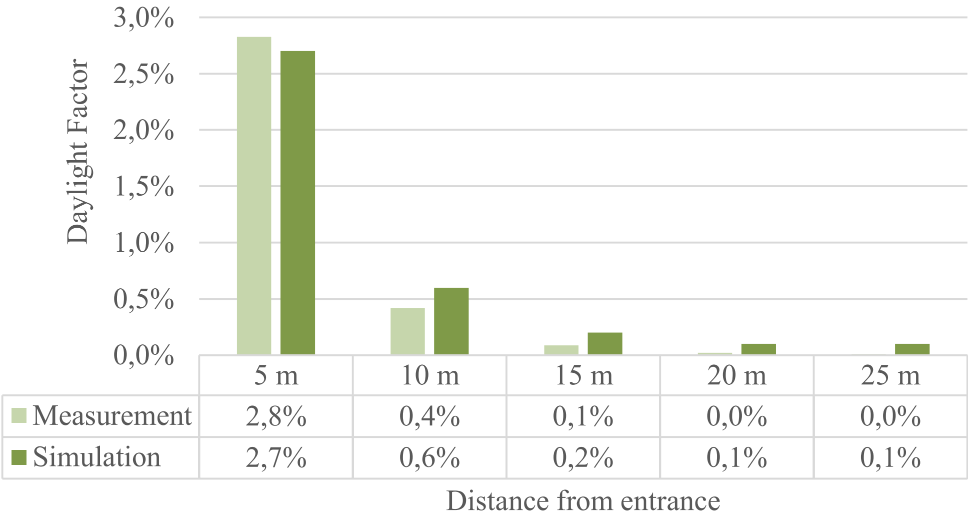


Figure 23 - DF point measurements compared to simulated value for the oldest building.

Figure 23 shows that the measured daylight factors in the oldest building were also similar to the simulated values, indicating that the model represents the real case in an acceptable way. On average, the difference in DF was 0.11% with a standard deviation of 0.04%.

4.1.2 Daylight autonomy

When viewing the results of the DA it should be noted that a 16-hour schedule was used. This results in more dark hours compared to a typical schedule for an office. The target of 150 lux also differs from the 300 lux that are commonly used when calculating DA in offices. The schedule allows for a maximum of 72.6% DA for an unobstructed surface. The DA The simulation results for DA in the existing buildings reveal a significant potential for energy savings, particularly in the new and middle buildings, if daylight could be effectively utilized to replace electric lighting. However, the potential for energy savings in the old building is very limited due to limited daylight access. This limitation becomes evident when examining the DF simulation results, which indicate that daylight in the old building is largely concentrated around the entrance area. As a result, the distribution of daylight throughout the old building is uneven, leading to minimal potential for energy savings compared to the new and middle buildings.

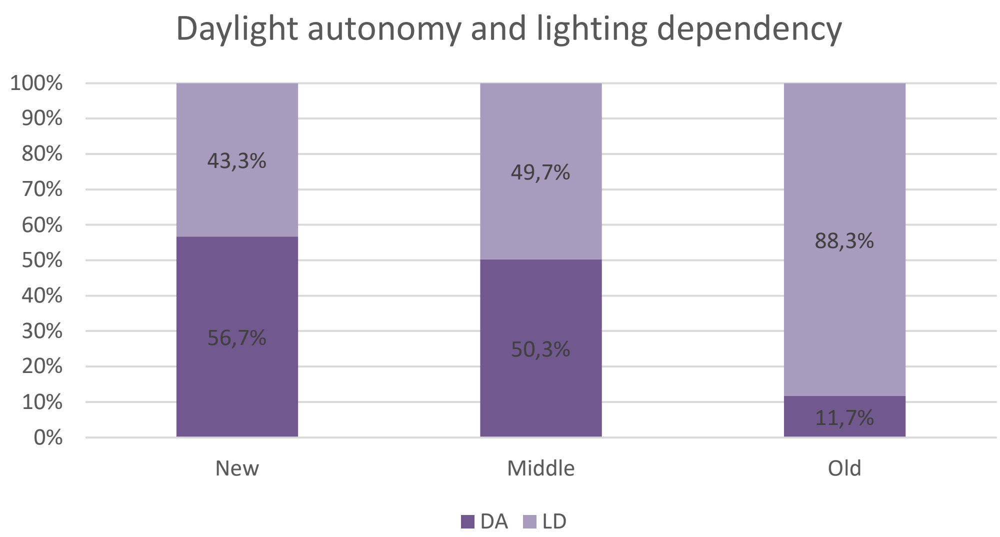
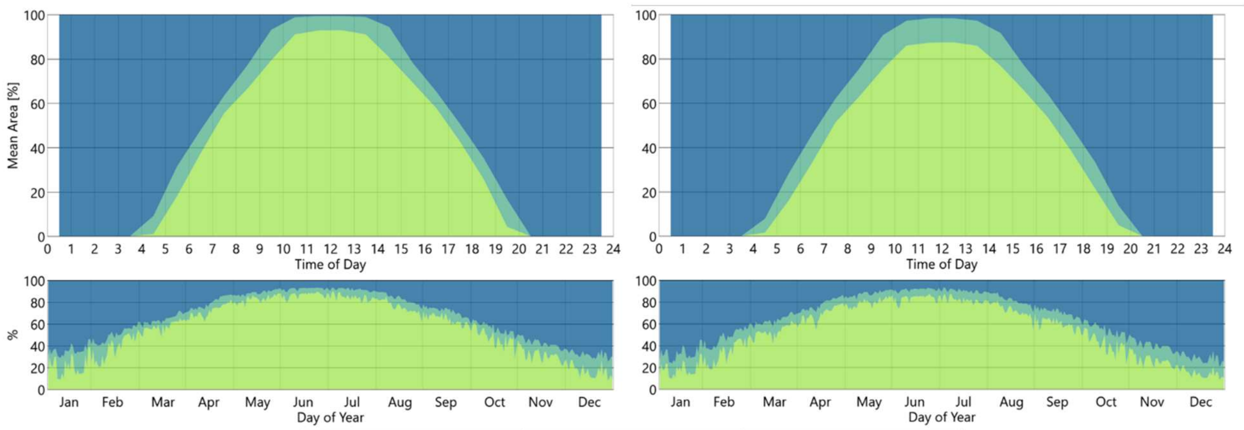


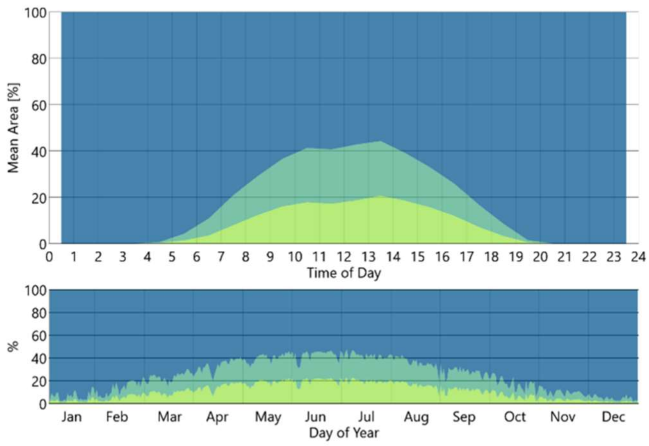
Figure 24 - Daylight autonomy and lighting dependency in buildings based on simulations.

Figure 25 and Figure 26 illustrate the differences between the three buildings. As expected, the largest potential for DA occurs between 11:00 and 13:00 and during the summer months. DA can be either full or partial, with DA in the new and middle buildings by majority being full DA. However, in the old building, a larger portion of the DA is partial, indicating that the illuminance levels are between 50 and 150 lux. 50 lux represents the lowest illuminance requirement in animal pens and using an on/off control for the electric lighting an illuminance below 50 lux could not contribute to daylight harvesting in the building.



No DA	Partial DA	Full DA
<50 lx	50-150 lx	>150 lx

Figure 25 - New Building DA (left), Middle Building DA (Right)



No DA	Partial DA	Full DA
<50 lx	50-150 lx	>150 lx

Figure 26 - Old building DA

4.1.2.1 Improved cases, old buidling

The simulation results after implementing improvements in Table 12 are depicted in Figure 27.

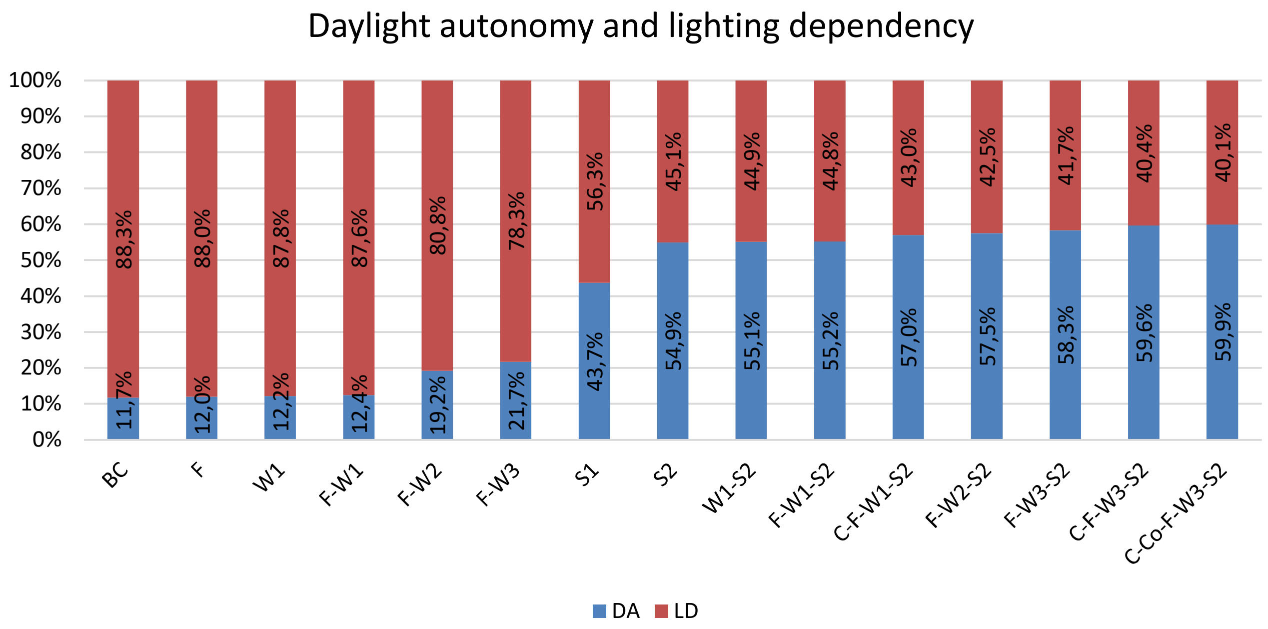


Figure 27 - Impact of improvement measures on DA and LD in the old building.

Changing the windows has minimal impact on DA, increasing it by 10% compared to the BC in the F-W3 scenario. Similarly, changing to a lighter fabric in the W1-case or painting the frames in the F-case do not significantly affect DA. The most impactful measure is the addition of the skylight. Implementing S1 and S2 results in a skylight – to - floor ratio of 4.6% and 9.3%, respectively. A combination of all measures achieves a DA of almost 60%. However, this is only 5% more than the DA achieved when only adding the larger skylight in case S2.

4.1.2.2 Improved cases, middle building

The simulation results after implementing improvements in Table 13 are depicted in Figure 28

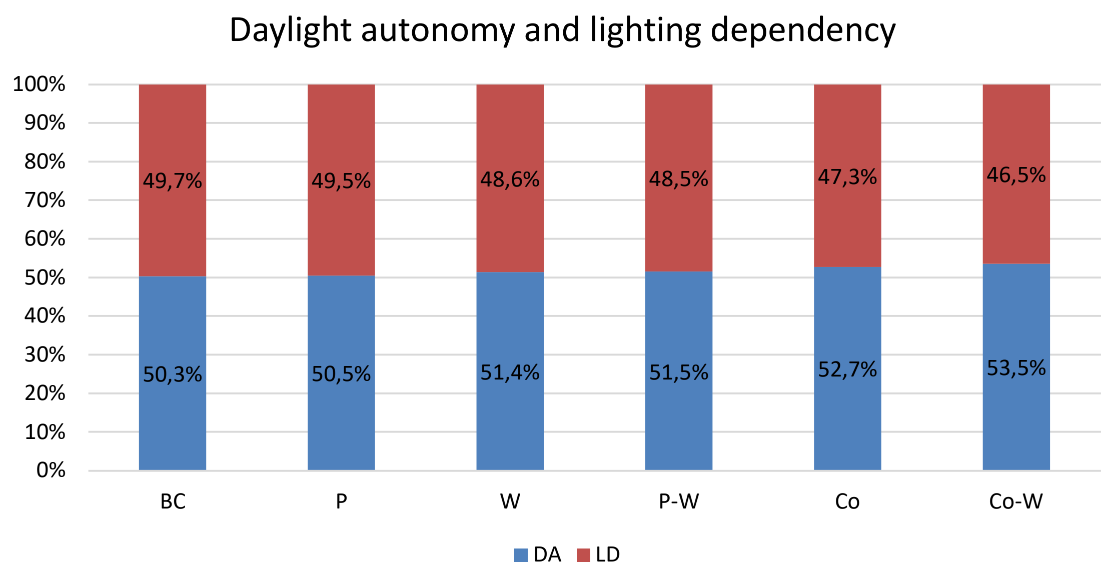


Figure 28 - Impact of improvement measures on DA and LD in the middle building.

The impact of the improvements on increasing DA is small. The low impact of increasing the reflectance of the walls was expected. The single largest impact would be to paint the supporting metal structure in a brighter colour, but the increase is relatively small. Overall, the middle building performs slightly worse than the old building with these improvements. The probable causes of this is that the improved old building had a greater skylight-to-floor ratio while also being narrower.

4.2 Electric lighting

The simulation results are evaluated against a threshold required to increase milk yield, aiming to achieve a minimum light illuminance of 150 lux in cows' pens, validating the period of light exposure regardless of the season. Assessing the lighting conditions during operating hours after sunset reveals that in the base case middle building, 80% of sensors fail to meet the 150-lux illuminance requirement in cow pens, while in the base case new building, only up to 28% of sensors are illuminated above 300 lux. Replacing fluorescent light luminaires to improve the old and middle buildings not only results in halving power profiles, but it also effectively increases lighting intensity.

The illuminance under the luminaires is compared with measured values, with only the old building used for comparing fluorescent lighting as the same luminaire is used in both the old and middle buildings. The comparison can be seen in Figure 29. The simulated values for the new building are slightly higher than the measured values, while the simulated values for the old building are slightly lower.

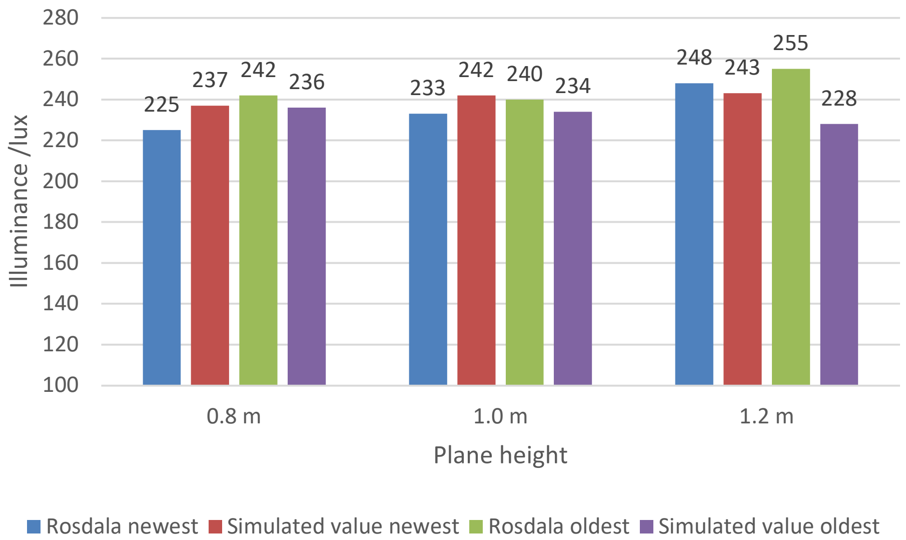


Figure 29 - Point illuminance under luminaires, measured values compared to simulated values.

Table 17 - Deviation between measured and simulated values of point illuminance under luminaires

Building	Relative difference at 0.8 m	Relative difference at 1.0 m	Relative difference at 1.2 m
New building	+5.1%	+3.7%	-2.1%
Old building	-2.5%	-2.6%	-11.8%

The relative differences could be that the luminaires in the simulation deviate in luminous flux or light distribution. Some sources of error include the assumption of the transmissivity of windows and skylights, as well as the reflectance of non-measured surfaces.

4.2.1 Base Case simulation results

4.2.1.1 New building

The new building is mainly equipped with 43 LED light sources, each emitting 8100 lumens per luminaire. Electric lighting simulations, including a total operating capacity of six fluorescent light sources, show a uniformity ratio of only 0.08, see Figure 42. Since the new building is the deepest, the distance between luminaires located in the pen and corridor creates low light intensity areas. Additionally, the installation of electric lighting above the corridor is very high, reaching up to the ridge, close to 10 meters in height. This results in the light intensity diminishing towards the targeted area, see Figure 31. The median lux in this building is the lowest, at 100 lux , resulting in only 23% of sensors receiving more than 150 lux.

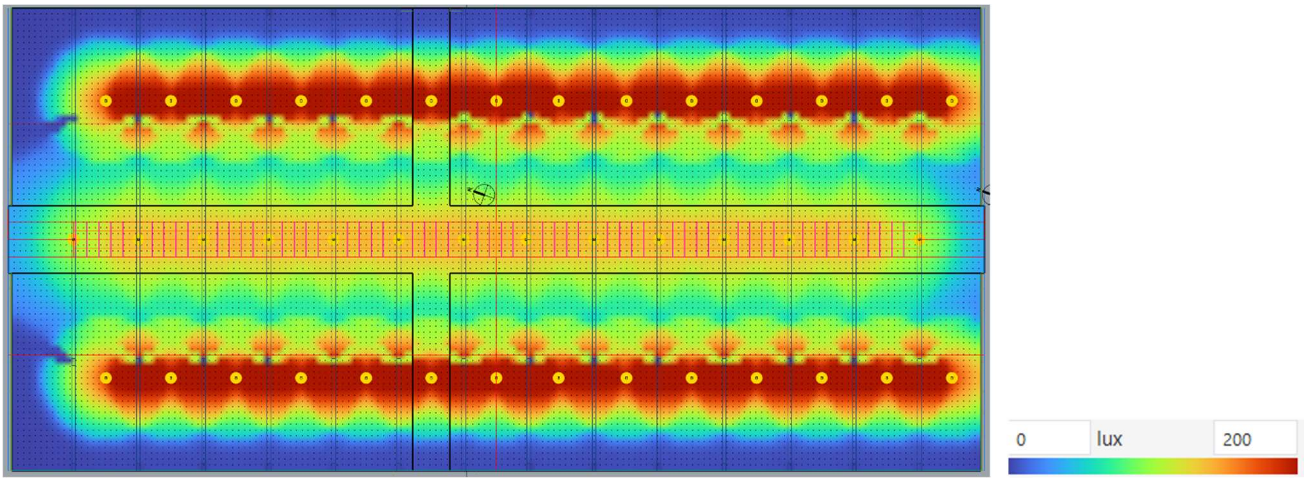


Figure 30 - Simulated electric lighting in newest building.

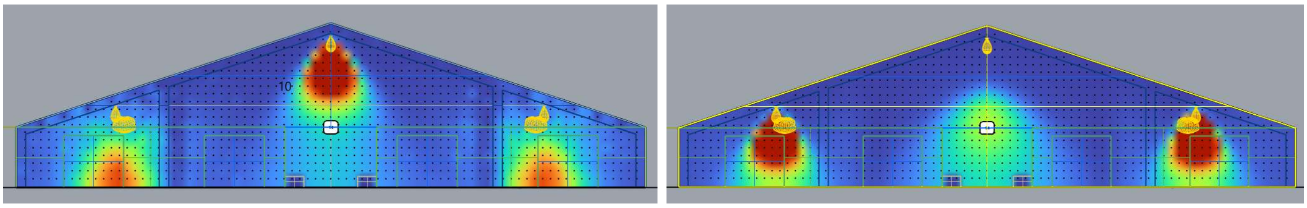


Figure 31 - Vertical simulation results (left Sec A-A, right Sec B-B)

4.2.1.2 Middle building

The old and middle buildings are illuminated by direct pendant fluorescent luminaires, each emitting 7290 lumens per luminaire. The C-plane of the luminaire polar diagram represents a wider beam of light, accompanied by a light distribution angle greater than 180°, leading to additional reflection created by the diffusive and specular nature of the metal roof.

In the middle building, there are no luminaires dedicated directly to the main corridor, creating a longer space gap between the nearest lighting fixtures located on each side of the passageway. This results in lower levels of light during night operating hours, as half of the luminaires are installed at a higher level than the rest, positioned 5 meters above the ground.

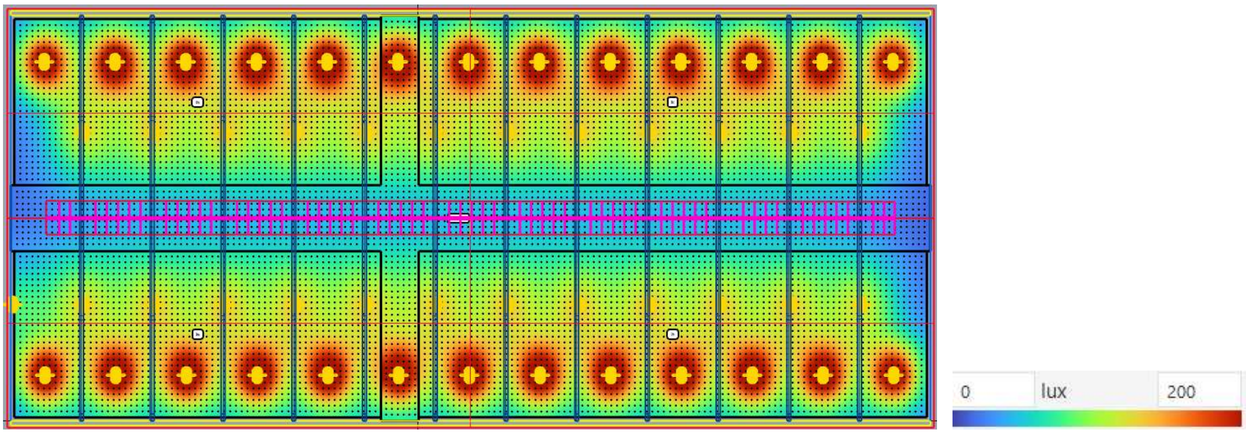


Figure 32 - Simulated electric lighting in middle building

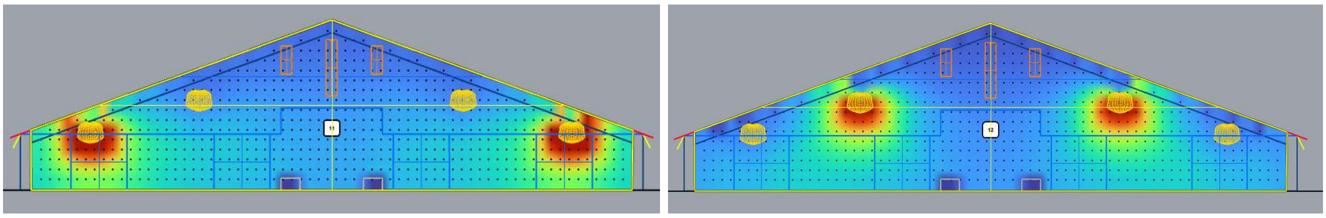


Figure 33 - Vertical simulation results (left Sec A-A, right Sec B-B)

4.2.1.3 Old building

The old building has the greatest number of luminaires per area, resulting in an even distribution of light, meeting the 150-lux target in cow pens. Moreover, it is not overly illuminated, as none of the sensor points are receiving more than 300 lux, while the mean and median illuminance is about 170 and 180 lux, respectively. The building was constructed many years ago, and its narrow plan leads to a shorter distance between luminaires.

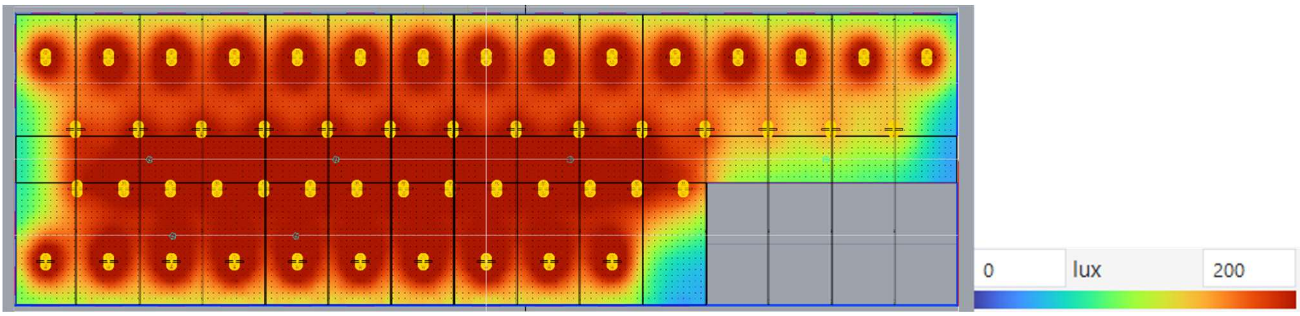


Figure 34 – Simulated electric lighting in oldest building

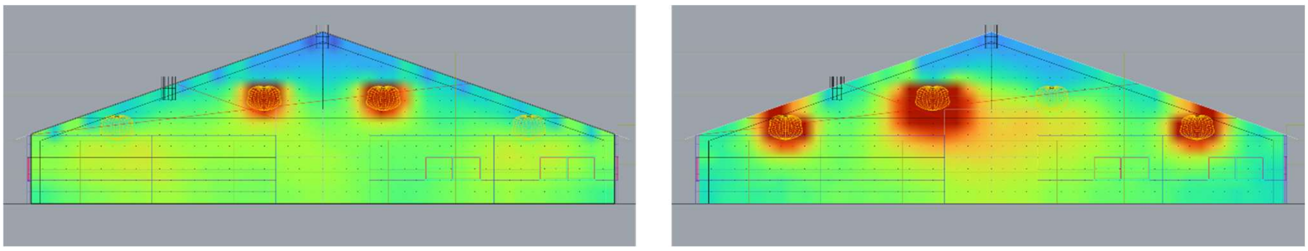


Figure 35 - Vertical simulation result of old building

4.2.1.4 Percentage of illuminance at the points, mean and median lux values.

Most of the sensors in all three buildings show illuminance above 75 lux in the pen areas, as shown in Figure 36. In the cow pen area of the old building, 73% of the sensors reach 150 lux. However, 80% of sensors in the middle building and 77% in the new building do not meet that threshold.

In the base case of the new building, corridor luminaires fixed just below the roof ridge intersection, which happens to be the highest point and measured to be at 10 meters above the ground level, only provide 2% of the illuminance above 200 lux. Meanwhile, in the old building, fluorescent lights in the corridor illuminate 58% of the sensors above 200 lux, but in the middle building, only 4% of sensors reach above that point. In the base cases, less than 1% of the sensors obtain an illuminance above 300 lux.

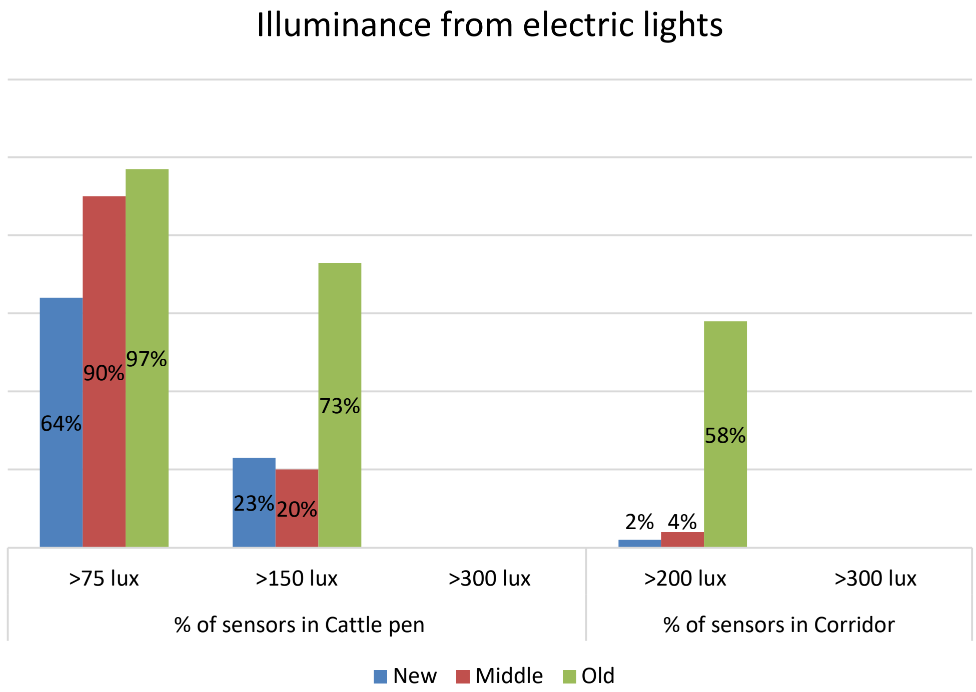


Figure 36 - Percentage of sensors above threshold values for illuminance from electric lights.

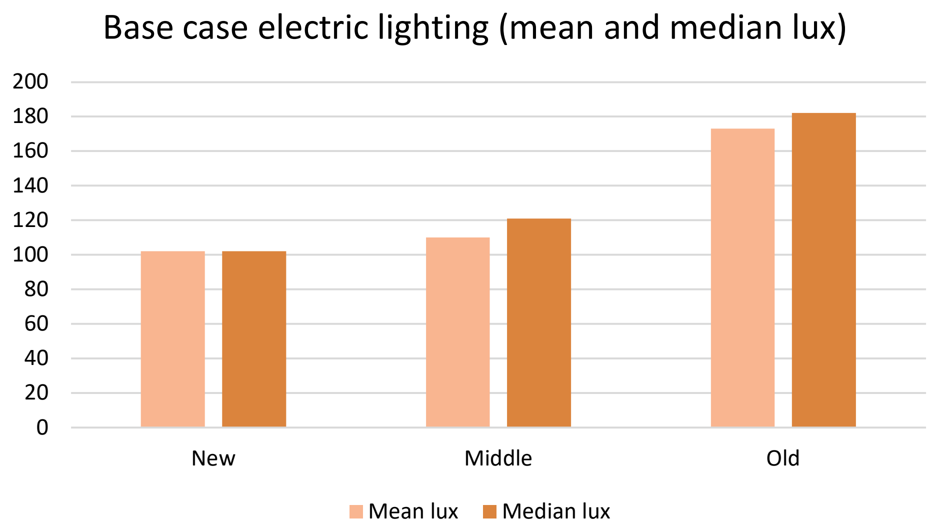


Figure 37 - Mean and median illuminance for Base Case electric lighting.

4.2.2 Improved old building

The 53 fluorescent luminaires, each using 136 W, were replaced by 48 LED luminaires, each using 55 W. The central luminaires were placed at 4.9 meters above floor level, while the luminaires closest to the wall were placed at 3.75 meters above floor level. The placement of the luminaires can be seen in Figure 38.

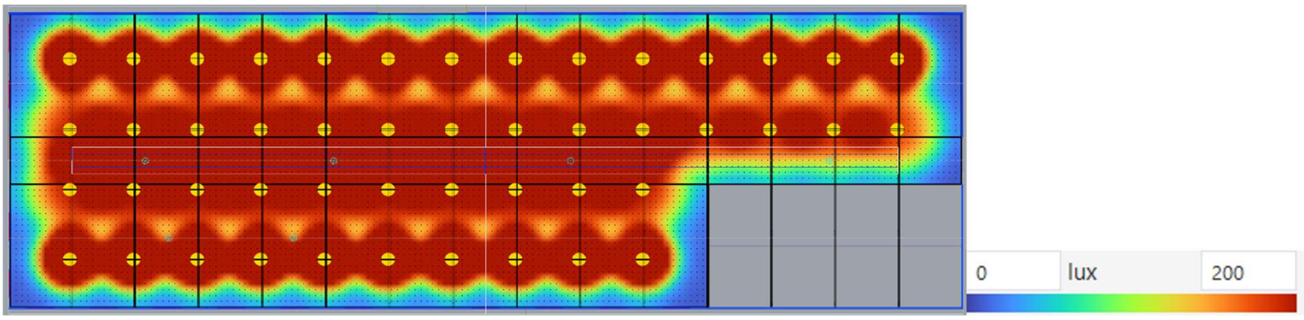


Figure 38 - Old building with placement of new 55W LED lighting.

Table 18 - Comparison with power and illuminance between electric lighting in Base Case and Improved cases for Old Building.

Case	Solution	Total power	Mean Illuminance	Median Illuminance
Base Case	Fluorescent	7208 W	173 lx	182 lx
Improved Case 1	LED 55 W	2640 W	184 lx	201 lx
Improved Case 2	LED 55 W with white ceiling and columns	2640 W	188 lx	206 lx

The 55 W LED luminaires provided a higher illuminance to the building compared to the fluorescent luminaires while using only 37% of the power. Given that the fluorescent luminaire should provide a similar luminous flux as the LED (7290 and 7200 lumens respectively), the result on illuminance is surprising. The expectation would be that the fluorescent solution provides a 12% higher mean illuminance, but the simulation results in a 6% lower mean illuminance. A possible explanation is that the fluorescent light has a different, wider light distribution than the LED, and part of the light is reflected off surfaces before reaching the measurement plane, resulting in some light loss in these reflections.

The new lighting solution reduces the power for electric lights from 4 to 1.5 W/m², resulting in greater energy savings than the expected 50%. However, the lighting intensity of 4 W/m² is higher than the average of 2.8 W/m² (Reksen et al., 1999) found in our literature review. The energy use per year for the old building is shown in Figure 39.

Providing a brighter ceiling and columns in the building does not significantly increase the illuminance. This is likely due to the combination of a direct lighting solution and a very dark floor, meaning that only a small fraction of the light reaches the ceiling and column surfaces to be re-reflected.

The energy use for the old building is calculated to be approximately 35,500 kWh/year. With the LED solution suggested, the energy is calculated to be approximately 13,000 kWh/year, which corresponds to a reduction of approximately 63%. If the smaller skylight is introduced as a single measure, the energy use could be reduced to 20,000 kWh/year using fluorescent lighting and 7,300 kWh/year using LED. If the skylight size is doubled, the energy use could be reduced to 16,000 kWh/year using fluorescent lighting and 5,900 kWh/year using LED. If all measures are implemented, the energy use could be reduced to 14,200 kWh/year using fluorescent lighting and 5,200 kWh/year using LED.

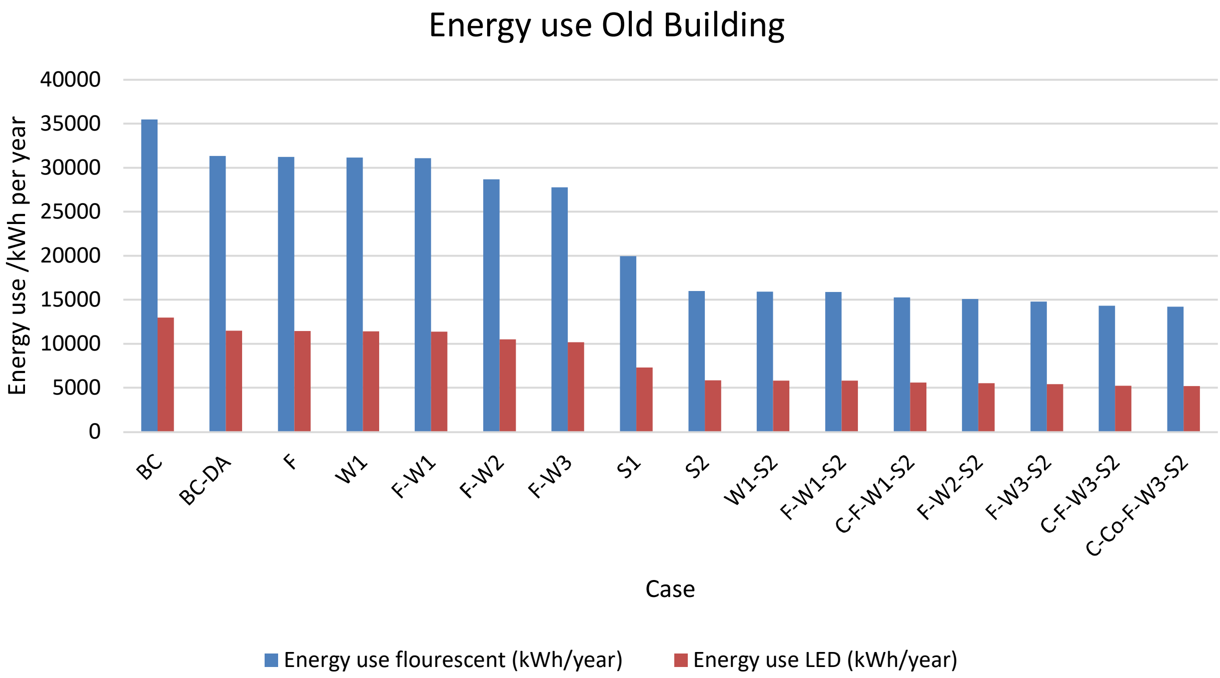


Figure 39 - Energy use per year for the different Old Building cases.

When utilizing daylight as a replacement for electric light, the operating hours of the electric light sources are reduced, thereby decreasing the frequency with which they need to be replaced. The average expected lifetimes and energy usage expressed as kWh/m²; year are shown in Table 19.

Table 19 - Operating hours, energy use and average time between light source replacement for the different Old Building cases.

Code	Operating hours with LD (h/year)	Energy use fluorescent (kWh/m²/year)	Average lifetime fluorescent (years)	Energy use LED (kWh/m²/year)	Average lifetime LED (years)
BC	4922	19.61	3.05	7.18	10.16
BC-DA	4346	17.32	3.45	6.34	11.50
F	4331	17.26	3.46	6.32	11.54
W1	4322	17.22	3.47	6.31	11.57
F-W1	4312	17.18	3.48	6.29	11.60
F-W2	3977	15.85	3.77	5.80	12.57
F-W3	3854	15.36	3.89	5.62	12.97
S1	2771	11.04	5.41	4.04	18.04
S2	2220	8.84	6.76	3.24	22.52
W1-S2	2210	8.81	6.79	3.23	22.62
F-W1-S2	2205	8.79	6.80	3.22	22.68
C-F-W1-S2	2116	8.43	7.09	3.09	23.62
F-W2-S2	2092	8.34	7.17	3.05	23.90
F-W3-S2	2052	8.18	7.31	3.00	24.36
C-F-W3-S2	1988	7.92	7.54	2.90	25.14
C-Co-F-W3-S2	1974	7.86	7.60	2.88	25.33

4.2.3 Improved middle building

The 50 fluorescent luminaires, each using 136 W, were replaced by 64 LED luminaires, each using 55 W. The central luminaires were positioned at a height of 4.5 meters above floor level, while the luminaires closest to the wall were positioned at a height of 3.3 meters above floor level.

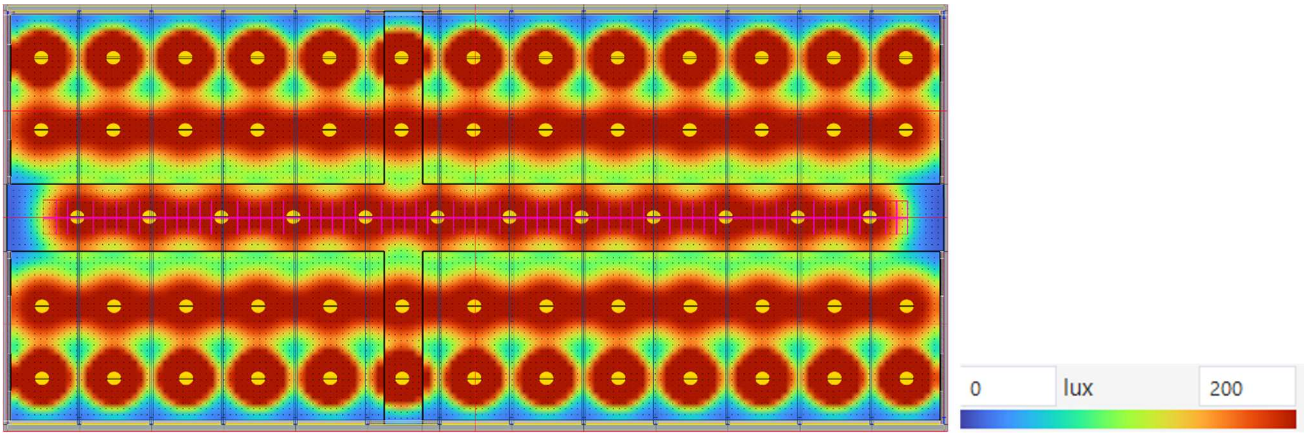


Figure 40 - Middle building with placement of new 55W LED lighting.

Table 20 - Comparison with power and illuminance between electric lighting in Base Case and Improved cases for Old Building.

Case	Solution	Total power	Mean Illuminance	Median Illuminance
Base Case	Fluorescent	6800 W	110 lx	121 lx
Improved Case	LED 55 W	3520 W	175 lx	173 lx

The new LED lighting solution in the middle building increased both the mean and median illuminance levels while reducing the total power required for electrical lighting. Specifically, the power for electric lights decreased from 2.5 to 1.3 W/m², aligning closely with the expected saving potential of 50% identified in the literature review. The energy use per year is shown in Figure 41.

The energy use for electric lighting in the middle building is calculated to be approximately 33,500 kWh/year. With the suggested LED solution, the energy use is estimated to be approximately 17,300 kWh/year, representing a reduction of 48%. By utilizing the existing skylight to replace electric lighting, the energy use could be further reduced to 16,600 kWh/year using fluorescent lighting and 8,600 kWh/year using LED. Additionally, cleaning the windows could result in a reduction of energy use to 16,300 kWh/year using fluorescent lighting and 8,400 kWh/year using LED. If all measures are combined, the energy use could be further reduced to 15,600 kWh/year using fluorescent lighting and 8,100 kWh/year using LED.

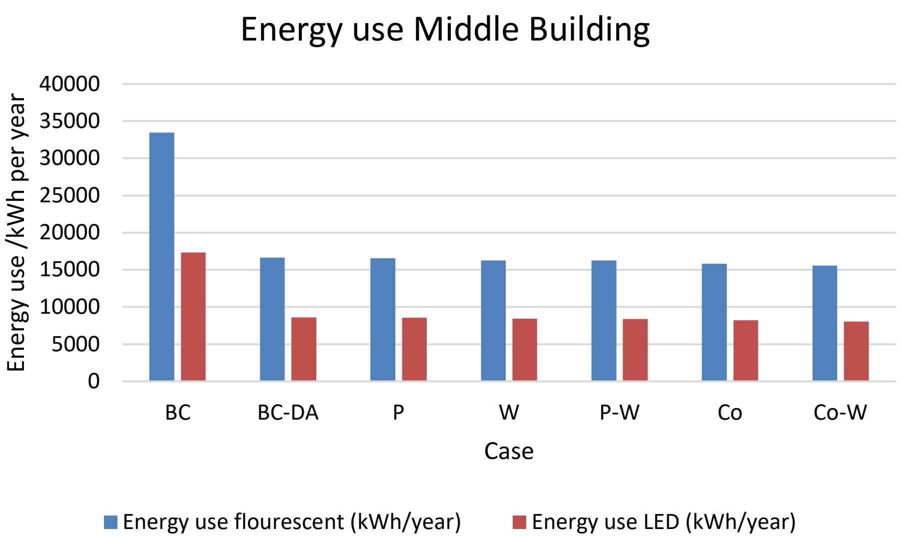


Figure 41 - Energy use per year for the different Middle Building cases.

The average expected lifetimes and energy usage expressed as kWh/m²/year are shown in Table 21. Utilizing daylight in the middle building could significantly extend the intervals between replacing existing fluorescent light sources or increase the lifespan of a future LED installation.

Table 21 - Operating hours, energy use and average time between light source replacement for the different Middle Building cases.

Code	Operating hours with LD (h/year)	Energy use fluorescent (kWh/m²/year)	Average lifetime fluorescent (years)	Energy use LED (kWh/m²/year)	Average lifetime LED (years)
BC	4922	12.47	3.05	6.46	10.16
BC-DA	2446	6.20	6.13	3.21	20.44
P	2436	6.17	6.16	3.20	20.52
W	2392	6.06	6.27	3.14	20.90
P-W	2387	6.05	6.28	3.13	20.95
Co	2328	5.90	6.44	3.05	21.48
Co-W	2289	5.80	6.55	3.00	21.85

4.2.4 Uniformity Ratio

In the base case, the middle building and the old building show a uniformity ratio of around 0.25. However, the former building has low illuminance, specifically bellow 150 lux for both mean and median lux values, whereas the latter building exceeds 150 lux.

After the improvements, the uniformity ratio resulting from changing to energy-efficient light sources decreased by more than two-fold in both middle and old buildings. This is because the higher illuminance level produced by the higher luminous efficacy of LED lights, compared to that of existing fluorescent lights, creates a larger disparity in light levels between the average of well-illuminated areas and the minimum value of low-lit areas, especially at the corners. For these reasons, the LED lighting in the middle and new buildings only achieves a uniformity ratio of 0.1, which is significantly less than the required level of 0.4. The uniformity ratio in the old building is even lower due to a decrease in the number of light sources, from 53 fluorescent lights to 48 LEDs. Another contributing factor in the old building is the location of luminaires at the ends of the building, which are farther from the corners compared to the base case. Lastly the LED-luminaires have a narrower light distribution meaning the light is less distributed into the corners, directly or through reflection off surfaces. If only the area occupied by the cows are considered the ratio is higher with 0.34 and 0.19 for the improved middle and old building respectively. The uniformity ratios are shown in Figure 42.

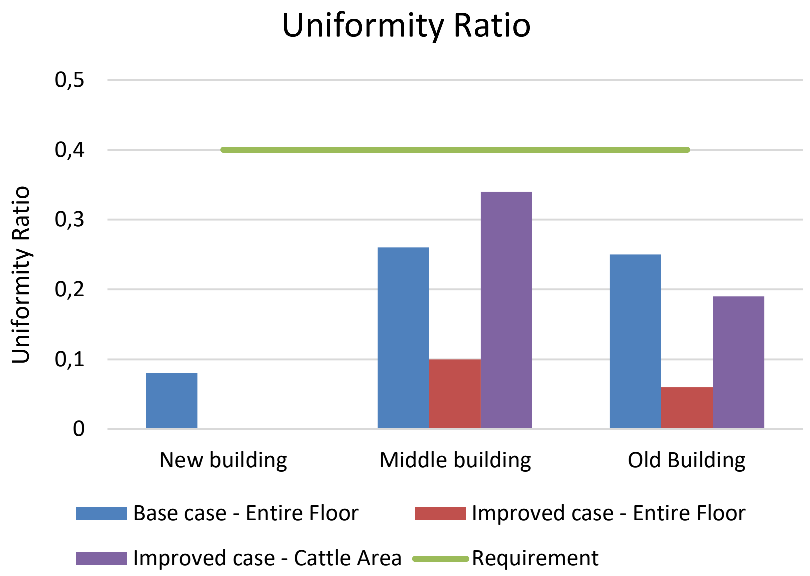


Figure 42 - Uniformity ratio in Base cases and Improved cases compared with requirement set by SS-EN 12464-1:2021.

4.3 Circadian lighting

The building with skylight exhibits peak illuminance because of clear sky simulation settings during both the winter solstice and equinox. The M/P ratio consistently approaches approximately one as the sun ascends toward the zenith in the middle and old buildings due to direct sunlight illumination through skylights. In both the base and improved cases, every building fails to meet the EML criterion for illumination when using only electric lighting.

The resulting α-opic irradiances on the separate opsins are observed using the species-specific toolbox (bioRxiv, 2023), as depicted in Figure 43. Regarding melanopic irradiance, the irradiance is 12% higher for cattle under the fluorescent light source and 6% higher under the LED light source compared to human irradiance. This means that from a human perspective, replacing the fluorescent light source with LED would result in a 12% increase in melanopic irradiance, while for cattle, the increase is 6%. Melanopsin, rods, S-cones, and M-cones in cattle are slightly more sensitive to the irradiance from both light sources compared to humans.

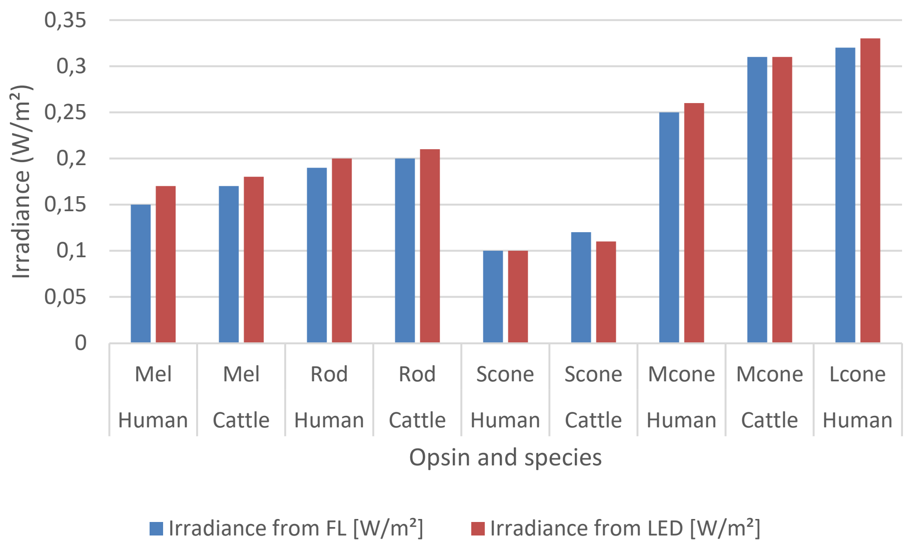


Figure 43 - Irradiance of the different opsin in human and cattle using CIE standard illuminants providing 200 lux.

4.3.1 Base case new building

The result of ALFA simulations for the base case new building are shown in Figure 44 and Figure 45. The electric lighting in the graphs represents EML supplied by the electric lighting while the photopic lux and equivalent melanotic lux represents both electric lighting and daylight combined.

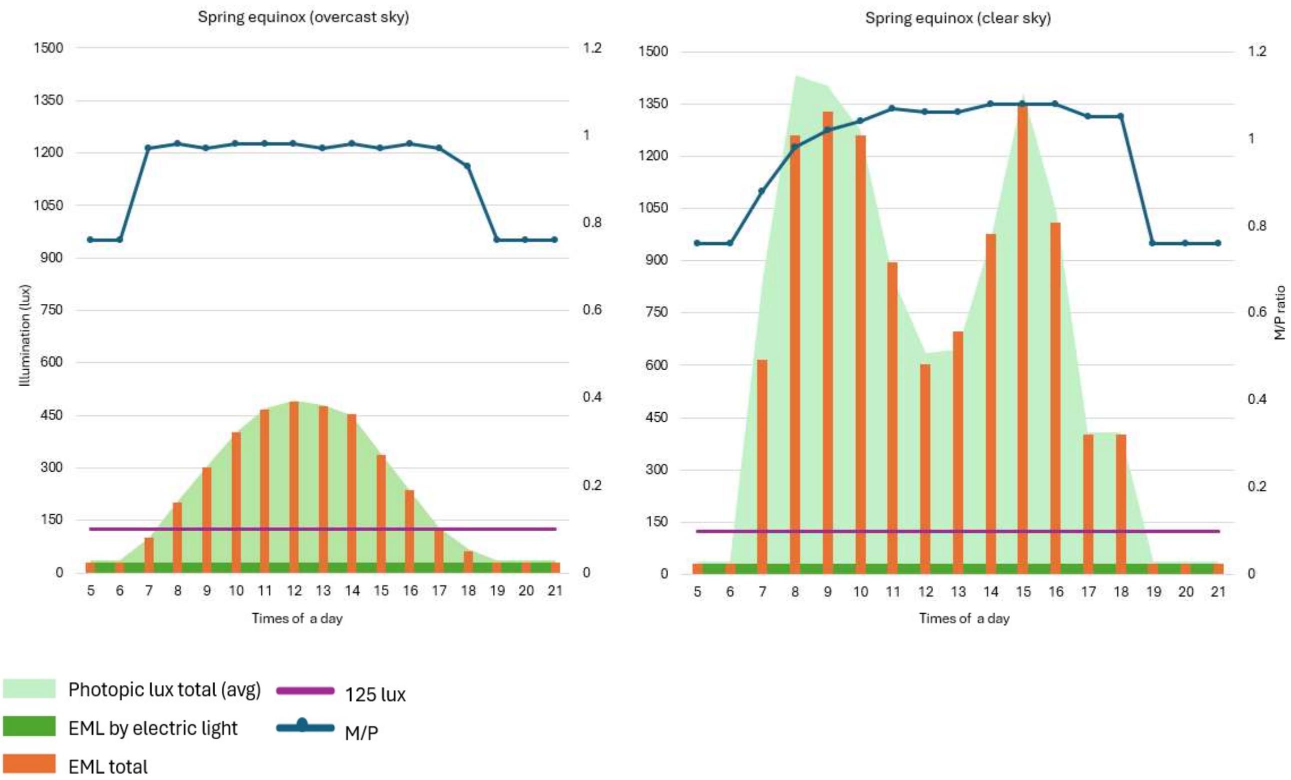


Figure 44 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the new building during spring equinox under an overcast (left) and clear (right) sky.

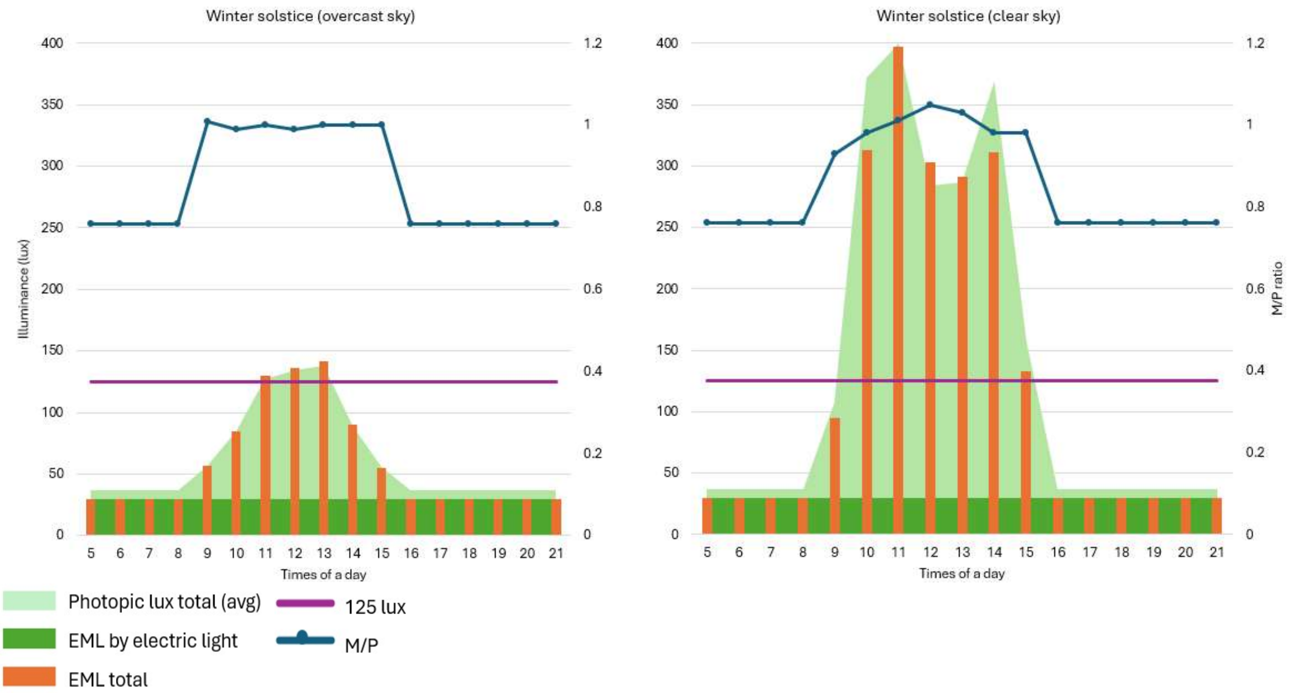


Figure 45 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the new building during winter solstice under an overcast (left) and clear (right) sky.

The new Building obtained the highest EML with a maximum value of close to 1350 EML at 09:00 and 15:00 from sunlight on the day with a clear sky. The new building was constructed with the highest window-to-wall ratio among the buildings, and no buildings are blocking the sun towards the west. Due to this the EML benchmark is reached at the most an hour after sunrise. The exception is on overcast days on the winter solstice where the building only reaches the benchmark of 125 EML in the middle of the day, 11:00-13:00.

4.3.2 Base case middle building

The result of ALFA simulations for the base case middle building are shown in Figure 46 and Figure 47.

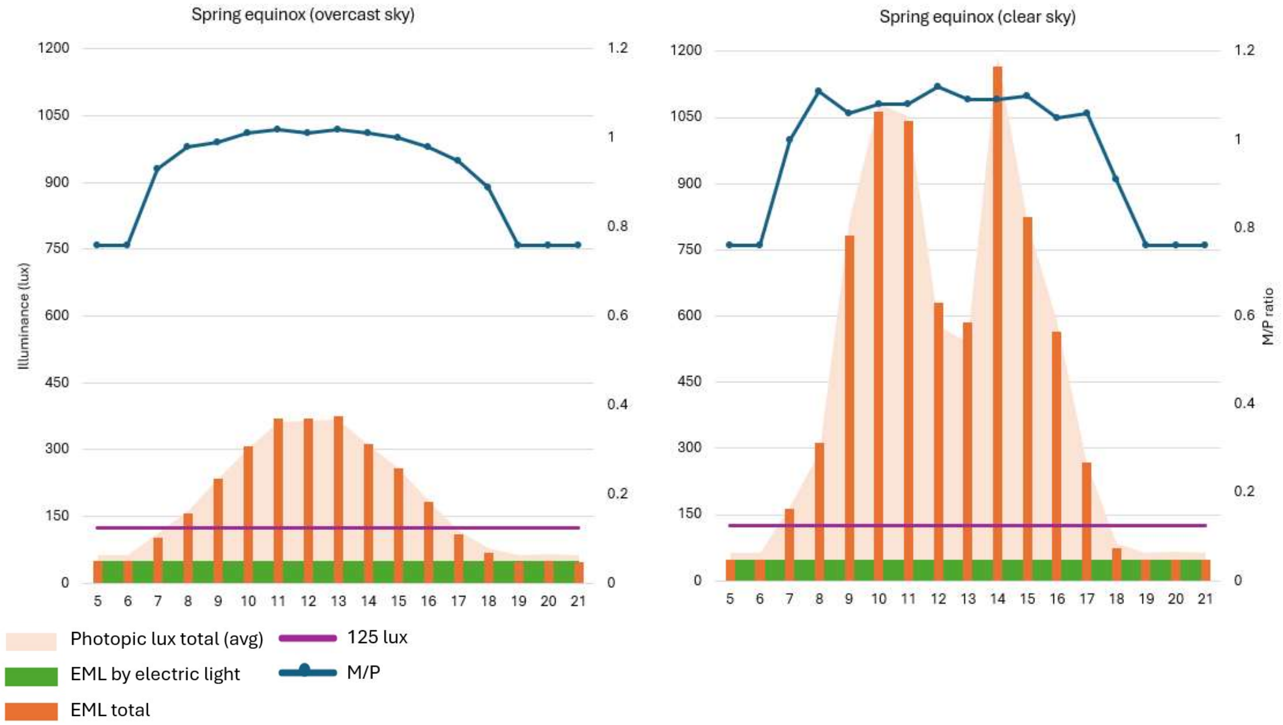


Figure 46 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the middle building during spring equinox under an overcast (left) and clear (right) sky.

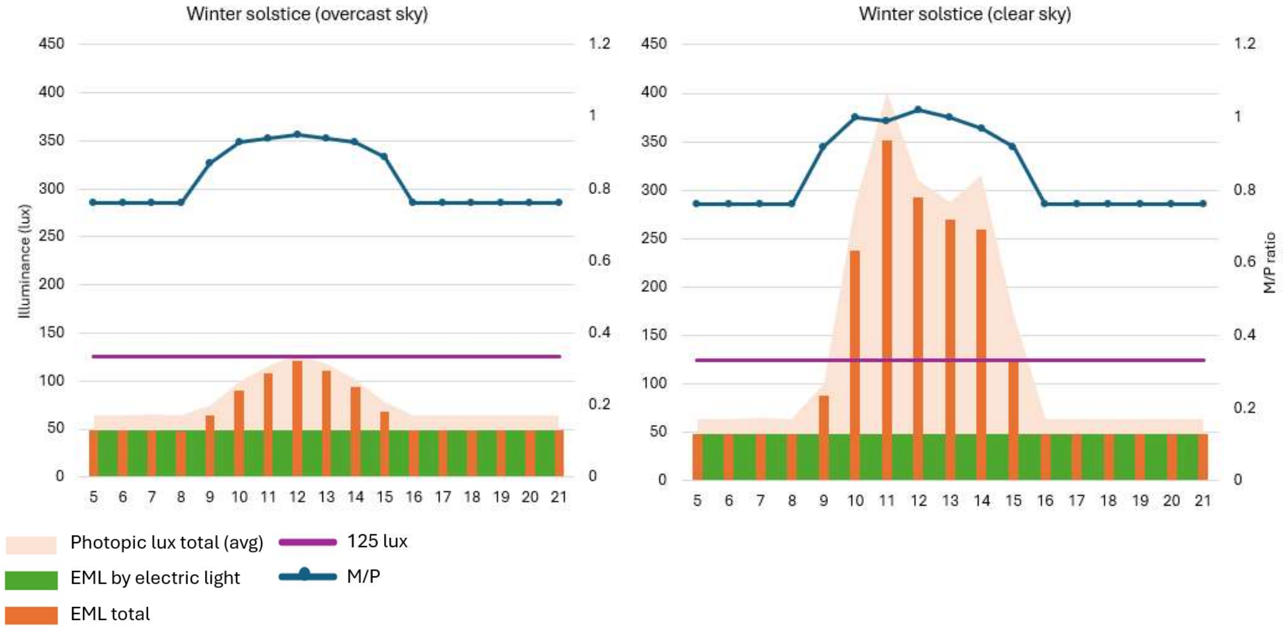


Figure 47 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the middle building during winter solstice under an overcast (left) and clear (right) sky.

At the spring equinox, 8 hours during overcast days and 6 hours during clear days fail to meet the EML benchmark despite the fact that the equinox daylength is about 12 hours. Around 10:00 and 14:00 hours, the EML peaks at 1050 and 1150 lux, respectively, with a decline to 600 lux between these two peaks due to the absence of exposed sensors in the corridor at noon under clear skies. Meanwhile, the sloping skylight at the top of the pitched roof allows direct sunlight to significantly illuminate the sensors located on either side of the corridor. This occurs as the sun's trajectory moves from east to west through the elongated skylight, which is oriented towards the north. Since the M/P ratio exceeds one at 12:00 hours, the average EML on a clear day during the spring equinox is higher than the average photopic lux.

During the winter solstice, the middle building fails to reach the EML benchmark under overcast skies. However, with clear skies, approximately five out of seven hours of daylight on the shortest day are above 125 EML. Photopic lux and EML peaks at 11:00 hours when the sun shines directly through the skylight due to clear skies.

4.3.3 Base case old building

The result of ALFA simulations for the base case old building are shown in Figure 48 and Figure 49.

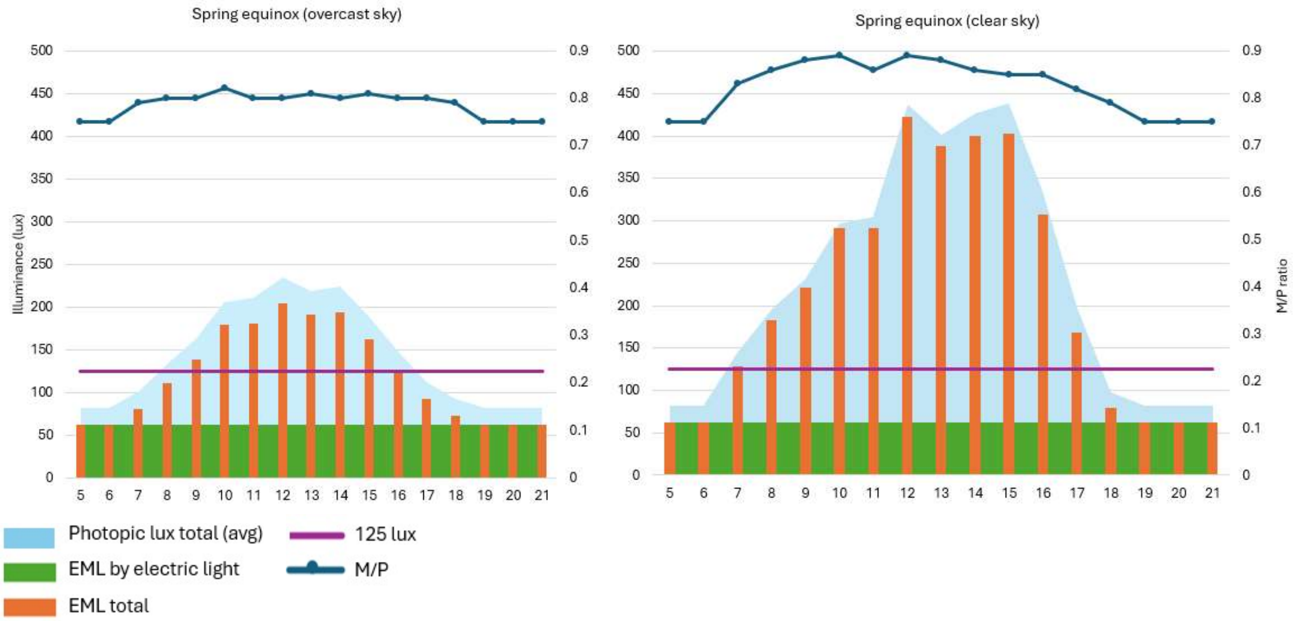


Figure 48 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the old building during spring equinox under an overcast (left) and clear (right) sky.

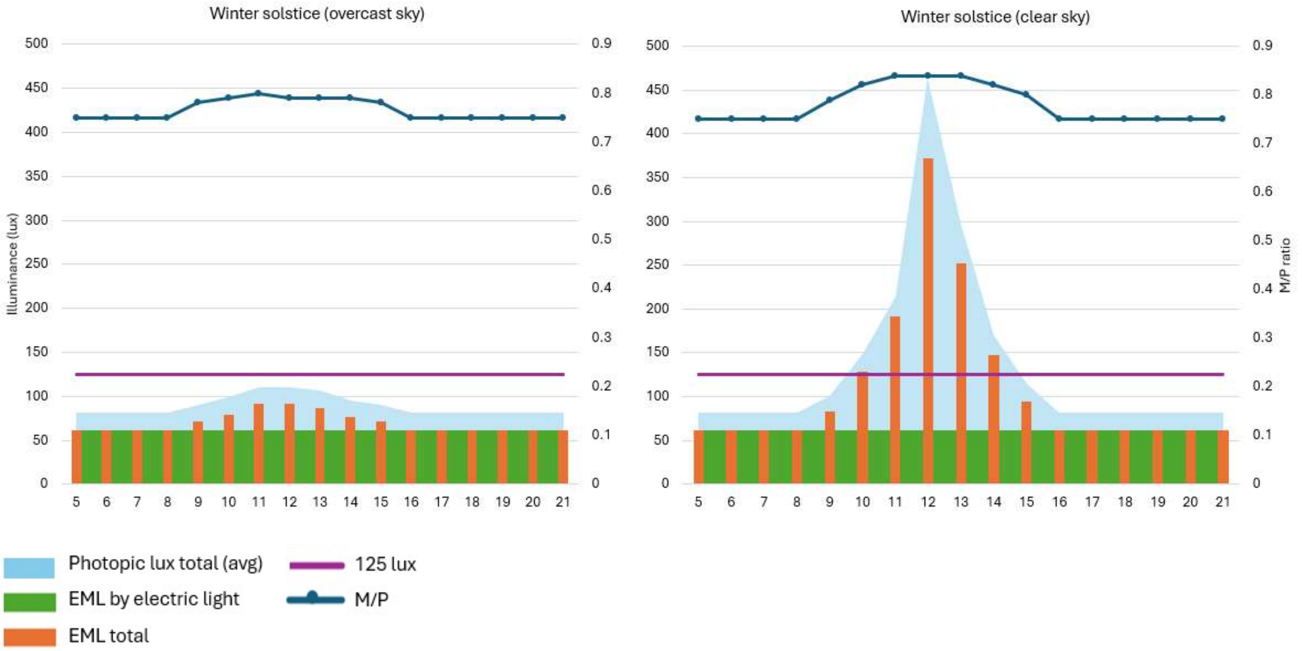


Figure 49 -- EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the old building during winter solstice under an overcast (left) and clear (right) sky.

In the old building, illuminance levels peak at 425 and 210 EML at 12:00 hours during the spring equinox under clear and overcast skies, respectively. The M/P ratio consistently remains below 0.9 in this building, resulting in lower EML values compared to photopic lux. The absence of skylights in this building explains the lack of a noon dip in EML, which occurred in other barns on clear days.

During the winter solstice, neither electric lighting nor most daylighting is sufficient to meet the threshold, except for a few hours when the sun is near the horizon and light enters through the main entrance. This is due to the lack of skylights that would have provided additional illumination in this building. The peak illuminance under clear skies is primarily due to the high illuminance levels incident on a few sensors points near the gate entrance opening facing south.

4.3.4 Improved old building

The result of ALFA simulations for the improved case for the old building are shown in Figure 50 and Figure 51.

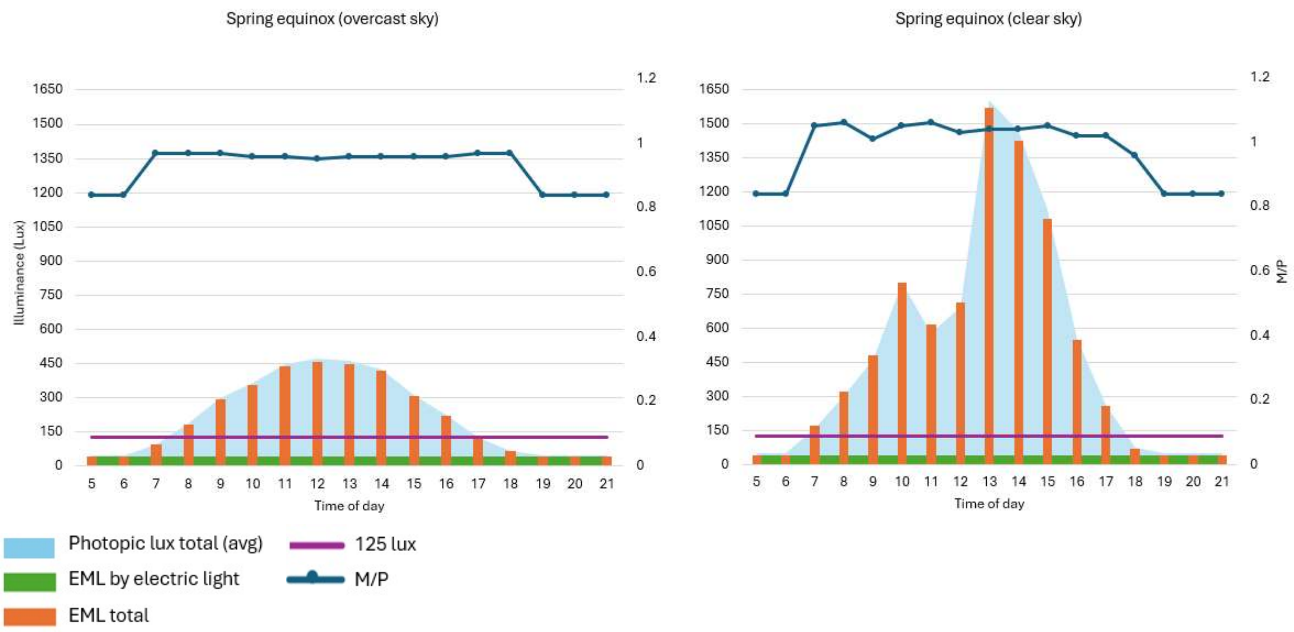


Figure 50 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the improved old building during spring equinox under an overcast (left) and clear (right) sky.

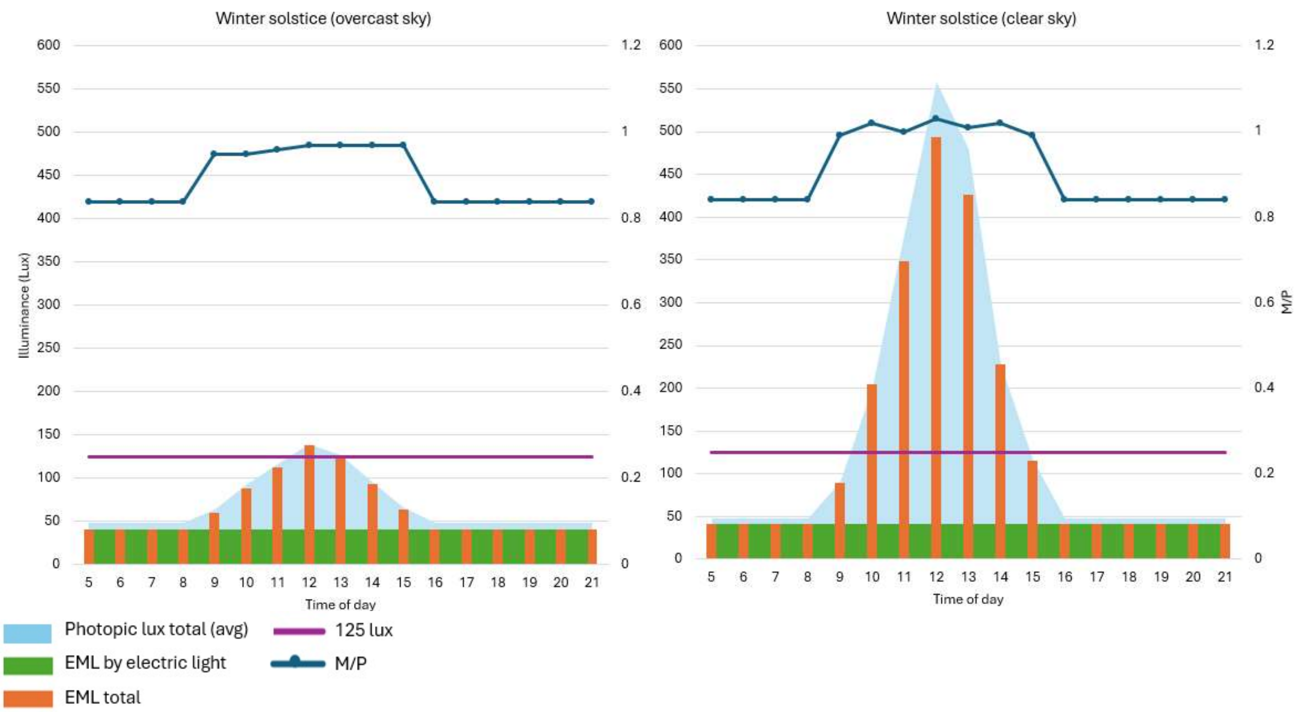


Figure 51 - EML from electric lighting, average EML, average photopic lux, M/P and threshold values for the improved old building during winter solstice under an overcast (left) and clear (right) sky.

In the improved case for the old building, fluorescent electric lighting is replaced with LED lighting, and a skylight in case S2 is added. The peak is 1570 EML at 13:00 hours during the spring equinox under clear skies. The cow areas receive more direct sunlight in the afternoon, partly due to the storage area located in the southeast corner of the building. This results in fewer sensors receiving direct sunlight through the skylight and gate.

Another contributing factor is the reduced obstructions towards the east, as the west-facing windows have the sky obstructed by the nearby milking building. During the spring equinox, the building fails to reach the EML threshold for 6 out of 16 hours on a clear day and 8 out of 16 hours on an overcast day. Winter solstice did not meet the EML threshold for 11 out of 16 hours on a clear day and 14 out of 16 hours on an overcast day.

Despite having a higher mean illuminance on the horizontal plane and a higher M/P ratio Table 16, the contribution towards EML from electric lighting is lower in the improved case compared to the old building's base case (41 compared to 62 EML). This is attributed to the luminaires having a narrower photometric light distribution, resulting in the vertical plane where EML is measured being less illuminated by direct or indirect light from the luminaires or reflected surfaces.

4.3.5 Improved middle building

The middle building was improved without drastically changing its envelope. Consequently, the EML results were very similar to the base case results obtained by changing fluorescent to LED light sources. Table 22 displays the EML results simulated after the sunset operating hour at 9 pm. Despite an increase in space illuminance, as indicated in Table 20, the EML was slightly lower compared to the base case. This is because the luminous distribution angle in LED lighting is narrower than that of fluorescent lighting when EML is measured on the vertical plane.

Table 22 - Middle building EML results

Improved middle Building		
Case	Base case	Improved case
Light source	Fluorescent	LED 55W
M/P	0.76	0.77
Equivalent melanopic lux (avg)	49	44
Photopic lux (avg)	64	53

5 Discussion

Daylight

Both the new building and middle building had an existing high potential for daylight harvesting to replace electric lighting, with the new building having the highest potential. Despite the new building being wider than the middle building. There are some key differences in the buildings affecting daylight provision, one being the roof height which governs the placement of the skylight. The newer building, being taller, allowed for the light from the skylight to be distributed over a larger floor area. The skylight-to-floor ratio of the new building was slightly lower, 6% compared to 7% of the middle building. This should allow for more light per floor area to enter through the skylight but as the skylight in the middle building extends closer to the gate, which allowed light to enter, this extra light did not necessarily contribute fully to increase the DA in the building.

Another great difference was in the side lighting. Measuring the floor to ceiling on the sides of the buildings, the new building was considerably higher than the middle building, 3.8 meters compared to 2.8. The sides of the new building were covered with translucent cloth. While the transmittance of this material was lower than that of the windows in the middle building the greater height allowed the light to reach further into the room and the WWR were also much higher in the new building. Finaly the new building was also unobstructed towards the east while the middle building had buildings on either side.

In the old building, the potential for daylight harvesting was low and while a skylight could introduce a high daylight autonomy in the building, this would represent a major change in the building. With the 16-hour days and 150 lux thresholds used in this study, reaching a DA of approximately 60% was possible, but this required several measures, including maintaining a high reflectance of surfaces and transmission of windows. Such values may not be sustainable due to the environment inside the buildings where surfaces constantly accumulate dirt and dust.

With a skylight, a DA above 50% was possible to obtain in the existing buildings and under current conditions. It was found that an increase in reflectance of interior surfaces did not substantially increase the daylight autonomy, or the illuminance provided from electric lighting. The interpretation is that this is due to the dark floor absorbing much of the incoming light, both natural and electrical, and only low amount of light reaches the other interior surfaces to be reflected. A brighter floor could potentially have a large impact, but maintaining a high reflectance of the floor would not be practical due to defecation in the cow area and machines running through the middle feeding alley.

Adding a skylight would entail some consequences for the old building. A skylight can provide a very high illuminance inside the building especially during long photoperiods in summer, with the risk of the light being excessive. Introducing more light through a skylight introduces additional solar heat gains, but it also gives the opportunity to improve the ventilation in the building through openable skylight windows. There was no active cooling in the buildings that would be affected by the skylight, however there are ceiling mounted fans which energy use might increase to remove excess heat. Neither was there any heating system to affect the energy use, as the cows accept a low THI.

Electric light

The energy savings potential from replacing the fluorescent lighting in this study was found to be 63% in the old building and 48% in the middle building. The new building, which in our study was assumed to use LED-lighting, the saving potential instead is found in utilizing daylight harvesting. A reason for the larger saving in the old building is that this building did not need to increase the illuminance to achieve the target of 150 lux. Another reason is that the luminaires in the old building were initially uneven distributed, where the north-east part of the building houses more luminaires per floor area compared to the north-west part. The replacing luminaires in the old building are evenly spread in the room.

Both the old and middle buildings had an increase in illuminance from the improved electric lighting. The increase in the middle building was higher as the base case of the middle building did not meet the illuminance target. When replacing the lighting system, the illuminance of the old building increased even though the total luminous flux provided by the luminaires decreased. In the improved case a greater part of the light from the luminaires was directly illuminating the measurement plane while the base case luminaires reflected some of its light off ceiling and wall surfaces, where light were absorbed. This resulted in a lower illuminance per produced lumen for the base case.

Energy use

The energy saving potential was found to be similar for daylight harvesting and electric lighting replacement. The DA in the buildings were 50 to 60% while the savings from improved electric lighting were 48 and 63%. Using both strategies the energy use for electric lighting could be reduced with 77% in the middle building and 83% in the old building compared with the base cases. In the new building the DA of 57% also represents a substantial savings potential.

In both simulations and energy calculations, we assumed that all luminaires were operational. During site visits, this was not the case as some luminaires were switched off completely or only half of the light sources inside the luminaire were operational. Consequently, the simulations did not fully reflect reality, however, comparing a non-functioning older installation with a fully functioning new installation would not result in a fair comparison.

Uniformity ratio

The replacement of the electric light reduced the uniformity ratio of the buildings. Both when considering the entire building and the specific areas housing the cattle the uniformity ratio did not meet the requirements. As such the specific luminaires used in the study cannot be recommended as a replacement in the specific cases studied.

Circadian conditions

In this study the EML benchmark set to an average of 125 EML for 4 hours was not reached during winter solstice with an overcast sky in any of the cases, but it was reached for the other conditions for all cases. There is a large difference between clear and overcast days, however, overcast days on spring equinox still resulted in a high average EML in the base case new and middle buildings as well as the improved old building with added skylight. In none of the cases did the electric lighting alone achieve the benchmark. In our study the implementation of the new LED-lighting led to a reduction in EML which we in large part attribute to the narrow luminous distribution of the selected luminaire.

The reason for the base case old building achieving the benchmark is due to the daylight through the entrances achieving a very high illuminance at individual sensor planes, raising the average of the building. In the improved case of the old building the EML was noticeably higher in the afternoon. This occurs as the east part of the building is partially occupied by a storage area which does not contain any sensor planes. This can also be seen in the base case results as the direct sunlight from the southern entrance does not directly hit any sensor planes in the morning. In the new and middle building there was a distinct drop in EML near midday on clear days. This drop is interpreted as the time where the direct sunlight through the skylight hits the feeding alley between two cattle areas. This area had no sensor planes. Another reason for the drop is that the high angle of the sun reduces the number of vertical sensor planes hit by the direct sunlight. The new building had a higher EML before noon than after as the west side of the building is unobstructed.

The species-specific toolbox used in the study was employed to estimate the error resulting from using EML measures designed according to human photoreceptors spectral sensitivity functions. The result showed a small difference between cows and humans in α-opic irradiance on the melanopsin when comparing standard CIE illuminants with SPDs closely resembling the light sources used in the study. The α-opic irradiance on the melanopsin was 12% higher for the fluorescent and 6% higher for the LED in cows compared to humans. Between the cows and humans there are a small difference in peak sensitivity of the melanopsin which could explain the difference in irradiances.

6 Conclusion

The purpose of this study was to investigate the energy-saving potential of efficient lighting and daylight harvesting in livestock buildings for dairy cows, with a secondary goal of evaluating circadian lighting conditions. In the study, the daylighting potential of three buildings was evaluated based on DA. In two of the buildings, the electric lighting solutions were changed to reduce energy use, along with several measures aimed at increasing DA. Five cases, three base cases and two improved ones, were simulated in ALFA on the spring equinox and winter solstice, on both clear and overcast days.

We found that the buildings did fulfill the Swedish workplace illuminance requirements in these types of buildings but fell short in fulfilling recommendations from LBK, as well as ASABE 2006 which requirements aim at increasing milk yield. An improvement on the proposed solution in this study could be a wider luminous distribution of the luminaires as the uniformity ratio requirement was not fulfilled. The requirement from Swedish Board of Agriculture on providing night lighting were investigated in literature studies but were not taken into account in simulations or energy calculations.

The implementation of LED lighting to replace fluorescent lighting proved effective at reducing electricity consumption. The LED luminaires used in the study were marketed for industrial use in the food industry. Replacing the existing lighting revealed a savings potential of 48 to 63%. While energy use was reduced, the illuminance in the improved buildings increased to above 150 lux, surpassing the values of the base cases.

The DA in the existing buildings was 12%, 50%, and 57% for the old, middle, and new buildings, respectively. The DA in the old building could be increased to 55% by implementing a skylight and up to 60% with several additional measures. Similarly, the DA in the middle building could be increased to 54% through higher transmittance of windows and brighter interior surfaces. We found that the energy-saving potential from utilizing daylight harvesting was comparable to that of replacing the existing fluorescent lighting with LED.

At the time of the study, there were no set benchmark values for circadian lighting in livestock buildings within requirements or recommendations. However, there were general requirements stating that lighting should support the circadian rhythm and behavioural needs of the animals. With the addition of a skylight, the buildings could achieve an average EML above 125 for more than 4 hours a day during spring and on sunny days during winter, meeting the requirements for learning environments in the WELL standard. The EML provided by electric lighting decreased when LED lighting was implemented, which can be attributed to the narrower luminous distribution of the LEDs. Our study, using point-in-time illuminance in ALFA simulations, demonstrated that daylight had a significant impact on the EML in the buildings compared to electric lighting. Increasing the illuminance from electric lighting on the horizontal plane did not necessarily result in a corresponding increase in EML on the vertical plane, even when using lighting with a higher M/P ratio. A luminaire with a distribution profile more similar to the base case fluorescent luminaire would have been a better choice, both for providing a higher uniformity but also for increasing the EML.

The challenges in this study revolved around determining the optimal lighting environment for dairy cows, rather than simply meeting requirements often geared toward human needs or maximizing milk production. There was a lack of species-specific guidelines and research concerning circadian lighting for dairy cows. In performing the photopic and circadian simulations we found a lack of shared material resources related to melanopic reflectance between ALFA and ClimateStudio, necessitating two sets of material selections and increasing the risk of errors. Furthermore, the point-in-time simulations in ALFA were time-consuming as they had to be initiated manually.

In future research, employing α-opic irradiance based on the opsin gene of cows could offer better insights into the effects of varying irradiances and photoperiods while enhancing comparability between studies. A preliminary step in this direction could involve summarizing existing results by converting photometric lux and light source spectrums into α-opic irradiances. In our study, we observed only small difference between humans and cattle concerning α-opic irradiances; however, this distinction may be more pronounced with other species or when using light sources with specific SPDs.

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Divisions of Energy and Building Design, Building Physics and Building Services
Department of Building and Environmental Technology